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Interactive Effects of Soil Texture and Sowing Depth on Seedling Emergence Dynamics of Bambara Groundnut (*Vigna subterranea* L. Verdc.)

Yaya TOURE [a*], Arthur Martin AFFERY [a], Tchoa KONE [b] and Mongomaké KONE [b]

[a] Department of Agronomy and Forestry, UFR Agricultural, Forestry and Environmental Engineering, Université de Man, Man, Côte d'Ivoire.
[b] Laboratory of Plant Biology and Crop Improvement, UFR Natural Sciences, Université Nangui Abrogoua, Abidjan, Côte d'Ivoire.

Authors' contributions

This work was carried out in collaboration among all authors. Author YT did the Conceptualization, data curation, formal analysis, investigation, methodology, writing original draft. Author AMA did the Conceptualization, Investigation, writing review and editing. Author TK did the Conceptualization, investigation, methodology, writing review and editing. Author MK did the Conceptualization, writing review and editing, supervision. All authors read and approved the final manuscript.

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Abstract

Aims: Bambara groundnut (*Vigna subterranean* L. Verdc.) is an underutilized African legume with high nutritional value and strong adaptation to marginal environments, yet its field establishment is often unreliable due to poor seedling emergence. This study aimed to evaluate the combined

**Corresponding author: E-mail: toureyaya12@yahoo.fr;*

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effects of soil texture and sowing depth on seedling emergence dynamics in order to identify optimal practical, soil-specific sowing recommendations that can enhance crop establishment and productivity for smallholder farmers.

Study Design: A completely randomized factorial experiment combining three soil textures and six sowing depths

Place and Duration of Study: The experiment was conducted under greenhouse conditions using soils representative of major Bambara groundnut production zones in West Africa. The trials were repeated three times at one-month intervals, between January and May 2025.

Methodology: Three soil types (sandy, gravelly and clayey) were used. Seeds were sown at six depths (2, 3, 4, 5, 6 and 7 cm) in pots. Seedling emergence was monitored daily. Emergence parameters including First Day of Emergence, Last Day of Emergence, Time Spread of Emergence, Mean Emergence Time, Coefficient of Velocity of Emergence and Emergence Percentage were determined. Data were analyzed using two-way analysis of variance.

Results: Sowing depth significantly affected all emergence parameters. Shallow sowing (2-4 cm) resulted in rapid, synchronized and high-percentage emergence, with values reaching up to 98%. Deeper sowing (>4 cm) significantly delayed emergence, extended emergence duration and reduced final emergence percentages. Soil texture had a secondary but significant effect, particularly at greater depths. Sandy soil consistently promoted faster and more uniform emergence, whereas gravelly and clayey soils limited emergence due to increased mechanical resistance and reduced aeration.

Conclusion: Optimal emergence of Bambara groundnut occurs at shallow sowing depths, particularly in sandy soils. These results provide clear, agronomically relevant guidance for farmers, supporting soil-specific sowing depth recommendations that can improve stand establishment, reduce early crop failure and enhance yield reliability.

Keywords: Bambara groundnut; sowing depth; soil texture; seedling emergence; emergence synchrony.

1. Introduction

Bambara groundnut (*Vigna subterranea* (L.) Verdc.), also known as Bambara bean, earth pea or jugo bean, is an indigenous African legume of high nutritional, agronomic and ecological importance. It is well adapted to low-input farming systems and marginal environments, owing to its tolerance to drought and poor soils. Despite these advantages, Bambara groundnut remains one of the most underutilized food legumes in sub-Saharan Africa (Mabhaudhi and Modi, 2013). In terms of production and consumption, it ranks third after groundnut (*Arachis hypogaea*) and cowpea (*Vigna unguiculata*) (Mateva et al., 2023). Its seeds provide a valuable source of protein and carbohydrates and play an important role in household food and nutrition security, particularly in Southern African Development Community (SADC) countries (Azam-Ali, 1993). Nevertheless, Bambara groundnut productivity remains low and highly variable across production areas. Yield instability is attributed to several constraints, including drought stress, low soil fertility, temperature variability, biotic pressures, and socio-economic limitations (Majola et al., 2021). Among agronomic factors, successful crop establishment is a critical determinant of final yield. Soil type and sowing depth are particularly important because they directly influence seed germination, seedling emergence, early vigor and stand uniformity (Zuo et al., 2017).

In Côte d'Ivoire, Bambara groundnut is mainly cultivated on sandy and gravelly soils, while clayey soils are exploited primarily in lowland areas during dry seasons (Touré et al., 2013). These soil types differ markedly in their physical and hydrological properties, affecting seed–soil contact, moisture availability, aeration and mechanical resistance during germination and emergence. Despite this variability, sowing practices are largely empirical, and farmers rarely adjust sowing depth according to soil texture or moisture conditions (Sparg et al., 2005). Such practices often result in irregular seedling emergence, weak plant stands and reduced yields. Previous studies have demonstrated that seedling emergence is closely linked to final crop performance and that inappropriate sowing depth can severely limit plant establishment (Touré et al., 2012, Ugwu et al., 2025). While the effects of soil texture or sowing depth have been studied independently in several grain legumes, information on their interactive effects on Bambara groundnut

emergence remains scarce, particularly under contrasting edaphic conditions. This knowledge gap constrains the development of precise, soil-specific agronomic recommendations for improving crop establishment.

Therefore, the present study aimed to evaluate the combined effects of soil texture and sowing depth on the seedling emergence dynamics of Bambara groundnut. The objective was to identify optimal combinations of soil type and planting depth that promote rapid, uniform and successful emergence, thereby contributing to improved stand establishment and sustainable productivity of Bambara groundnut under diverse soil conditions.

2. Materials and Methods

2.1 Plant Material Origin and Characteristics

The plant material consisted of seeds of Bambara groundnut exhibiting a beige coloration mottled with red (Fig. 1). The average individual seed mass ranged from 0.70 to 0.80 g. Seeds were collected from local farms in Korhogo, northern Côte d'Ivoire, where this landrace is the most commonly cultivated due to its high adaptability and grain quality (Touré et al., 2013). Prior to sowing, seeds were manually sorted to remove broken or deformed grains and stored under ambient laboratory conditions until use.

Fig. 1. Bambara groundnut seeds used in this study

2.2 Experimental Setup

The experiment was carried out in plastic pots (10 cm radius × 17 cm height) filled with one of three soil types: sandy, gravelly, and clayey soils collected from representative lowland sites in Côte d'Ivoire (Table 1). These soils correspond to the main edaphic environments in which Bambara groundnut is traditionally cultivated in West Africa. The experiment was arranged in a completely randomized block design with three replicates. Each treatment combination (soil type × sowing depth) comprised 20 pots, each containing a single seed. The entire experiment was repeated three times at one-month intervals to ensure reproducibility, between January and May 2025. In total, 1080 seeds were sown per trial.

2.3 Trial Management

Seeds were sown at six depths: 2, 3, 4, 5, 6, and 7 cm. Before planting, all soils were moistened to field capacity to ensure homogeneous conditions. Throughout the experiment, pots were irrigated daily in the evening with approximately 5 mm of water to maintain uniform soil moisture. The greenhouse was maintained under natural photoperiod and temperature conditions typical of the northern Ivorian environment during the experiment period. Emergence was monitored from the day of sowing until no further seedlings appeared.

2.4 Determination of Emergence Parameters

A seedling was considered emerged once its first two leaves were visible above the soil surface. The following emergence parameters were calculated based on daily counts, using formulas commonly applied to germination studies (Sparg et al., 2005; Zuo et al., 2017):

- First Day of Emergence (FDE): The number of days from sowing to the appearance of the first seedling on the soil surface. It indicates the earliness of emergence.
- Last Day of Emergence (LDE): The number of days from sowing to the emergence of the last seedling observed. It represents the duration of the emergence period.
- Time Spread of Emergence (TSE): It reflects the synchrony of emergence: a smaller TSE indicates more uniform emergence.
- Emergence Percentage (EP): The proportion of seedlings that successfully emerged compared to the total number of seeds sown, expressed as a percentage. It measures the success rate of seedling establishment.

$$\mathrm{EP} = \frac{\text{Number of emerged seedlings}}{\text{Number of seeds sown}} \times 100 \quad (1)$$

Table 1. Physical properties of experimental soils

Soils	Particulars	Value	Soils textures
Soil 1	Gravel (%)	41.5	Gravelly sand
	Sand (%)	56.1	
	Silt (%)	1.8	
	Clay (%	0,6	
Soil 2	Gravel (%)	2.5	Sandy loam
	Sand (%)	57.6	
	Silt (%)	25.7	
	Clay (%	14.2	
Soil 3	Gravel (%)	-	Clay
	Sand (%)	32,5	
	Silt (%)	22.9	
	Clay (%	44.6	

- Mean Emergence Time (MET): The weighted average time required for seedlings to emerge, calculated using the number of seedlings emerging each day. It indicates the average speed of emergence.

$$\mathrm{MET} = \frac{n_1 \times d_1 + n_2 \times d_2 + \cdots + n_i \times d_i}{N} \quad (2)$$

where ni represents the number of seedlings emerged on day di and N, total number of emerged seedlings.

- Coefficient of Velocity of Emergence (CVE): A parameter expressing the rapidity and uniformity of seedling emergence. Higher CVE values indicate faster and more synchronized emergence.

$$\mathrm{CVE} = \frac{N}{n_1 \times d_1 + n_2 \times d_2 + \cdots + n_i \times d_i} \times 100 \quad (3)$$

2.5 Data Analysis

Percentage data were transformed using the arcsine square-root (√x) transformation prior to analysis, although untransformed values were used for graphical representation. A two-way analysis of variance (ANOVA) was performed to assess the effects of soil type, sowing depth, and their interaction. When the F-test indicated significance at the 5% level, mean comparisons were carried out using the Student-Newman-Keuls (SNK). All statistical analyses were conducted using RStudio (version 2024.12.1 + 563; Posit Software, PBC, 2025) and R (version 4.3.3; R Core Team, 2024).

3. Results and Discussion

The two-way analysis of variance revealed a highly significant interaction between soil texture and sowing depth for all emergence parameters (P = 0.001), except for Mean Emergence Time (MET) and Coefficient of Velocity of Emergence (CVE), for which the interaction remained significant at the five percent probability level. This indicates that the response of Bambara groundnut emergence to soil texture depends strongly on sowing depth, highlighting the importance of considering both factors simultaneously when optimizing crop establishment.

3.1 Emergence Timing: First and Last Days of Emergence (FDE and LDE)

First Day of Emergence (FDE) and Last Day of Emergence (LDE) increased progressively with increasing sowing depth across all soil textures (Figs. 2 and 3). At the shallowest depth of 2 cm, emergence occurred earliest, approximately six days after sowing, reflecting favorable physical and physiological conditions for seedling breakthrough. At intermediate depths ranging from 3 to 5 cm, emergence was moderately delayed, while the deepest sowing at 7 cm resulted in the latest emergence, with FDE and LDE extending to about 9.5 and 12.5 days, respectively. This progressive delay with depth can be attributed to the increased distance seedlings must traverse to reach the soil surface, combined with reduced oxygen diffusion and greater mechanical resistance at deeper soil layers. Similar depth-dependent delays in emergence have been reported in other crops, where deeper burial limits gas exchange and slows hypocotyl elongation (Tang et al., 2016; Kanno et al., 2025). Among soil types, sandy soil consistently promoted earlier emergence completion, whereas gravelly and clayey soils induced longer delays, particularly at depths greater than 4 cm. This reflects the more favorable physical structure of sandy soil, which facilitates seedling penetration and aeration. Comparable responses have been observed in

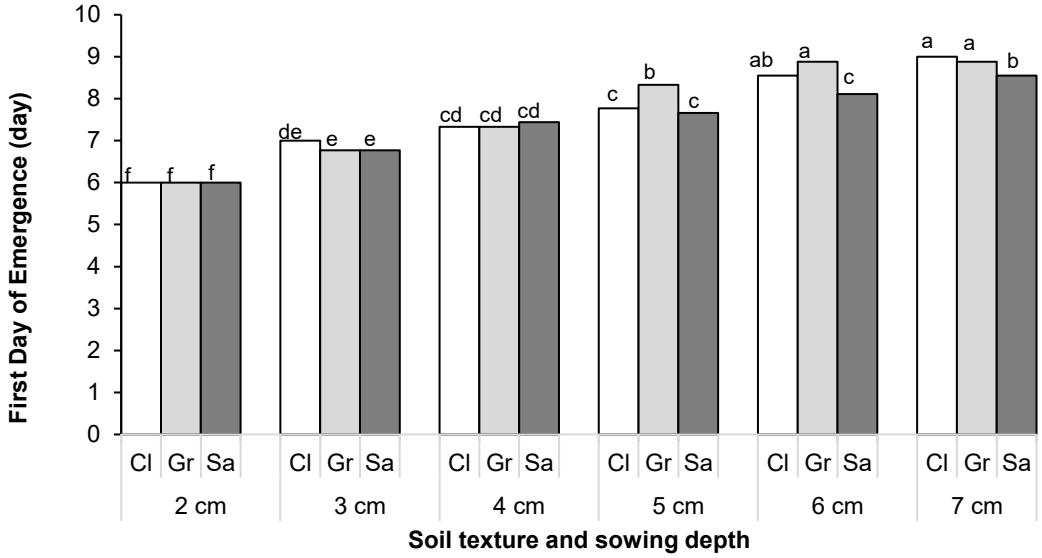

Fig. 2. Effect of sowing depth and soil type on the first day of Bambara groundnut seedling emergence (FDE)

Cl: Clayed soil; Gr: Gravelly sand soil; Sa: Sandy soil; Different letters indicate significant differences between means as determined by the Student-Newman-Keuls (SNK) post hoc test at the 5% significance level

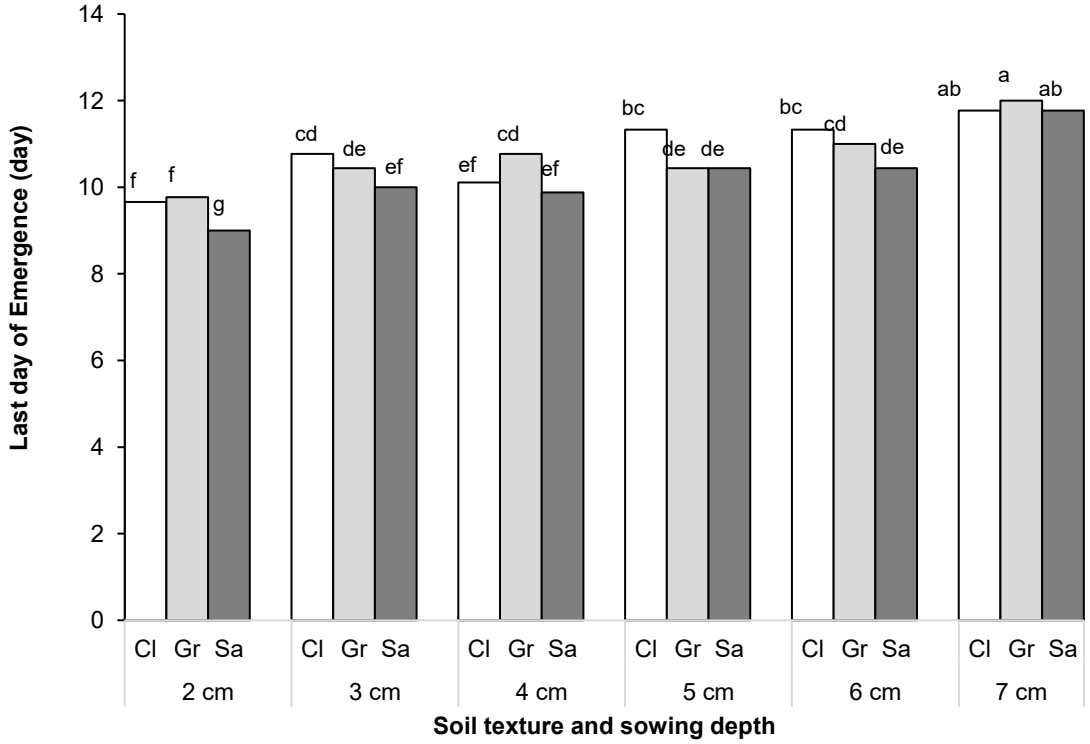

Fig. 3. Effect of sowing depth and soil type on the last day of Bambara groundnut seedling emergence (LDE)

Cl: Clayed soil; Gr: Gravelly sand soil; Sa: Sandy soil; Different letters indicate significant differences ($P < 0.05$)

Pericopsis elata and *Khaya senegalensis*, where shallow sowing in light-textured substrates enhanced emergence earliness (Onana 2009; Silué et al., 2021).

3.2 Emergence Synchrony: Time Spread of Emergence (TSE)

Time Spread of Emergence (TSE) decreased markedly between sowing depths of two and 6 cm, indicating improved synchronization of seedling emergence at moderate depths (Fig. 4). This suggests that, within this depth range, environmental conditions were sufficiently homogeneous to allow coordinated seedling development. At 7 cm, however, TSE increased again, reflecting greater variability in emergence timing due to intensified mechanical constraints and micro-environmental heterogeneity. Soil texture strongly influenced emergence synchrony. Sandy soil consistently exhibited the narrowest emergence period, whereas gravelly and clayey soils produced more extended emergence durations. This agrees with findings reported by Gerrano et al. (2021), who demonstrated that lighter-textured soils enhance emergence uniformity and early crop competitiveness. The loose structure and continuous pore network of sandy soil likely promote uniform moisture distribution and reduce physical barriers, thereby supporting synchronous seedling emergence.

3.3 Emergence Success: Emergence Percentage (EP)

Emergence Percentage (EP) declined significantly with increasing sowing depth (Fig. 5), highlighting the detrimental effects of excessive burial on establishment success. At shallow depths of 2 and 3 cm, emergence exceeded ninety percent across all soil types, indicating optimal conditions for seedling establishment. Beyond 4 cm, marked differences emerged among soil textures: sandy soil maintained high emergence rates, even at 6 cm, while gravelly and clayey soils showed pronounced declines, particularly from depths of 4 cm onwards. These results are consistent with previous studies reporting depth-related reductions in emergence for *Merwilla natalensis* (Sparg et al., 2005), rice (*Oryza sativa*) (Yang et al., 2022), and several weed species (Pereira de Moura et al., 2024). Higher emergence at shallow depths is likely associated with improved oxygen diffusion, greater thermal stability, and adequate moisture availability near the soil surface (Johnson et al., 2019). In contrast, deeper sowing increases the energetic cost of emergence, potentially exhausting seed reserves before seedlings reach the surface. The lower emergence observed in gravelly soil may be linked to irregular pore distribution and localised desiccation, while the compact structure of clayey soil likely restricts aeration and increases mechanical resistance, leading to transient hypoxia around germinating seeds (Dürr et al., 2001; Zuo et al., 2017).

3.4 Emergence Rate: Mean Emergence Time (MET) and Coefficient of Velocity of Emergence (CVE)

Mean Emergence Time (MET) increased steadily with sowing depth, from approximately 7.5 days at 2 cm to more than 10.5 days at 7 cm (Fig. 6). Differences among soil textures were relatively small and became statistically non-significant at depths greater than 6 cm, confirming that sowing depth was the dominant factor controlling emergence speed, overriding the influence of soil texture under deep burial conditions Shallow sowing, particularly at depths not exceeding 4 cm, clearly enhanced the rate of seedling establishment, whereas deeper sowing, especially beyond 5 cm, substantially slowed the process. In parallel, the Coefficient of Velocity of Emergence (CVE) declined progressively with increasing sowing depth, with the highest values recorded at shallow depths (Fig. 7). This decline indicates that deeper sowing not only delayed emergence but also reduced its uniformity. High CVE values at shallow depths reflect rapid and synchronized emergence, which is essential for uniform stand establishment and early crop competitiveness. Comparable findings have been reported in grain legumes and oilseed crops, where shallow sowing improved emergence velocity by minimizing mechanical constraints and maintaining favorable soil physical conditions around the seed (Zuo et al., 2017).

3.5 Agronomic Implications

Overall, sandy soil provided the most favorable environment for Bambara groundnut emergence, combining rapid, uniform, and high-percentage seedling establishment. Gravelly and clayey soils, in contrast, imposed physical and aeration-related constraints that limited emergence success beyond moderate sowing depths. These findings highlight the necessity of adjusting

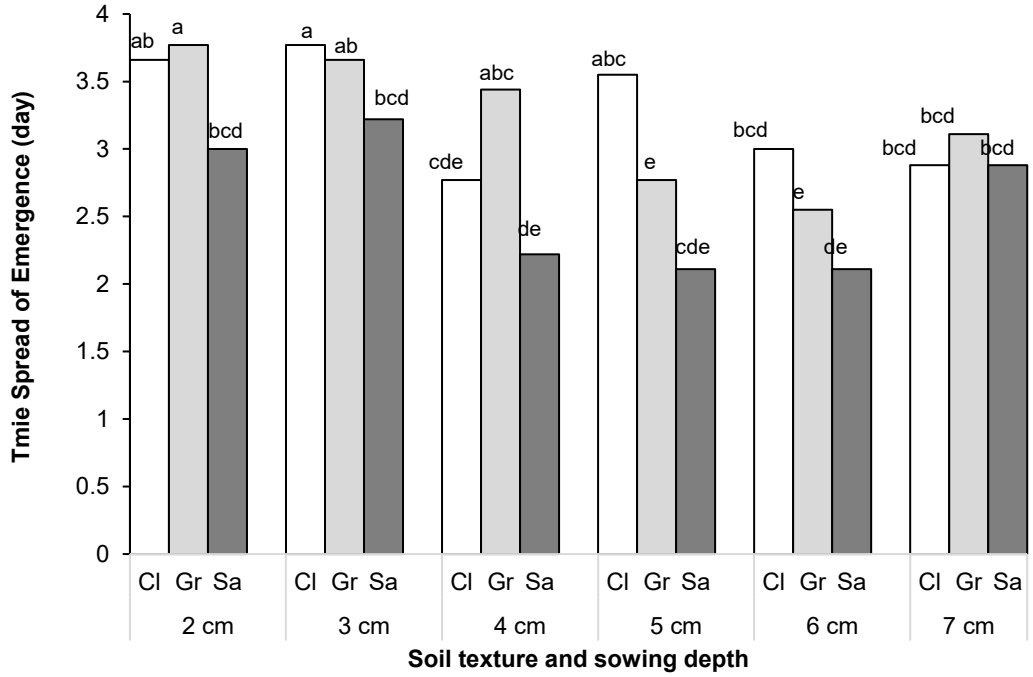

Fig. 4. Time Spread of Emergence (TSE) of Bambara groundnut seedlings as affected by sowing depth and soil type

Cl: Clayed soil; Gr: Gravelly soil; Sa: Sandy soil; Different letters indicate significant differences (P < 0.05)

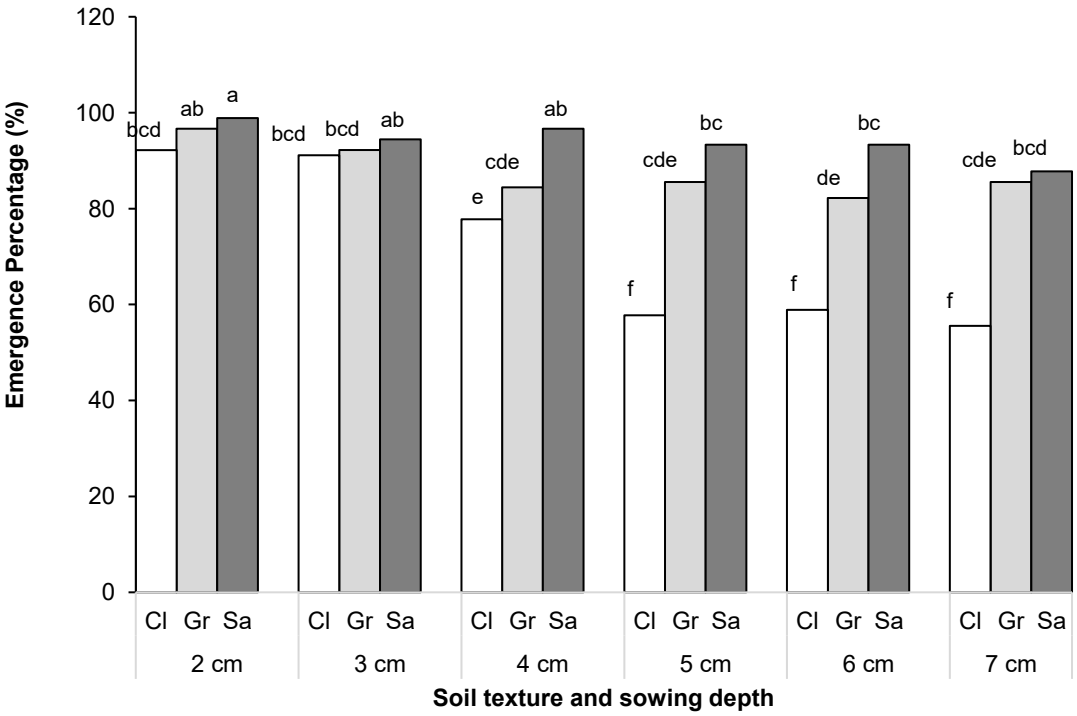

Fig. 5. Effect of sowing depth and soil type on seedling Emergence Percentage (EP) of Bambara groundnut

Cl: Clayed soil; Gr: Gravelly soil; Sa: Sandy soil; Different letters indicate significant differences (P < 0.05)

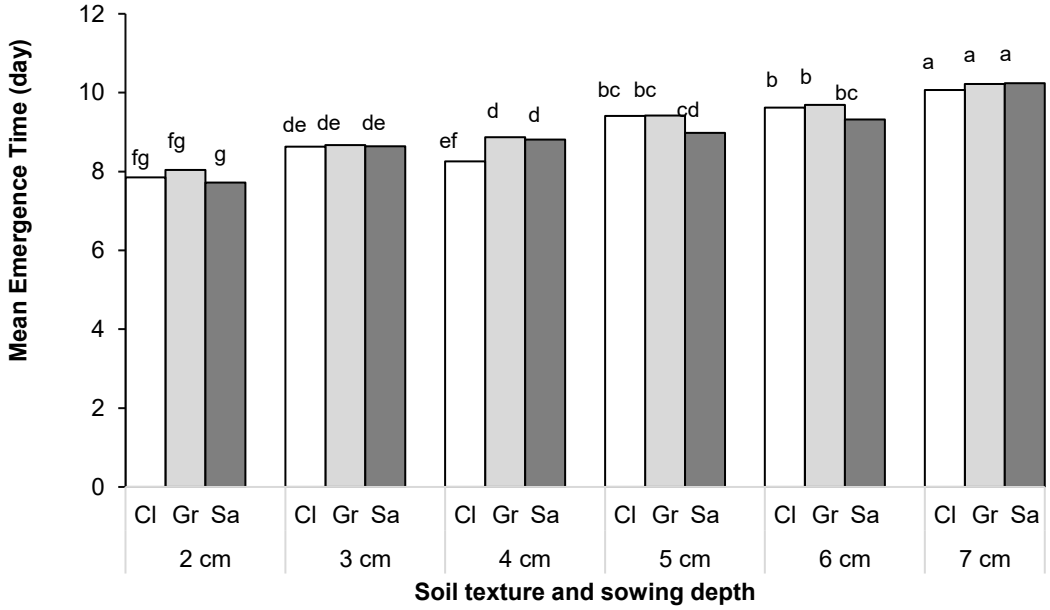

Fig. 6. Mean emergence time (MET) of Bambara groundnut seedlings in response to sowing depth and soil type

Cl: Clayed soil; Gr: Gravelly soil; Sa: Sandy soil; Different letters indicate significant differences (P < 0.05)

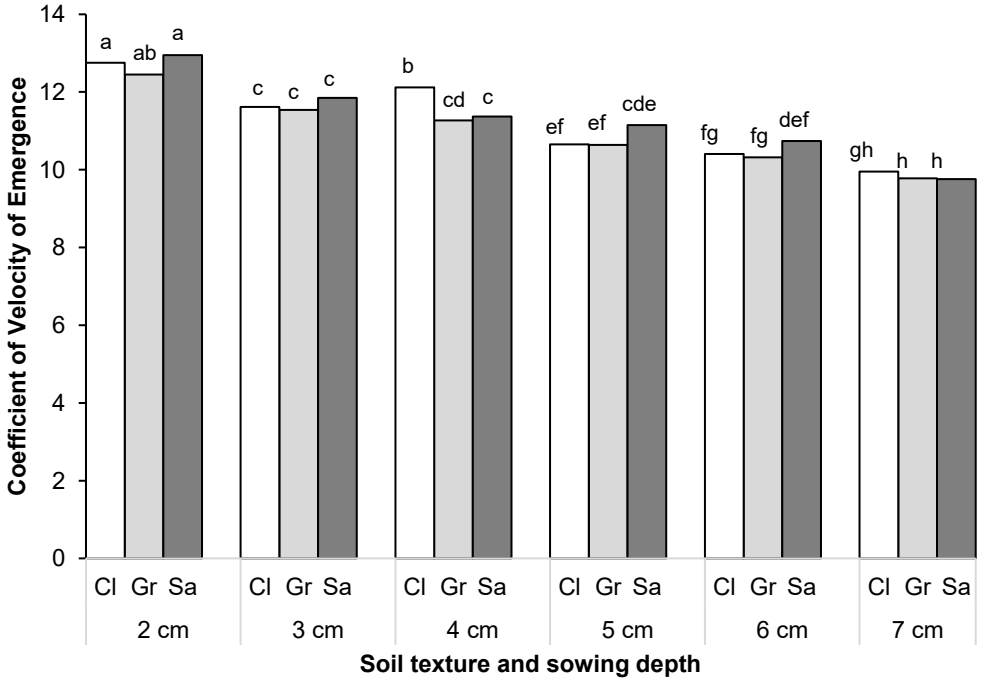

Fig. 7. Coefficient of velocity of emergence (CVE) of Bambara groundnut seedlings as influenced by sowing depth and soil type

Cl: Clayed soil; Gr: Gravelly soil; Sa: Sandy soil; Different letters indicate significant differences (p < 0.05)

sowing depth according to soil texture. Under sandy conditions, sowing depths ranging between 3 and 5 cm appear optimal, whereas in heavier or gravelly soils, shallower sowing, generally not exceeding 4 cm, is required to minimize mechanical resistance and ensure uniform emergence.

4. Conclusion

Sowing depth was identified as the primary factor governing the dynamics of Bambara groundnut seedling emergence, influencing the timing, rate, synchrony, and overall success of establishment. Shallow sowing, particularly at depths of 4 cm or less, consistently promoted rapid, uniform, and high-percentage emergence, whereas deeper placement resulted in delayed and less efficient emergence. Although soil texture played a secondary role, its influence became increasingly important as sowing depth increased. Sandy soil provided the most favorable conditions for seedling progression and allowed successful emergence at depths of up to 6 cm. In contrast, gravelly and clayey soils imposed greater mechanical and aeration constraints, making sowing depths not exceeding 4 cm more suitable for optimal emergence. These results underline the importance of adjusting sowing depth according to soil texture to improve stand establishment, which is a critical prerequisite for vigorous early growth, uniform crop development, and enhanced yield potential in Bambara groundnut production systems.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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