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Impact of *Senna spectabilis* on soil properties: Evidence from the Mayaga and Eastern Savannah in the Eastern Province of Rwanda

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Abstract

This research assesses the impact of *Senna spectabilis* on soil properties. Laboratory analysis of soil samples was carried out. Samples were collected from 16 sites of Mayaga and Eastern Savannah Agro-ecological zones in the Eastern Province of Rwanda. From each site, a composite soil sample under the tree canopy (treatment) as well as a control composite sample was taken away from trees. Each sample was taken at a depth of 0-30 cm. Results show that *Senna spectabilis* has various effects on soil. It increases soil nutrients such as Nitrogen, Phosphorus, Potassium, Calcium and Magnesium. It has improved the soil organic carbon (50%), soil aggregate stability (9.1%), soil pH (7.0%), and soil moisture content (23.9%). Moreover, it reduces the exchangeable acidity (20%). Our findings validate the hypotheses that *Senna spectabilis* has a positive effect on soil chemical, and physical properties. Although the results suggest planting more *Senna spectabilis* in agroforestry systems due to its capacity to improve soil properties, further research could focus on assessing factors that affect its adoption by farmers and studying nutrient dynamics beneath its canopy as well as its nutrient uptake patterns.

Keywords: *Senna spectabilis, soil nutrients, soil fertility, Rwanda.*

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Introduction

The increasing population growth remains one of the significant challenges for agriculture in Rwanda (MINAGRI, 2009, 2018; World Bank Group, 2018). This has led to land degradation, deforestation, loss and reduction of biodiversity, water shortages, and a struggle to ensure food security (C. Li et al., 2021; Muhirwa, 2017). Furthermore, soil degradation is exacerbated by physical, biological and chemical processes. (Hossain et al., 2020; Dragović & Vulević, 2021). The physical process includes reduction of arable soil (Ngendo et al., 2021) through the decline of soil structure, resulting in erosion, compaction and environmental pollution (Hossain et al., 2020; Dragović & Vulević, 2021). Biological processes include the reduction of land biodiversity (Hossain et al., 2020; Dragović & Vulević, 2021) and decrease in both the total and biomass carbon levels (Dragović & Vulević, 2021). Chemical processes include acidification (Ngendo et al., 2021), decline and loss of organic matter and nutrients, salinization and pollution (Dragović & Vulević, 2021; Hossain et al., 2020) Land degradation threatens agriculture growth (Meena, 2022). The current rainfed agricultural and forestry resources are insufficient to meet the needs of the growing population in terms of food and employment (MINAGRI, 2018; Nishimwe et al., 2020). This requires the conversion of low-productive and exploitable land into more productive ones through adopting agroforestry for diversification of production and maintainable biomass production (Muhirwa, 2017; Plieninger et al., 2020).

Agroforestry is identified as a holistic (Bansal et al., 2017) and potentially sustainable approach to achieving healthy soil, which is crucial for increasing agricultural production (Dollinger & Jose, 2002; Kumar et al., 2023; Sollen-Norrlin et al., 2020; Vinodhini et al., 2023). Agroforestry is seen as an appropriate way to enhance the livelihoods of rural communities through increased diversity of wood and non-wood products (Ahmad et al., 2020; Bansal et al., 2017;Vinodhini et al., 2023). The cultivation of suitable tree species alongside crops within agroforestry systems is identified as a strategy to decrease poverty and improve food security among farmers (Bansal et al., 2017; Vinodhini et al., 2023). Furthermore, agroforestry is recognized for its positive impact, potentially contributing to environment sustainability (Uwineza, et al., 2019; Bansal et al., 2017; Vinodhini et al., 2023). The decision of farmers to grow agroforestry trees, including *Senna spectabilis*, depends on numerous factors such as socio-economic characteristics, behaviour, and environmental factors

(Rwaburindi et al., 2019; Mukhlis et al., 2022).

Senna spectabilis is one of the agroforestry tree species found in Rwanda, and especially in the Eastern Province. It is a shrub with a resistance to drought, termite attacks, and rapid growth (Duarte-Vargas et al., 2021; Namirembe et al., 2009). It has an excellent good adaptation to infertile and acidic soils (Garrity & Mercado, 1994). Despite being a legume specie, *Senna spectabilis* is not nodulated. It has a capacity to produce large amount of foliage, which is useful for increasing soil nutrients for a companion crop (Gaisie, 2011; Mwungura, 2020), and to produce enough woody biomass to be used as source energy or fuelwood (Gaisie, 2011). *Senna spectabilis* also serves as an ornamental plant and a traditional medicine tree species. Additionally, its high content of minerals, proteins, and fat makes it a valuable forage compared to the other options (Duarte-Vargas et al., 2021).

Around three-quarters of Rwanda's soils are acidic, with a pH below 5.5. Moreover, there is a deficiency in nitrogen or phosphorus in these soils (MINAGRI, 2018). The agro-climatic zone of Mayaga and Eastern Savannah (Peripheral Bugesera) is the driest in the Eastern Province. The dominant soil type is Ferralsol, known for strong weathering and poor agriculture value (Kabirigi et al., 2017)This study aimed to contribute to existing knowledge by assessing the role of *Senna spectabilis* in improving soil fertility properties and crop production in the Eastern Province of Rwanda. It was guided by the following research question: Does Senna spectabilis improve soil fertility properties, reducing soil acidity in the Eastern Province of Rwanda.

Methodology

Study area

The study was conducted in the Mayaga and Eastern Savannah Agro-climatic zone, which known for prolonged dry spells associated with the problem of termites (Mukuralinda et al.,2016). It covers large parts of the districts of Bugesera and Ngoma and a small portion of Rwamagana. This research was conducted as part of the Enabel/DeSIRA project, which selected 16 villages in the study area for a survey.

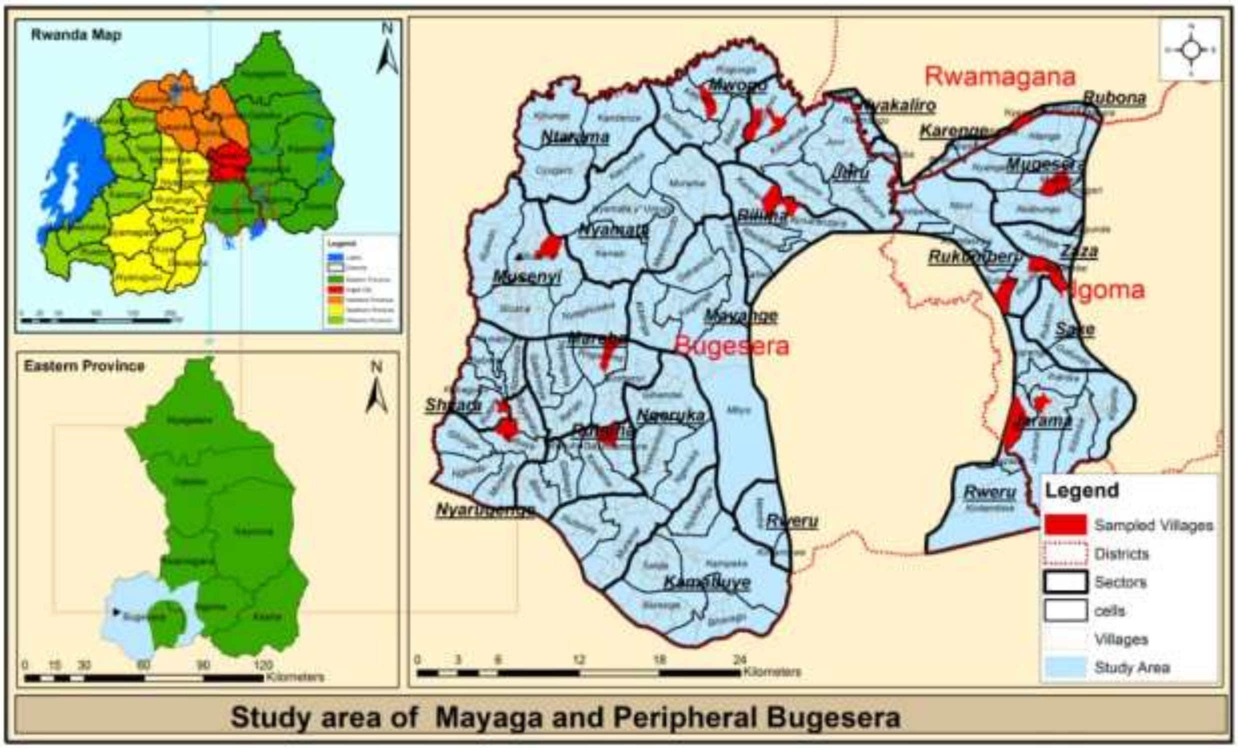

Figure 2 The study area of Mayaga and Peripheral Bugesera within Rwanda, sampled villages are in red, and detailed boundaries of districts, sectors, cells, and villages. The study area encompasses districts of Bugesera, Rwamagana, and Ngoma districts, Sebasore,2021

Sixteen pairs of composite soil samples were collected from Bugesera, Ngoma and Rwamagana districts. The sampling was done using the radial arm method (Vagen & Winowiecki, 2020).The Y pattern was followed to collect four soil samples taken at a depth of 30 cm (see Figure 2) and geographical coordinates were taken in the centre of Y. The sampling depth range was assumed to be relevant for assessing soil fertility and crop root activity. These four soil samples were mixed to form one composite sample under the *Senna spectabilis* tree canopy (treatment) and away from the tree (control). The creation of composite samples helps capture the overall variability within each treatment and control group, providing a representative picture of soil properties. *Senna Spectabilis* trees with a minimum tree age of five years were considered, while control samples were taken away from trees within similar environmental conditions but without Senna spectabilis influence (at 20m from the tree). This helps control for spatial variations in soil properties. Soil samples were collected in December 2021.

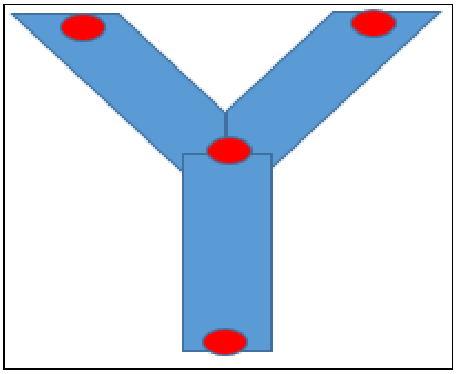

Figure 3 The Y-shaped sampling pattern is used for soil collection for soil fertility and root activity. Four soil samples at a depth of 30 cm, represented by a red dot at the arms and base of the Y. The Centre of the Y is the georeferenced point of the plot.

Soil Analysis Methods

For the analysis of composite soil samples, different methods were used. Titration (Walkley - Black procedures) was used to analyse soil carbon; block digester for soil nitrogen, Bray's method No.2 for available phosphorus, Flame photometric method for basic cations (K^+, Ca^{2+} and Mg^{2+}), titration method for exchangeable acidity, and pH of soil sample using pH meter after mixing sample with distilled water (Okalebo et al., 2002).

Statistical analysis

The data was analyzed using different statistical methods. This included descriptive statistics using SPSS software (IBM SPSS 20) and a t-test to compare the means of treatment and control groups. Paired samples were compared to analyze mean differences, followed by correlation analysis to explore relationships between soil properties. The correlation analysis aimed to assess the impacts of one property on another. The difference between treatments mean was analyzed at 5 % significance level.

Results

Soil physical properties

Results in Table 1 show significant differences between treatment and control groups in terms of soil moisture content (SMC) and soil aggregate stability (SAS). The SMC under tree canopy was 11.4%, while it was 9.149% away from tree canopy. The SAS mean value was 0.721 under tree canopy compared to 0.650 outside the tree canopy. This suggests that the planting of *Senna spectabilis* has positive impacted some soil physical properties.

Table 4. *Comparison of soil physical, organic, and chemical properties between treatment and control groups. the mean values and standard errors of the mean (Mean ± SE) are presented*

Parameter (Mean ±SE)	Treatment	Control	p-value
Physical properties			
SMC (%)	11.3± 0.93	9.149± 0.95	0.001
SAS (.)	0.7± 0.02	0.650± 0.02	0.000
Organic properties			
SOC (%)	1.8±0.14	1.22±0.06	0.000
SOM (%)	3.2±0.24	3.15±0.24	0.000
Chemical properties			
Soil pH	5.5±0.10	5.13±0.10	0.000
Total N (%)	0.3±0.02	0.19±0.01	0.000
Available P (mg/kg)	74.5±3.59	55.86±4.60	0.000
K^+ (cmol/kg)	0.1±0.00	0.04±0.00	0.000
Ca^{2+} (cmol/kg)	1.0±0.03	0.92±0.02	0.000
Mg^{2+} (cmol/kg)	0.4±0.02	0.37±0.02	0.001
Al^{3+} (cmol(+)/kg)	0.10±0.01	0.13±0.01	0.000
H^+ (cmol(+)/kg)	0.22±0.02	0.26±0.02	0.004
T.E. Acidity (cmol(+)/kg)	0.32±0.02	0.40±0.02	0.000

Correlation between soil moisture and aggregate stability

Correlation results reveal specific relationships between SMC, SAS, and various soil parameters (Table 2). There was a positive and significant correlation between SMC and nitrogen as well as phosphorus (P). this suggests that as the SMC increases, and the levels of total Nitrogen and available P also increased. However, there was no significant correlation between SMC and other elements such as soil pH, SAS, soil organic carbon (SOC) and soil organic matter (OM). Similarly, a positive and significant correlation was observed between SAS and all parameters, except SMC. This indicates that as SAS improves, there was a tendency for the associated parameters to increase as well, contributing to improved soil health and fertility.

Table 5. ***Correlation showing the relationships between soil parameters, significant correlations are marked with * (p < 0.05) and ** (p < 0.01)***

Parameter	pH	SMC	SAS	SOC	SOM	N	P
SMC	0.321	1.000	0.245	0.104	0.106	0.393*	0.348*
SAS	0.486**	0.245	1.000	0.565**	0.566**	0.351*	0.467**

Soil organic properties

There was a significant difference in Soil Organic Carbon (SOC) between treatment and control groups. Specifically, SOC levels were measured at 1.83% under tree canopy and 1.22% away from the canopy (Table 1). The analysis has also shown a positive correlation between SOC and soil pH, SAS, SOM, total N, and available P, as well as negative correlations with Aluminium (Al3+), hydrogen (H+), and total exchangeable acidity (TEA) (Table 3).

Table 6 Correlation coefficients between soil organic carbon (SOC) with soil aggregate stability (SAS), soil organic matter (SOM) , H^+,Nitrogen (N) , and phosphorus (P) , aluminum (Al3+) , and total exchangeable acidity (TEA) Asterisks indicate significance levels: *p < 0.05, **p < 0.01

Parameter	pH	SAS	SOC	SOM	N	P	Al^{3+}	H^{+}	TEA
SOC	0.643**	0.565**	1.000	1.000**	0.594**	0.446**	-0.369*	-0.507**	-0.577**

Soil chemical properties

The analysis of soil chemical properties has shown a significant difference in soil chemical properties between the treatment (under canopy) and control groups (outside the tree canopy) (see Table 1). The soil pH was higher under the tree canopy (5.49) compared to outside the tree canopy (5.13). Additionally, the concentration of total exchangeable acidity elements (Al^{3+} and H^+) was lower under tree canopy than in outside tree canopy. Furthermore, the amounts of total N and available P were higher under the tree canopy compared to away from the tree canopy. Similarly, the concentration of all basic cations (K^+, Ca^{2+}, and Mg^{2+}) was higher under the tree canopy compared to outside the canopy.

Correlation between soil pH and various chemical properties

The notable relationships observed in the study included a high significant negative correlation between pH and Al^{3+} ($r = -0.512$, $p < 0.01$). Additionally, a high significant positive correlation was identified between H^+ and T.E.A ($r = 0.942$, $p < 0.01$). These findings yield valuable insights into the intricate interactions among vital soil nutrients and chemical properties, thus contributing to a deeper understanding of soil fertility dynamics.

Table 7. ***Correlation matrix between soil pH and various chemical properties including nitrogen (N), phosphorus (P), potassium (K+), calcium (Ca2+), magnesium (Mg2+), Aluminum (Al3+), hydrogen (H+), and total exchangeable acidity (TEA) Asterisks indicate significance levels: *p < 0.05, **p < 0.01.***

	pH	N	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H^+	T.E.A
pH	1.000								
N	0.526^{**}	1.000							
P	0.512^{**}	0.402^{*}	1.000						
K^+	-0.004	0.382^{*}	-0.034	1.000					
Ca^{2+}	-0.049	0.359^{*}	0.026	0.283	1.000				
Mg^{2+}	0.290	0.319	0.380^{*}	0.466^{**}	-0.222	1.000			
Al^{3+}	-0.512^{**}	-0.536^{**}	-0.433^{*}	-0.346^{*}	-0.333	-0.337	1.000		
H^+	-0.484^{**}	-0.174	-0.366^{*}	0.029	0.222	-0.151	0.040	1.000	
TEA	-0.624^{**}	-0.330	-0.472^{**}	-0.077	0.127	-0.249	0.354^{*}	0.942^{**}	1.000

Discussion

The effects of Senna spectabilis on soil physical properties

Senna spectabilis was found to increase soil moisture content (Table 1). This enhanced the availability of water to plants. Furthermore, the presence of *Senna spectabilis* contributed to an improvement of soil aggregate stability (Table 1). This is beneficial for soil structure and health. The decomposition of *Senna spectabilis*' leaves plays a role in enhancing soil porosity. This process results in improved water infiltration and storage in the soil. Further, the growing roots of *Senna spectabilis* are identified as a factor contributing to increased porosity in the soil. This is supported by the research of Sarto et al.(2022) on deep soil water content and forage production in a tropical agroforestry system. Fungi and bacteria release organic glue during the decomposition process, therefore binding soil particles together and contributing to the formation of stable soil aggregates (Obalum et al., 2017). The findings of study (table 2) indicated that the increase in the level of soil organic carbon also rises the level of soil aggregation as supported by Tomar et al., 2021. Organic carbon was straightly connected to aggregation of soil because it has ability to form organic core that bound soil particles and aggregates (Guo et al., 2019). The increase of soil aggregate stability protects nitrogen and phosphorus from loss (Liu et al., 2019).

The effects of Senna spectabilis on soil organic properties

This study highlighted the positive impact of *Senna spectabilis* on soil organic matter and organic carbon storage (Table 1). This could have been done through the process of carbon sequestration. Researches have shown that carbon sequestrated is first stored in biomass and then in soil through the decomposition of biomass from the plant (Lal et al., 2015; Morgan et al., 2010).The organic matter is reported to contain around 58% of organic carbon, with the remaining portion occupied by other nutrients. The increase of soil organic carbon is a good indicator of fertile soil (Ndlovu et al., 2013). Agroforestry systems, which include the cultivation of tree species like *Senna spectabilis,* contribute significantly to the increase of soil organic carbon storage compared to conventional cropping systems (Tsufac et al., 2019; Ndlovu et al., 2013). The correlation findings presented in table 3 support the notion that an increase in soil organic carbon leads to higher levels of soil pH, nitrogen, and available phosphorus, which is alined with others researches (Wibowo & Kasno, 2021; Prasad & Chakraborty, 2019).This is backed by research from Naramabuye and Haynes (2006), who found that organic matter has the ability to reduce soil acidity by forming complexes with Aluminum.

The effects of Senna spectabilis on soil chemical properties

The study found that Senna spectabilis had a positive impact on soil pH by reducing exchangeable acidity, mainly through Aluminum complexation (Table 1). The increase in soil pH is due to *Senna spectabilis*'s ability to produce more organic matter. This organic matter releases basic cations like K+, Ca2+, and Mg2+ into the soil. As organic matter decomposes, the concentration of basic cations in the soil increases, helping to neutralize soil acidity and raise the soil pH. This process reduces the saturation of exchangeable acidity in the soil, improving plant growth conditions. The researchers also found that an increase in organic matter reduces Aluminum toxicity(Muchane et al., 2020; Ndlovu et al., 2013;; Gaisie, 2011; Sileshi et al., 2014; Naramabuye & Haynes, 2006).

Moreover, soil pH increases, and total nitrogen and available phosphorus also increase (Table 1) as an impact of *Senna spectabilis*. This aligns with preview research, which found that foliar pruning from *Senna spectabilis* increased total nitrogen, available phosphorus, potassium, calcium, and Magnesium (Mwungura, 2020). *Senna spectabilis* also produces large amount of foliage, which is useful in increasing plant soil nutrients for companion crops (Gaisie, 2011; Udawatta et al., 2017).

The correlation of pH with nitrogen and available phosphorus was positive (Table 4). This means that soil pH increases with the increase in total nitrogen and available phosphorus. This is due to litter fall from *Senna spectabilis* which decomposed to release nitrogen, phosphorus and other nutrients including basic cations which neutralized soil acidity. soil pH affects the availability of nutrients. In high acidic soil (pH <5), phosphorus becomes unavailable to plants due to its fixation by cations (Zama et al., 2022). On the other hand, the increase of soil pH affects positively the availability of phosphorus, while a high pH level above 8 reduces availability of phosphorus (Khaidem & Thounaojam, 2018; Nathan M. V., 2009; Oswalt, 2024).

The correlation of pH with acidity parameters (Aluminum and hydrogen) was negative (Table 4). As the soil pH decreased, the concentration of soluble aluminium increased, making it toxic. When the pH fell below 5, aluminium became soluble, but when the pH rose above 5, aluminium precipitated out of the soil solution. This correlation between pH and aluminum was negative, as confirmed by (W. Li & Johnson, 2016; USEPA, 2003). The presence of a large amount of cations neutralized soil acidity, resulting in a reduction of soil pH level (Muchane et al., 2020; Sileshi et al., 2014).

Conclusion

The study aimed to assess the effects of *Senna spectabilis* on the physical, organic, and chemical properties of soils in the Eastern Province of Rwanda. The research involved laboratory analysis comparing soil properties of composite soil samples collected under the canopy of Senna spectabilis with those of composite samples collected 20 meters away from the canopy. The results showed that *Senna spectabilis* has a positive impact on soil properties to improve water retention, soil structure, aggregate stability, and nutrient content. Specifically, it increased soil nutrients such as Nitrogen, Phosphorus, Potassium, Calcium, and Magnesium by 68.4%, 33.3%, 25.0%, 6.5%, and 16.2% respectively. Additionally, it enhanced soil organic carbon, soil aggregate stability, soil pH, and soil moisture content while reducing exchangeable acidity by 50%, 9.1%, 7.0%, 23.9%, and 20.0%, respectively. The findings suggest that *Senna spectabilis*, as part of agroforestry systems, enhances organic carbon storage, contributing to soil fertility and nutrient availability. Furthermore, the tree positively influences soil pH, reduces exchangeable acidity, and creates favourable conditions for companion crops. The research findings support the promotion of *Senna spectabilis* in the study area as a comprehensive solution to address soil-related challenges, resistance to termites and drought, and to promote sustainable agriculture. This strategy can yield positive outcomes for farmers and the environment in the region. While the current study focused on soil properties, it is advisable to conduct further research on the evaluation of nutrient content in the biomass of *Senna spectabilis*, particularly in its leaves and pods, and to assess the dynamics of nutrients under its canopy (along the soil profile below 30cm). This would contribute to a more comprehensive understanding of nutrient cycling in such an agroforestry system. Furthermore, there is a pressing need to investigate its contribution to crop yield and the factors associated with a compromise or synergy with associated crops.

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Disclosure

We declare no conflict of interest regarding the authorship and publication of this paper.

Data availability

Data will be made available on request.

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