Quality seed production to optimize the success of reforestation and agroforestry based on local indigenous forest species: case of Khaya senegalensis (Meliaceae) and Parkia biglobosa (Fabaceae) in West Africa

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Abstract

Seed size is a key factor that can affect the regeneration process of plant populations. This study aims to identify efficient seeds that can optimise the cultivation of two overexploited native forest species in Côte d'Ivoire, namely *Khaya senegalensis* and *Parkia bliglobosa*. Sets of 1080 seeds per species were tested for their germination and seedling vigour in two distinct environments (dry and humid) in Côte d'Ivoire. The results showed that, for optimized germination, large seeds were preferable for *Khaya senegalensis* while for *Parkia biglobosa*, on the contrary, small and medium seeds were preferable. However, the most vigorous seedlings were generated by germinating large seeds regardless of species and study site. In this case, pre-treatment tests on large seeds in *Parkia biglobosa* are possible to improve their germination performance. Large seeds appear to be the best candidates for high quality, high performance seeds that can optimise the cultivation of *Khaya senegalensis* (0.25-0.37g) and *Parkia biglobosa* (0.25-0.37g) in Côte d'Ivoire. They can be provided to farmers to assist in the success of replanting programmes (reforestation and agroforestry) using the target species in Côte d'Ivoire. These results can contribute to the sustainable management of the target species and serve as a basis for restructuring forest regeneration policy in Côte d'Ivoire.

Key Messages

Anthropic pressure on endangered native agroforestry species such as *Khaya senegalensis* and *Parkia bliglobosa* is of increasing concern. There is, therefore, an urgent need to conserve them through artificial regeneration techniques that consider the size of the seed and the original and foreign maternal environment.

Introduction

In Côte d'Ivoire, deforestation due to unreasonable agriculture and population growth is a serious threat to biodiversity and the environment (Amani et al. 2022b). This threat used to be localised in the dense forest zone in the south of the country. Today, it is spreading and increasing in the open savannah forests in the north of the country. This obviously causes climatic disruption and a drastic loss of plant genetic resources. Furthermore, the preservation of forest species and commercial trees is a major concern in Côte d'Ivoire, which has banned the exploitation of trees above the 8th parallel. Also, the country committed at the Bonn Summit (Bonn, 2016) to restore about 5,000 hectares of forest by 2030.

In the search for a strategy and important support tools for the restructuring of the forest regeneration policy in Côte d'Ivoire, the Ivorian government is asking the structures in charge of forest management and the rural populations to practice intensive reforestation and agroforestry based on local pioneer species. In this context, it was observed after investigation that some indigenous agroforestry species have a major economic development potential for rural populations living in the north of Côte d'Ivoire. These species include *Khaya senegalensis* and *Parkia biglobosa*. According to the World Conservation Monitoring Centre (IUCN, 1998), *K. senegalensis* is Vulnerable (VU), while *P. biglobosa* is listed as a species of least concern (IUCN, 2020).

Despite the fact that these two native tree species are often found in field crops or open dry forests in the central and north parts of the country (Hérault et al. 2020), they are still overexploited for their multiple uses and exposed to a loss of diversity that may eventually lead to their extinction (Adji et al. 2020; 2021c). This high pressure is a real threat to their diversity and survival (Assane et al. 1993).

It is therefore necessary to develop new strategies for their conservation and sustainable use. But how? What are the strategies that can optimise the success of their pure cultivation (reforestation) and/or in crop association (agroforestry)? What are the trajections for obtaining high-performance seeds that can guarantee good germination dynamics and make it possible to obtain genotypes that are adapted, vigorous and resilient to a changing climate? To all these questions, we think that a first line of defence could be domestication and the search for quality seed. These quality seeds could optimise the success of reforestation and agroforestry based on these species in Côte d'Ivoire and West Africa.

Furthermore, in some studies seed size is reported to affect germination rate and seedlings' growth performance in some tree species (Chacon et al. 2001; Mao et al. 2019), but not for others (Agboola, 1996 ; Mtambalika et al. 2014). Thus, one important step toward producing marketable seeds for forestation and afforestation program is to gain knowledge about the relationship between seed size, germination rate and seedling growth. The need for efficient availability of vigorous seedlings and adapted genotypes from germination studies of sorted seeds is a major asset for the above problem.

In this context, the selection of the best seeds and the monitoring of the seedlings are crucial for plant establishment and recruitment in the field (Khan, 2004). In some tree species, viz. Gmelina arborea and Afzelia quanzensis (Mtambalika et al. 2014; Fornah et al. 2017), appropriate seed size for producing vigorous seedlings is well known. In contrast, for most of the Ivorian tree species, such knowledge is still lacking. In this study, we analyse the effect of seed size on germination rate and growth performance of *Khaya senegalensis* and *Parkia biglobosa* seedlings to optimise their reforestation success.

Material And Methods

Plant material

The analyses were carried out upon two forest tree species *Khaya senegalensis* (Desr.) A.Juss., 1830 and *Parkia biglobosa* (Jacq.) R.Br. ex G.Don. 1830. Two types of plant material were used in this study. The first comprised 1,080 shelled seeds of *Khaya senegalensis* and *Parkia biglobosa* collected from ripe fruits of seed trees in good physiological condition from four locations in Côte d'Ivoire (Table 1). The second type of material comprised 360 four-month-old and 90 twelve-month-old seedlings by specie, resulting from the germination of the seeds we collected. These seedlings were reared in a nursery in two different locations in Côte d'Ivoire. The dendrometric characteristics, the number of seed trees, and the number of healthy seeds selected after hulling according to their provenance are listed in Table 1. The plant material used is the property of the village communities whose plots we surveyed at each location. Authorizations to use this plant material were given to us orally by these rural populations as part of this study.

Table 1
Dendrometric characteristics and Provenance of *Khaya senegalensis* and *Parkia biglobosa* seed trees used

Species	Provenances	GPS coordinates		Number of seed trees	DBH (cm)			Height (m)			N° of healthy seeds
		Longitude	Latitude		Min	Max	Mean	Min	Max	Mean	
Khaya senegalensis	Katiola	5°7'35,814"W	8°13'53,94"N	7	43.12	87.6	63.6 ± 22.1 b	13.5	35	22.64 ± 6.8 b	426.61 ± 58.3 b
	Niakara	5°18'40,735"W	8°40'47,97"N	10	57.34	108.65	72.34 ± 19.3 ab	16.3	28.5	18.31 ± 7.42 b	793.4 ± 78.6 a
	Korhogo	5°36'12,316"W	9°33'24,69"N	10	55.93	98.22	69.91 ± 20.5 ab	24.5	39.5	28.94 ± 8.78 a	804 ± 104.53 a
	Ferké	5°23'43,396"W	9°36'1,87"N	9	47.69	126.77	88.3 ± 48.4 a	21.6	42.5	31.52 ± 11.2 a	856.11 ± 153.5 a
	Pr > F						0.0131			0.021	0.001
Parkia biglobosa	Katiola	5°7'35,814"W	8°13'53,94"N	15	18.4	47.23	21.84 ± 5.1 b	6.5	23.6	12.54 ± 3.3 b	434 ± 87.5 b
	Niakara	5°18'40,735"W	8°40'47,97"N	14	20.6	55.81	26.7 ± 7.34 ab	8.5	27.5	20.1 ± 6.5 a	1026 ± 209.6 a
	Korhogo	5°36'12,316"W	9°33'24,69"N	20	19.7	63.33	33.4 ± 11.3 a	11.5	26.5	18.77 ± 6.2 a	1009 ± 303.7 a
	Ferké	5°23'43,396"W	9°36'1,87"N	12	23.56	38.11	28.7 ± 8.6 a	13.7	21.6	17.64 ± 8.32 ab	579.34 ± 179.82 b
	Pr > F						0.016			0.037	0.001

Min = minimum; Max = maximum. In the same column, values with identical letters are statistically identical, while values with different letters are significantly different at the 5% threshold.

Methods

Experimental sites

The experiments took place from March 2020 to May 2021 in nurseries at two sites with different climatic characteristics (Daloa and Korhogo) in Côte d'Ivoire (Fig. 1). Daloa, with a humid climate, is located in a dense forest zone in the west of the country; while Korhogo with an arid climate is located in a savannah zone in the north of the country. The characteristics of the two study sites are listed in Table 2.

Table 2
Geographical location and characteristics of study sites (Guillaumet and Adjanohoun 1971; Louppe and Ouattara 1996; Hérault et al. 2020; Adji et al. 2021e)

Study sites	Coordinates	Vegetation	Climate	Temperature (°C)	Rainfall (mm/y)	RH (%)	Soil type
Korhogo	9°570'80556" N; 5°542'88889 " W	Clear open forest (wooded and grassy savannah)	Tropical dry (Sudano-dry zone)	26.6–35.7	817–1216	20–80	Ferruginous (80%) and ferralitic (20%); superficial gravelly acidic soil, deep gravel with a heavy texture (sandy loamy clay), low in organic matter, highly desaturated, low in calcium, magnesium, potassium and phosphorus
Daloa	6°909'6363" N 6°438'1157" W	Dense rain forest (Dense humid vegetation)	Wet tropical (subequatorial; Guinean-humid zone)	21.0–27.2	1000–1900	42–95	Ferralitic, deep, acidic and desaturated in exchangeable bases, rich in organic matter (calcium, magnesium, potassium and phosphorus)
RH = relative humidity							

Collecting and grading seeds

For each species, seeds were collected from seed trees that were chosen for their good physiological condition in the four (4) localities mentioned above: Katiola, Niakara, Korhogo and Ferké (Table 1). The sampled seeds from all provenances were mixed in a tray. A random and repetitive batch of 100 seeds was drawn from the tray for size measurements. For each seed, mass, length, width and thickness were measured.

Thus, in *Khaya senegalensis*, about 29 lots of 100 seeds were obtained and measured (427 in Katiola + 793 in Niakara + 804 in Korhogo + 856 in Ferké = 2880 seeds). A total of about 31 lots of 100 seeds were obtained and measured for the species *Parkia biglobosa* (434 in Katiola + 1026 in Niakara + 1009 in Korhogo + 579 in Ferké = 3048 seeds).

The seeds were divided into three size categories: large, medium and small (Fig. 2), according to their morphometric characteristics (mass, length, width and thickness) using an analysis of variance (ANOVA) test (Table 3). The distribution of the number of seeds collected by seed size category is presented in Fig. 3. This distribution follows a normal distribution. The small and large seeds (end of the curves) are low in number, while the average number of seeds is much higher. In a seed collection, the probability of finding medium-sized seeds is higher than that of finding small and large seeds (Fig. 3).

Table 3
Morphometry (Means ± SE) of seeds in different classes sorted by species

Species	Seeds size	Mass (g)	Lenght (mm)	Width (mm)	Thickness (mm)
Khaya senegalensis	Large	0.31 ± 0.03a	30.7 ± 3.2a	21.2 ± 2.3a	2.6 ± 0.38a
	Min-Maxi	(0.25–0.37)	(23–36)	(17–25)	(1.79–3.2)
	Medium	0.21 ± 0.02b	23.7 ± 3.6b	17.3 ± 2.4b	2.37 ± 0.43a
	Min-Maxi	(0.17–0.24)	(18–32)	(14–22)	(1.61–3.59)
	Small	0.1 ± 0.03c	19.4 ± 2.4c	14.6 ± 3.1c	1.95 ± 0.55a
	Min-Maxi	(0.05–0.16)	(14–24)	(11–22)	(0.7–2.97)
	Pr > F	**0.001**	**0.001**	**0.02**	**0.194**
Parkia biglobosa	Large	0.27 ± 0.03a	11.1 ± 0.9a	7.9 ± 0.9a	5.54 ± 0.42a
	Min-Maxi	(0.2–0.32)	(10–13)	(6–11)	(4.88–6.4)
	Medium	0.17 ± 0.01b	9 ± 0.8ab	6.7 ± 0.7ab	5.13 ± 0.34a
	Min-Maxi	(0.16–0.19)	(8–11)	(5–8)	(4.61–5.99)
	Small	0.12 ± 0.05c	7.2 ± 0.8c	5.5 ± 0.9c	4.71 ± 0.62a
	Min-Maxi	(0.04–0.13)	(5–9)	(4–7)	(3.42–5.89)
	Pr > F	**0.002**	**0.031**	**0.004**	**0.182**

In the same column, values with identical letters are statistically identical at the 5% level.

Setting up trials and sowing

Black polythene bags, 20 x 10 cm in size, were filled with local potting soil and then grouped into two blocks representative of the two-target species. Each block consists of three sub-blocks, one for each size category (large, mediaum, and small), and containing 90 bags each. Then, 180 seeds per category were randomly selected, soaked in water (about one hour), and immediately sown to a depth of 2 cm, with two seeds per bag. The result is: 2 seeds * 90 bags * 3 categories of seeds = 540 seeds (180 large seeds + 180 medium seeds + 180 small seeds) per species and per site. The seeds were treated with granulated FURADAN against rodents. Maintenance in the nurseries consisted of daily watering and manual weeding.

Measurements

The germinated (emergence) seeds were counted every day. These measures allow assessing the following variables:

- Waiting time or latency: this is the time in days needed for the first seed to germinate in a batch set (number of days needed for the first germination);
- Germination delay: the time in days between sowing and germination for a given seed in a set of lots (number of days needed for germination of each seed sown);
- Germination speed: is the average time in days until 50% of the seeds in a batch germinate (number of days needed for half the seeds sown to germinate);
- Germination duration or spread: this is the time in days between the first and last germination of a batch (number of days between the first and last germination);
- and Germination rate: this is the proportion of germinated seeds in relation to the total number of seeds sown. It is expressed in percentage (ratio of the number of germinated seeds over the number of sown seeds, in percentage);

Seedling growth and mortality

After seedling emergence, the pre-leaves were treated with DECIS to limit insect and larval attacks. The growth of the seedlings was monitored for up to 1 year.

In a first step, we randomly selected 60 seedlings aged four) months after emergence in each seed category and on each site (Daloa and Korhogo). They were destructively measured to assess seedling vigour: total seedling height, seedling crown diameter, number of single and compound leaves, root length and diameter. Dry weights of each compartment were also measured: total seedling dry weight; total leaf dry weight; stem dry weight; root dry weight.

The dry mass of the organs was obtained after oven drying at 60°C for 72 hours. After drying, the organs were kept in silica gel until measurements were made. All parameters were measured using a ruler graduated in centimetres, an electronic caliper in millimetres, a 0.001 g precision balance, an oven and a Nikon Coolpix 4500 digital camera with 45 mega pixels.

In a second step, 30 well-monitored 12-month-old seedlings originating from each seed category (30 large + 30 medium + 30 small seeds = 90 seedlings total) were randomly selected from the population of each species in Daloa for a mortality study. For each seedling provenance (large, medium and small seeds) and per species, height, diameter and mortality rate (quotient of the number of dead seedlings at 12 months over the number of seedlings selected and monitored at baseline after germination, expressed as a percentage) were measured on the 12-month-old seedlings.

Statistical analyses

Statistical analyses were first performed using one-dimensional descriptive statistics. All variable influences were compared using analysis of variance in SAS version 9.4 (SAS Institute, Cary, NC, USA). A Student-Newman-Keuls and a LSD test at the 5% threshold were used for post hoc comparison. XLSTAT was used to perform linkage analyses (linear and non-linear regressions) between the variables.

Results

Seed germination or emergence

Germination in Khaya senegalensis

The influence of seed size and experimental sites on the germination rate are presented in Fig. 4. It shows that the seed category has a significant effect, with large seeds exhibiting the best germination rate whatever the site. In addition, the Korhogo site recorded better germination rate performances than the Daloa site.

Figure 5 shows the daily germination dynamics by seed category in Daloa (Fig. 5a) and Korhogo (Fig. 5b). The number of seeds germinating every 5 days increases exponentially from day 10th in Daloa and day 15th in Korhogo to day the 50th and 40th in Daloa and Korhogo respectively. No seed germinated after these dates was observed in Daloa (50th) and Korhogo (35th). Regardless of the site, large seeds have a higher dynamic than the other two seed size categories (Fig. 5).

For large seeds, the latency time was 16 days in Korhogo against 10 days in Daloa; the germination delay of large seeds varied from 16 to 40 days with an average of 22.25 ± 5.59 days in Korhogo and from 10 to 41 days with an average of 18.84 ± 9.08 days in Daloa; the germination speed was 22 days in Korhogo against 17 days in Daloa; the total duration of germination was 24 days in Korhogo against 31 days in Daloa; the germination rate was 85% in Korhogo against 75% in Daloa.

For medium seeds, the waiting time for germination was 14 days in Korhogo against 8 days in Daloa; the germination delay of medium seeds varied from 14 to 40 days around an average of 22.85 ± 7.1 days in Korhogo and from 8 to 44 days with an average of 19.02 ± 7.75 days in Daloa; The germination speed was 24 days in Korhogo against 23 days in Daloa; the total duration of germination was 26 days in Korhogo against 36 days in Daloa; the germination rate was 76.66% in Korhogo against 66.66% in Daloa.

For small seeds, the waiting time for germination was 16 days in Korhogo against 7 days in Daloa; the germination delay of small seeds varied from 16 to 37 days around an average of 23.93 ± 5.58 days in Korhogo and from 7 to 49 days with an average of 24.97 ± 13.05 days in Daloa; the germination speed was 37 days in Korhogo against 49 days in Daloa; the total duration of germination was 21 days in Korhogo against 42 days in Daloa; the germination rate was 51.66% in Korhogo against 50% in Daloa.

Germination in Parkia biglobosa

In *Parkia biglobosa*, the results also showed that seed size and study site had a significant influence on seed germination (Fig. 6).

In large seeds, the latency to germination was 17 days in Korhogo against 11 days in Daloa; the germination delay of large seeds varied from 17 to 56 days with an average of 39.93 ± 10.62 days in Korhogo and from 11 to 39 days with an average of 22.81 ± 7.57 days in Daloa; The germination speed was 56 days in Korhogo against 34 days in Daloa; the total duration of germination was 39 days in Korhogo against 28 days in Daloa; the germination rate was 50% in Korhogo against 50.33% in Daloa.

For medium seeds, the waiting time for germination was 10 days in Korhogo against 4 days in Daloa; the germination delay of each medium seed varied from 10 to 51 days around an average of 19.82 ± 8.20 days in Korhogo and from 4 to 27 days with an average of 14.57 ± 4.29 days in Daloa; The germination speed was 23 days in Korhogo against 19 days in Daloa; the total duration of germination was 41 days in Korhogo against 23 days in Daloa; the germination rate was 83.33% in Korhogo against 66.66% in Daloa.

For small seeds, the waiting time was 10 days in Korhogo against 6 days in Daloa. Germination delay varied from 10 to 29 days with an average of 17.55 ± 4.12 days in Korhogo and from 6 to 24 days with an average of 14.64 ± 4.66 days in Daloa. The germination rate was 24 days in Korhogo and 21 days in Daloa. The total duration of germination was 19 days in Korhogo against 18 days in Daloa. In the end, the germination rate was 86.66% in Korhogo compared to 71.66% in Daloa (Fig. 6).

Figure 7 shows the daily germination dynamics by seed category in Daloa (Fig. 7a) and Korhogo (Fig. 7b). The number of seeds germinated per day is higher for small and medium seeds than for large seeds. On the other hand, germination stabilised more quickly in the latter than in the large seeds (Fig. 7). Regardless of the medium, small and medium-sized seeds have a higher number of germinated seeds per day than large seeds. In Daloa seed germination stabilizes on the 25th, 30th and 40th day respectively in large, medium and small seeds (Fig. 7a). In Korhogo seed germination stabilizes on the 30th, 30th and 60th day respectively in large, medium and small seeds (Fig. 7b). After these dates, the seeds no longer germinate.

Seedling growth

Effect of seed size and site on seedling growth in Khaya senegalensis

Comparison of seedling vigour variables by seed category (Table 4 and Fig. 8), showed a significant difference in seedling growth by seed category *(P*< 0.05). Large seeds had greater mean stem heights (17.77 cm) than medium (12.36 cm) and small (8.28 cm) seeds. These results are similar for the parameters of mean stem diameters (3.07 mm vs. 2.07 mm and 1.6 mm respectively for seedlings from large, medium and small seeds), mean number of simple leaves of stems (7.43 vs. 5.67 and 4.43 respectively for seedlings from large, medium and small seed germination), mean number of compound leaves of stems (0.4 vs. 0, 11 and 0) respectively for seedlings germinated from large, medium and small seeds), main root length (13.9 cm vs. 11.6 cm and 8.78 cm) respectively for seedlings germinated from large, medium and small seeds) and the variable main root diameter (2.97 mm vs. 2.23 mm and 1.83 mm) respectively for seedlings germinated from large, medium and small seeds.). Seedlings from small seeds did not develop compound leaves. The seedlings resulting from the germination of large seeds were completely different from the rest with high vigour.

Table 4
Seedling development parameters according to seed category and dry biomass of young plants in *Khaya senegalensis*. Within a column, values with identical letters are statistically identical at the 5% level.

Development parameters	**Height (cm)**	**Diameter (mm)**	**Number of single leaf**	**Number of compound leaf**	**Root length (cm)**	**Root diameter (mm)**
Large	17.77 ± 3.92^a	3.07 ± 2.6^a	7.43 ± 1.66^a	0.4 ± 1.1^a	13.90 ± 2.87^a	2.97 ± 0.52^a
Medium	12.36 ± 2.08^b	2.07 ± 0.33^b	5.67 ± 1.17^b	0.11 ± 0.46^b	11.6 ± 2.38^b	2.23 ± 0.39^b
Small	8.28 ± 2.11^c	1.6 ± 0.35^c	4.43 ± 0.85^c	0 ± 0^c	8.78 ± 2.43^c	1.83 ± 0.44^b
Pr > F	**0.0001**	**0.0001**	**0.0041**	**0.0007**	**0.0001**	**0.0063**

Dry biomass parameters	Total dry mass of seedlings (g)	Total dry mass of leaves (g)	Stem dry mass (g)	Root dry mass (g)
Large	0.71 ± 0.25^a	0.32 ± 0.11^a	0.48 ± 0.19^a	0.14 ± 0.05^a
Medium	0.41 ± 0.12^b	0.20 ± 0.06^b	0.32 ± 1.52^b	0.09 ± 0.04^b
Small	0.22 ± 0.11^c	0.1 ± 0.05^c	0.04 ± 0.02^c	0.05 ± 0.02^c
Pr > F	**0.0001**	**0.0001**	**0.0001**	**0.0001**

Table 4 shows the analysis of variance of seedling biomass parameters by seed category origin. It shows that the parameters evaluated differed from one seed category to another (*P*< 0.05). Large seeds had seedlings with higher average dry biomass than medium and small seeds for all parameters observed: total seedling dry biomass (0.71 g vs. 0.41 and 0.22 g), total leaf dry mass (0.32 g vs. 0.2 and 0.1 g), stem dry mass (0.48 g vs. 0.32 and 0.04 g) and root dry mass (0.14 g vs. 0.09 and 0.05 g).

Figure 8 shows the influence of seed size on the morphology of four-month-old seedlings in *Khaya senegalensis*. The larger the seed, the larger and better developed the resulting seedling.

Concerning the influence of the study site, the results showed that, with the exception of root diameter, the seedlings obtained in the Daloa nursery were more vigorous than those in the Korhogo nursery (Table 5 and Fig. 9). The variables were 15.85 cm in Daloa versus 10.93 cm in Korhogo for seedling heights, 2.76 mm in Daloa versus 1.91 mm in Korhogo for seedling diameters. They were 6.88 in Daloa against 5.18 in Korhogo for the number of simple leaves, 0.35 in Daloa against 0.04 in Korhogo for compound leaves and 12.78 cm in Daloa against 10.7 cm in Korhogo for the length of the roots of the seedlings.

Table 5
Developmental and dry biomass parameters of young plants according to the experimental site in *Khaya senegalensis*.

Development parameters	**Seedling height (cm)**	**Stem diameter (mm)**	**Number of single leaves**	**Compound leaves Number**	**Root length (cm)**	**Root diameter (mm)**
Daloa	15.85 ± 5.07^a	2.76 ± 2.39^a	6.88 ± 1.87^a	0.35 ± 1.02^a	12.78 ± 3.71^a	2.74 ± 0.64^a
Korhogo	10.93 ± 3.12^b	1.91 ± 0.44^b	5.18 ± 1.25^b	0.04 ± 0.26^b	10.7 ± 2.48^b	2.09 ± 0.51^a
Pr > F	**0.0001**	**0.0002**	**0.0075**	**0.0001**	**0.0069**	**0.076**

Dry biomass parameters	Total dry mass of seedlings (g)	Total dry mass of leaves (g)	Stem dry mass (g)	Root dry mass (g)
Daloa	0.61 ± 0.29^a	0.26 ± 0.13^a	0.29 ± 1.25^a	0.12 ± 0.06^a
Korhogo	0.24 ± 0.16^b	0.18 ± 0.09^b	0.08 ± 0.04^b	0.08 ± 0.04^b
Pr > F	**0.0001**	**0.0001**	**0.0001**	**0.0001**

Within a column, values with identical letters are statistically identical at the 5% level.

The seedlings obtained in Daloa showed higher dry biomasses (Table 5) than in Korhogo ($P < 0.05$) for the variable's total seedling dry mass (0.61 g vs. 0.29 g), total leaf dry mass (0.26 g vs. 0.18 g), stem dry mass (0.29 g vs. 0.08 g) and root dry mass (0.12 g vs. 0.08 g).

Figure 9 illustrates the detailed influence of seed category on seedling vigour for each experimental site. Regardless of seed category, the Daloa site produced large seedlings.

Figure 10 shows the relationships and regressions between the parameters assessed in *Khaya senegalensis*. Figure 10a shows an independence of seed size from seed germination time. There is a strong dependency between seed size and height growth of 4-month-old seedlings (Fig. 10b) and total biomass of 4-month-old seedlings (Fig. 10c). The larger the seed, the larger the resulting seedlings with a high above-ground biomass. The shorter the germination time, the greater the growth of the seedling (Fig. 10d). Figure 10f shows that seeds with larger aspect ratios (width/length) generate larger and larger seedlings.

Effect of seed size and site on seedling growth in Parkia biglobosa

In *Parkia biglobosa*, the results showed a significant difference in the majority of the vigour parameters of the young plants evaluated as a function of seed size ($P < 0.05$). Seedlings germinating from larger seeds were more vigorous (Fig. 11). The number of leaves and root diameter were statistically identical between seed categories ($P > 0.05$).

Table 6 shows the comparison of vigour parameters of the young plants evaluated by seed size category. The results were for stem heights of 13.18 cm, 11.53 cm and 10.09 cm respectively for seedlings from large, medium and small seeds. The results for stem diameters were 3.22 mm, 2.47 mm and 2.25 mm for large, medium and small seedlings respectively. They were for the number of compound leaves 3.9, 3.98 and 4.06 for the large, medium and small seeded seedlings respectively. They were for root length 11.51 cm, 12.22 cm and 10.63 cm respectively for seedlings from large, medium and small seeds. The root diameters were 2.28 mm, 2.31 mm and 2.05 mm for large, medium and small seedlings respectively.

Table 6
Seedling vigour and dry biomass by mother seed size category in *Parkia biglobosa*

Vigour parameters	**Seedling height (cm)**	**Stem diameter (mm)**	**Compound leaves Number**	**Root length (cm)**	**Root diameter (mm)**
Large	13.18 ± 7.13^{a}	3.22 ± 0.65^{a}	3.9 ± 1.54^{a}	11.51 ± 7.38^{b}	2.28 ± 0.89^{a}
Medium	11.53 ± 5.14^{b}	2.47 ± 0.42^{b}	3.98 ± 1.34^{a}	12.22 ± 4.52^{a}	2.31 ± 0.53^{a}
Small	10.09 ± 4.24^{c}	2.25 ± 0.31^{b}	4.06 ± 1.5^{a}	10.63 ± 4.41^{c}	2.05 ± 0.5^{a}
Pr > F	**0.0061**	**0.0095**	**0.867**	**0.0083**	**0.7705**

Dry biomass parameters	Total dry mass of seedlings (g)	Total dry mass of leaves (g)	Stem dry mass (g)	Root dry mass (g)
Large	0.46 ± 0.39^{a}	0.26 ± 0.22^{a}	0.09 ± 0.05^{a}	0.11 ± 0.1^{a}
Medium	0.38 ± 0.3^{b}	0.21 ± 0.20^{b}	0.08 ± 0.04^{a}	0.10 ± 0.08^{b}
Small	0.33 ± 0.19^{b}	0.18 ± 0.12^{c}	0.06 ± 0.02^{b}	0.09 ± 0.06^{c}
Pr > F	**0.0011**	**0.026**	**0.0121**	**0.0022**

Within a column, values with identical letters are statistically identical at the 5% level.

Table 6 shows as well that, seedlings from large seed germination had the highest dry biomass compared to those from medium and small seeds. The values of the observed parameters were 0.46 g, 0.38 g and 0.33 g for total dry mass in the large, medium and small seeded seedlings respectively. They were 0.26 g, 0.21 g and 0.18 g for the total dry mass of the leaves in the large, medium and small seeded seedlings respectively. They were 0.09 g, 0.08 g and 0.06 g for the stem dry mass in the large, medium and small seeded seedlings respectively. They were 0.11 g, 0.10 g and 0.09 g for root dry mass in large, medium and small seeded seedlings respectively.

The results showed that the study site influences seedling vigour. Seedlings obtained in Daloa were found to be more vigorous than those obtained in Korhogo (Table 7). All parameters differed statistically between sites ($P < 0.05$). The results showed that the height of the seedlings was 16.21 cm in Daloa and 6.79 cm in Korhogo. Stem diameter was 2.26 mm in Daloa and 2.78 mm in Korhogo. The number of compound leaves was 5.02 in Daloa and 3.08 in Korhogo. The root length was 15.42 cm in Daloa and 7.73 cm in Korhogo. The root diameter was 2.58 mm in Daloa and 1.84 mm in Korhogo.

Table 7
Vigour and dry biomass of young plants according to the experimental site in *Parkia biglobosa*

Vigour parameters	**Seedling height (cm)**	**Stem diameter (mm)**	**Compound leaves Number**	**Root length (cm)**	**Root diameter (mm)**
Daloa	16.21 ± 3.6^{a}	2.26 ± 0.37^{b}	5.02 ± 1.39^{a}	15.42 ± 3.87^{a}	2.58 ± 0.57^{a}
Korhogo	6.79 ± 1.17^{b}	2.78 ± 0.61^{a}	3.08 ± 0.69^{b}	7.73 ± 3.28^{b}	1.84 ± 0.44^{b}
Pr > F	**0.0001**	**0.0106**	**0.0061**	**0.0001**	**0.004**

Dry biomass parameters	Total dry mass of seedlings (g)	Total dry mass of leaves (g)	Stem dry mass (g)	Root dry mass (g)
Daloa	0.6 ± 0.26^{a}	0.34 ± 0.17^{a}	0.1 ± 0.04^{a}	0.15 ± 0.08^{a}
Korhogo	0.17 ± 0.08^{b}	0.08 ± 0.04^{b}	0.05 ± 0.02^{b}	0.04 ± 0.03^{b}
Pr > F	**0.0001**	**0.0001**	**0.0001**	**0.0001**

Within a column, values with identical letters are statistically identical at the 5% level

The analysis of variance of the biomass parameters evaluated showed a significant difference in parameters according to the study site ($P < 0.05$). The seedlings obtained in Daloa had higher biomass values than in Korhogo (Table 7) with total dry mass values of 0.6 g compared to 0.17 g, total leaf dry mass of 0.34 g compared to 0.08 g, stem dry mass of 0.1 g compared to 0.05 g, and root dry mass of 0.15 g compared to 0.04 g.

Figure 12 shows the variation in vigour of seedlings according to seed category and experimental site. This figure confirms that the seedlings are well developed in Daloa than in Korhogo with significantly greater stem height and root length.

Figure 13 shows the different relationships between seed size and 4-month-old seedlings in *Parkia biglobosa*. As with *Khaya senegalensis*, Fig. 13a shows that there is no significant relationship between seed size and time to seed germination. However, Fig. 13b and 13c show that seedling height and total biomass depend on seed size. The larger the seed size, the more vigorous the germination of the seedlings. Figure 13d shows that the shorter the germination time, the greater the height of the seedling. Figure 13f shows that the larger the shape index (width/length) of the seed, the larger the seedlings that are produced.

Assessment of mortality in 12-month-old seedlings

Table 8 shows that after 12 months of monitoring, the number of living seedlings is higher in the seedlings from large seeds. No mortality of 12-month-old plants from large seeds was observed in *Khaya senegalensis* (0%). While a higher rate (up to 72%) of plants from small seeds die during development and do not reach 12 months. However, it should be noted that the morphology of the plants is affected by environmental conditions. Individuals lose their capacity for increasing vigour according to the seed size category (from the largest to the smallest seeds). Table 8 shows that individuals have almost the same size at 12 months (height and diameter), regardless of seed size category ($P > 0.05$).

Table 8
Vigour and mortality of 12-month-old plants in *Khaya senegalensis* and *Parkia biglobosa*

Species	Seed size sources	Height (cm)	Collar diameter (cm)	Death rate (%)
Khaya senegalensis	Larges	167.11 ± 18.3 a	3.3 ± 0.2 a	0
	Mediums	142.7 ± 79.1 a	2.07 ± 0.53 a	47.2
	Small	89.52 ± 56.66 a	2.02 ± 1.37 a	72
	Pr > F	**0.603**	**0.83**	-
Parkia biglobosa	Larges	61.25 ± 23.8 a	0.7 ± 0.41 a	32.5
	Mediums	56.57 ± 17.1 a	0.68 ± 0.39 a	53.33
	Small	54.1 ± 33.3 a	0.66 ± 0.51 a	64.8
	Pr > F	**0.874**	**0.711**	-

Within a column, values with identical letters are statistically identical at the 5% level.

Discussion

We investigated seeds germination and seedlings growth in *Khaya senegalensis* and *Parkia biglobosa*, two local forest trees species highly exploited and threatened. The gained knowledge will be helpful for forestation and afforestation program in Côte d'Ivoire. These species showed short time to begin germination, generally less than 20 DAS. In addition, the germination was not spread out enough, less than 60 days. These results were similar to those previously found in *Terminalia superba*, *Mansonia altissima* and *Pterygota macrocarpa* (Akaffou et al. 2019) and in *Pterocarpus erinaceus* (Adji et al. 2021e). By contrast for some others trees species such as *Sideroxylon contrerasii* and *Elaeocarpus prunifolus*, the germination was long since 434 days and 146 days were required to reach maximum or mean germination respectively (Toledo-Aceves 2017 ; Iralu and Upadhaya, 2018).

Elsewhere the seeds germination dynamic and rate were significantly influenced by both seeds size and experimental site. For *Khaya senegalensis*, large and medium seeds showed fast germination and reached earlier maximum germination contrarily to small seeds. They also yield the highest germination rate. Conversely, for *Parkia biglobosa*, small and middle seeds this time exhibited earlier and fast germination and gave the best germination rate. Ours results did not support those of (Agboola, 1996 ; Mtambalika et al. 2014) who found no effect of seeds weight on germination rate in *Terminalia superba*, *Terminalia ivorensis*, *Gmelina arborea* and *Afzelia quanzensis.* In contrast our findings were consistent with those of (Burlem and Miller, 2001 ; Deb and Sundriyal, 2017) who reported fast and best germination in large seeds respectively in three and four tropical trees species. Such a result was also found by (Mao et al. 2019 ; Iralu and Upadhaya, 2018 ; Kuniya et al. 2013 ; Mandal et al. 2008) in *Pinus thunbergii*, *Elaeocarpus prunifilius* and *Terminalia bellerica*. In addition, the results obtained for *Parkia biglobosa* agreed with those published in *Copaifera langsdorffii* by (Souza and Fagundes, 2014) who reported that smaller seeds showed faster and greater germination than the larger ones. Hence, our results were not surprising. These contrast behaviour depending on species and well known in trees species were attributed to species strategies for their regeneration and early colonization of an area (Burlem and Miller, 2001).

The high germination rate obtained at Korhogo than at Daloa could be due to slightly warm temperature close to 30°C since this temperature is reported to be the optimal for seeds germination in trees species (Simao and Takaki, 2008 ; Vargas-Figneroa and Torres-Gonzales, 2018).

In final, the best germination rate found for large seeds in *Khaya senegalensis* and for small seeds in *Parkia biglobosa* were high, ranging between 71% and 86% on average. These rates were similar to that obtained in *Mansonia altissima*, *Pterygota macrocarpa*, *Terminalia superba* (Akaffou et al. 2019) and *Pterocarpus erinaceus* (Adji et al. 2021e). While they were superior than twice fold to those recorded in others trees species viz. *Ceiba pentadra*, *Delonix regia*, *Sterculia urens*, *Albizia lebbeck* and *Leucaena leucocphala* for which germination rate were very poor ≤ 30% (Nakar and Jadeja, 2014).

The growth analysis revealed that seedlings issued from large seeds, as well as in *Khaya senegalensis* as in *Parkia biglobosa*, showed best growth performance. This result was in conformity with the findings of (Ellis, 1992 ; Milberg and Lamont, 1997). These authors argued that best growth of seedlings issued from large seed should be due to efficient use of the more resources stored in these seeds.

Since in *Parkia biglobosa*, best growth performance was recorded for seedlings emerged from large seeds while they exhibited feeble germination rate (50%), research to increase their germination is required. Therefore, pre-soaking treatments in warm or hot water could be applied as done by (Fredrick et al. 2017).

The best growth performance scored at Daloa than that of Korhogo could be attributed to the favourable climatic conditions prevailing in the first experimental site, viz. more rainfall, 1300 mm vs 1000 mm and less hot temperature 26°C vs 30°C.

This study showed that seedling mortality is lower up to the age of 12 months in the target species. This fact clarifies, demonstrates and proves that large seeds can be recommended to farmers, agroforesters and forestry management structures as quality seeds for successful and optimised cultivation of target species. The results also showed that the individuals have statistically the same dimensions regardless of their origin at the age of 12 months. This was not the case at 4 months. Indeed, seedlings at the seedling stage are not yet independent. They therefore continue to use the seed's reserve (Milberg and Lamont, 1997). The larger the seed, the more starch reserves it contains. The seedling therefore draws on the reserve; it has more nutrient reserves in its procession to develop better than seedlings from small seeds (development and growth limited by the quantity of starch available in the seed).

Once the seedling regains its independence from photosynthetic activity, development and growth will depend on environmental conditions (soil fertility, availability of light and water etc.). Individuals therefore lose their vigour, which depends on the seed reserve. They acquire a growth capacity that depends on the environment. An individual resulting from the germination of small seeds under favourable conditions may have the same or greater vigour than an individual resulting from the germination of large seeds. In our study, the plants from the large seeds had slightly larger sizes than the other categories because of the identical environmental conditions. However, statistical analysis showed that these individuals were identical in size.

Even if the individuals tend to be morphologically identical later on, the most important thing is the selection of the right seed type for successful reforestation. In this sense, the mortality study is a priority and has shown that large seeds are the best candidates for any species.

Conclusion

This study focused on the search for quality seed through germination and seedling vigour in *Khaya senegalensis* and *Parkia biglobosa*. It was found that both species have a good potential for sexual regeneration. This potential is influenced by seed size and maternal environment. These results are the first in these species. In *Khaya senegalensis*, large seeds germinate well and produce vigorous seedlings regardless of the environment. However, in *Parkia biglobosa*, it is the small and medium-sized seeds that have good germination potential. However, the seedlings from the large seeds were more vigorous. In view of the above, the large seeds could be provided to farmers to assist agroforestry and reforestation programmes in Côte d'Ivoire.

However, we recommend germination tests on different provenances to select the best provenances for agroforestry and reforestation proposals. Also, multi-location and/or zonal trials by seed size category should be carried out to validate the choice of large seeds as quality seeds. In addition, pre-treatment tests (warm or hot water soaking, sulphuric acid, hull scouring) should be applied to lift the dormancy of large seeds in *Parkia biglobosa*. This will improve the germination performance of the seeds.

Declarations

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Ecoles of Côte d'Ivoire). The authors are grateful to the Centre de Coopération International de Recherche Agronomique pour le Développement (CIRAD) for providing the technical equipment required to conduct the study.

Data availability statement

The datasets produced and/or analyzed in the current study are available from: Adji, Beda Innocent, 2022, "Quality seed production for optimising the success of reforestation of native forest species: case of *Khaya senegalensis* (Meliaceae), *Pterocarpus erinaceus* (Fabaceae) and *Parkia biglobosa* (Fabaceae)", https://doi.org/10.7910/DVN/AEH9TP, Harvard Dataverse, V1.

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Figures

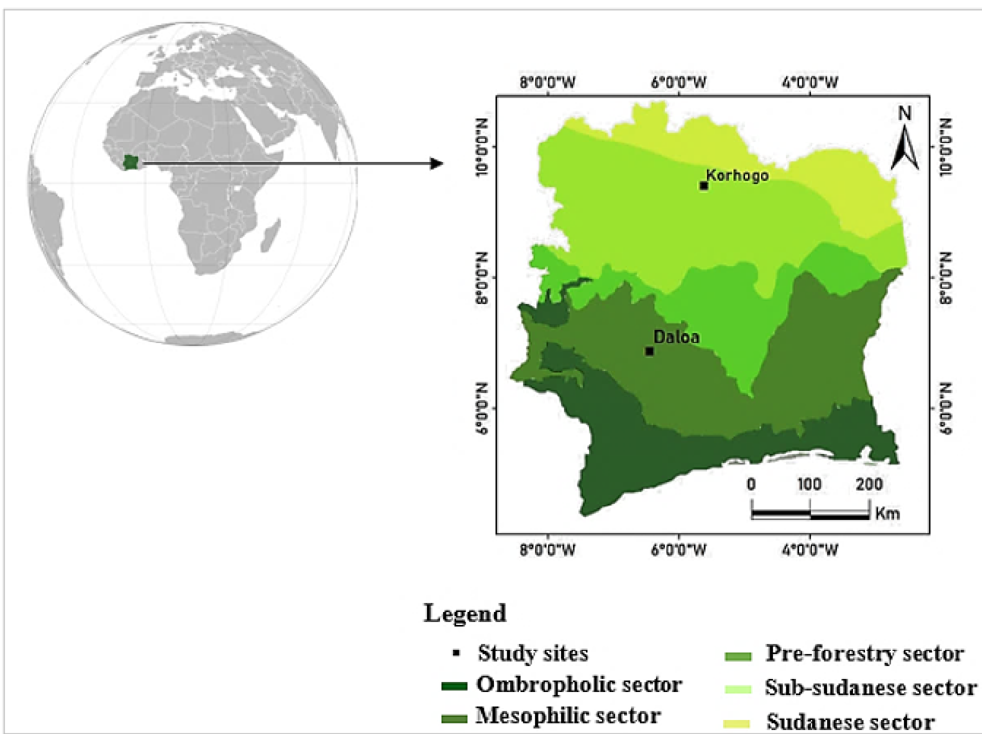


Figure 1

Geographical location of the study sites.

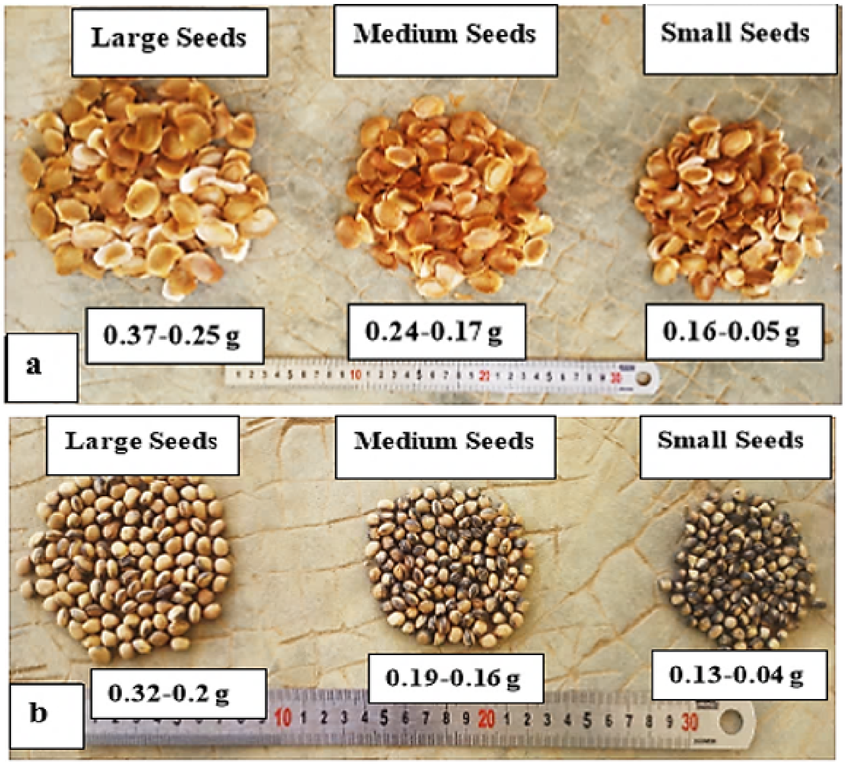


Figure 2

Classification of seeds by size category after dimension measurement in Khaya senegalensis (a) and Parkia biglobosa (b)

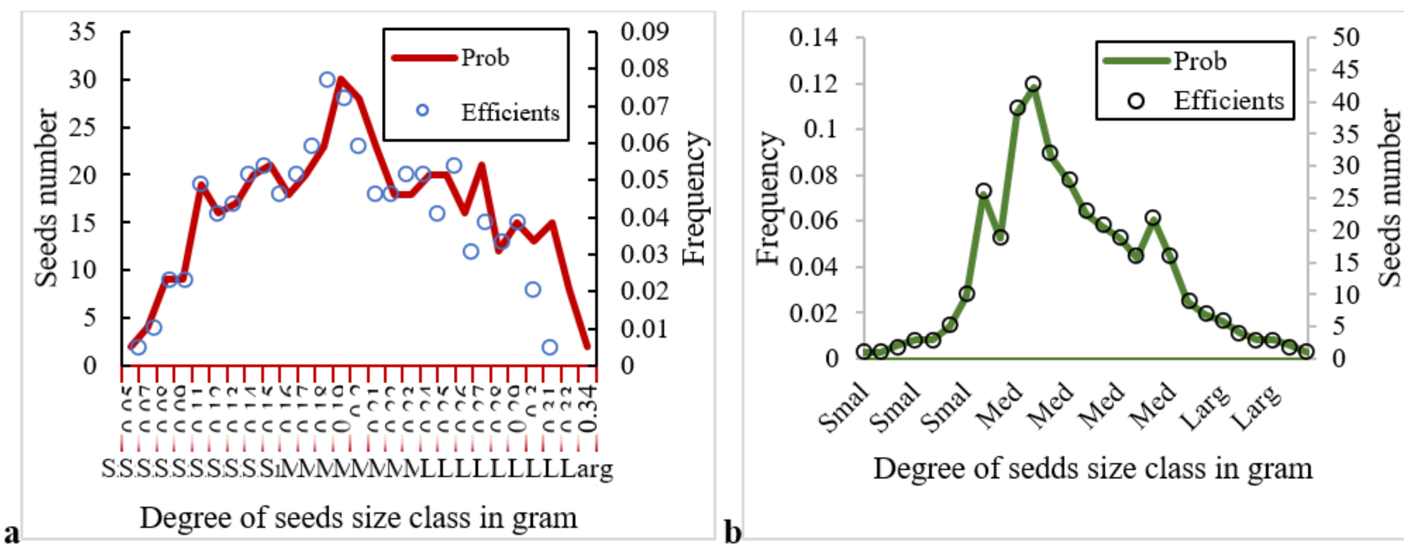


Figure 3

distribution of seeds number and frequency according their size in Khaya senegalensis (a) and Parkia biglobosa (b)

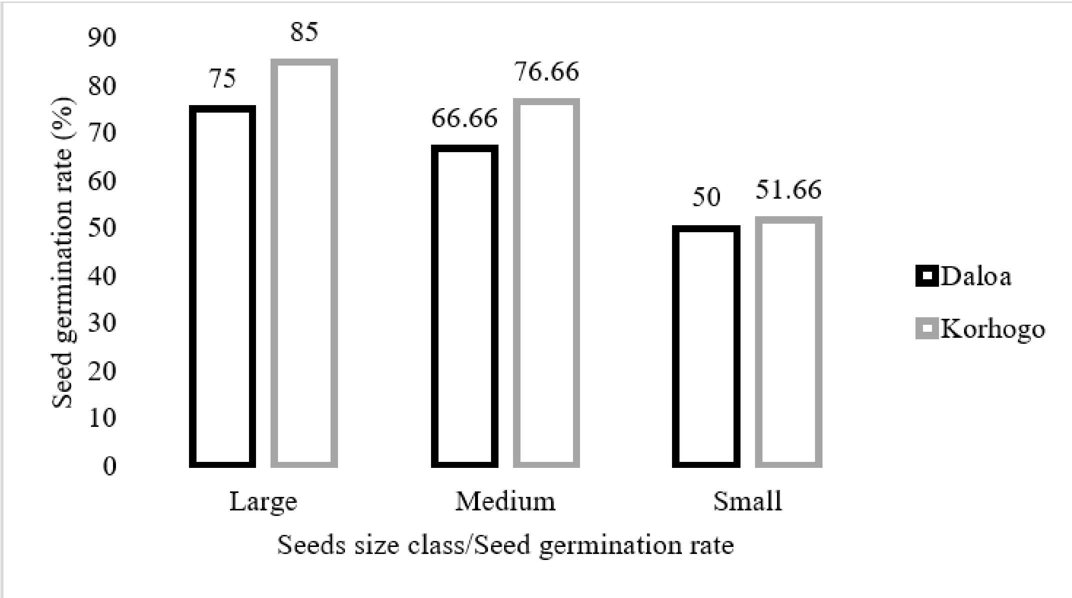


Figure 4

Effect of seed size and study site on germination rate of three sizes of seeds on Khaya senegalensis

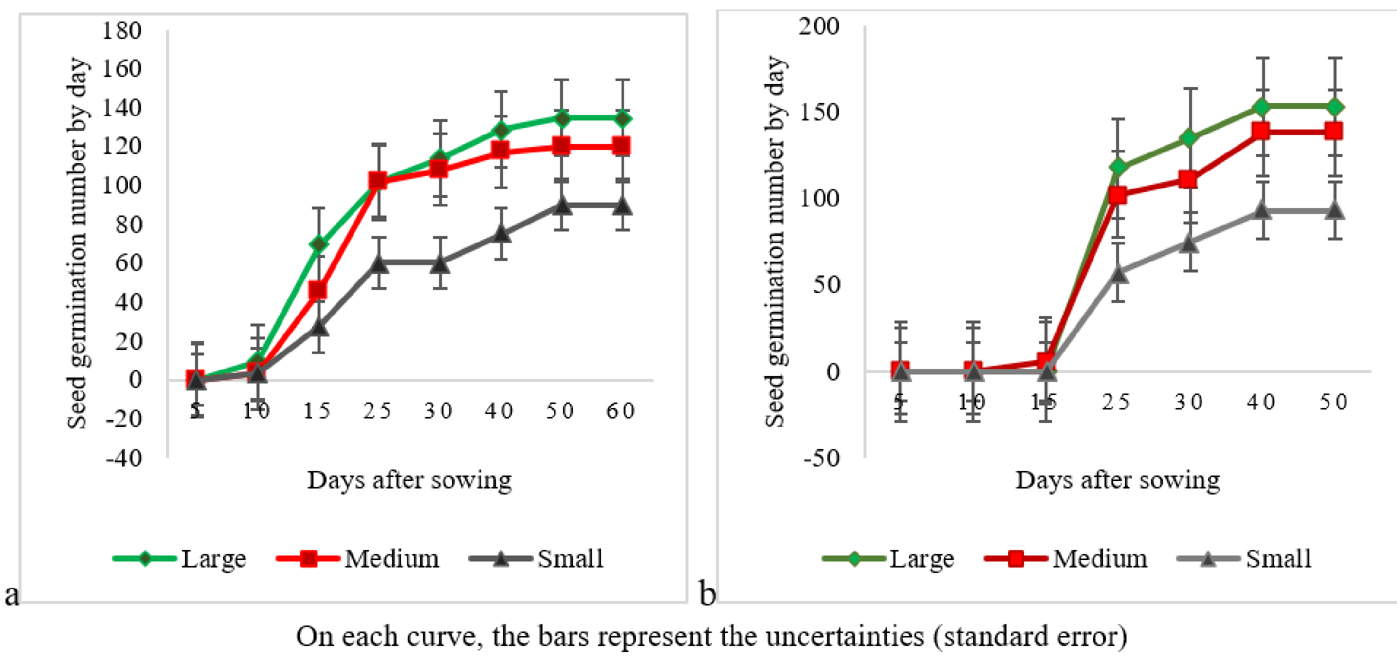


Figure 5

Germination dynamics of seed categories in Daloa (a) and Korhogo (b) in Khaya senegalensis

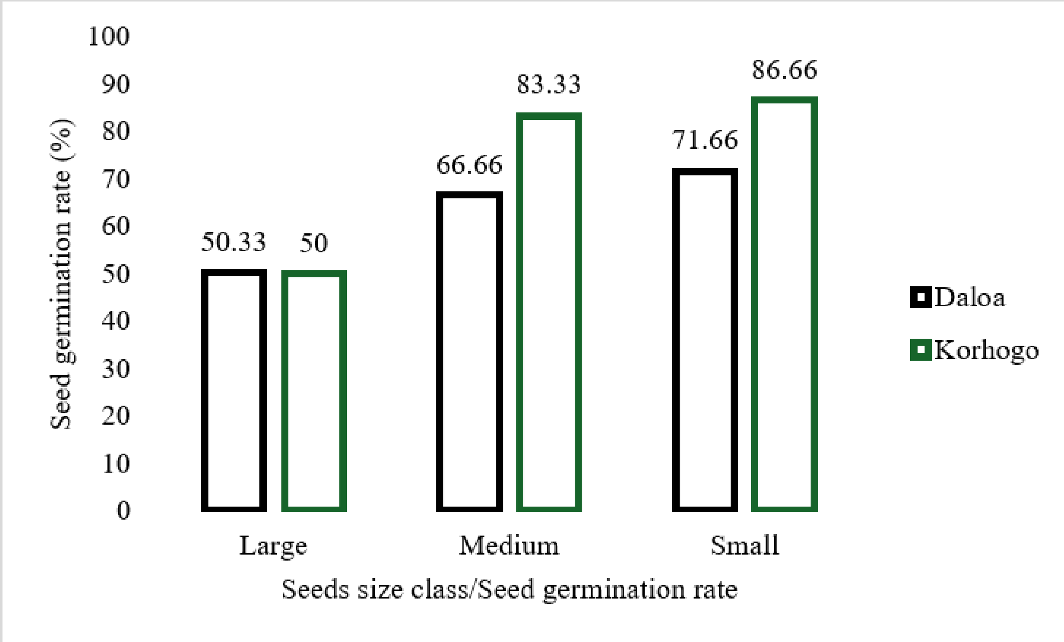
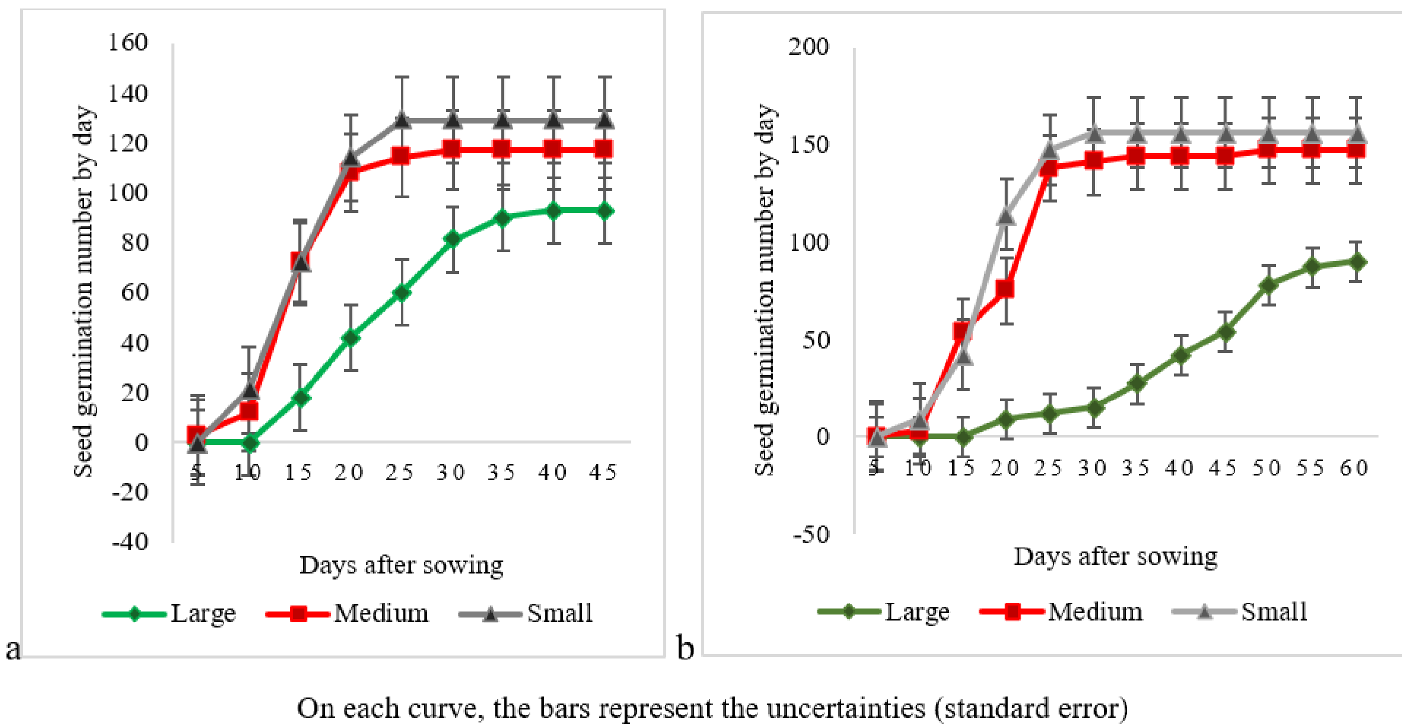


Figure 6

Effect of seed size and study site on germination rate of three sizes of seeds on Parkia biglobosa



On each curve, the bars represent the uncertainties (standard error)

Figure 7

Germination dynamics of seed categories in Daloa (a) and Korhogo (b) in Parkia biglobosa

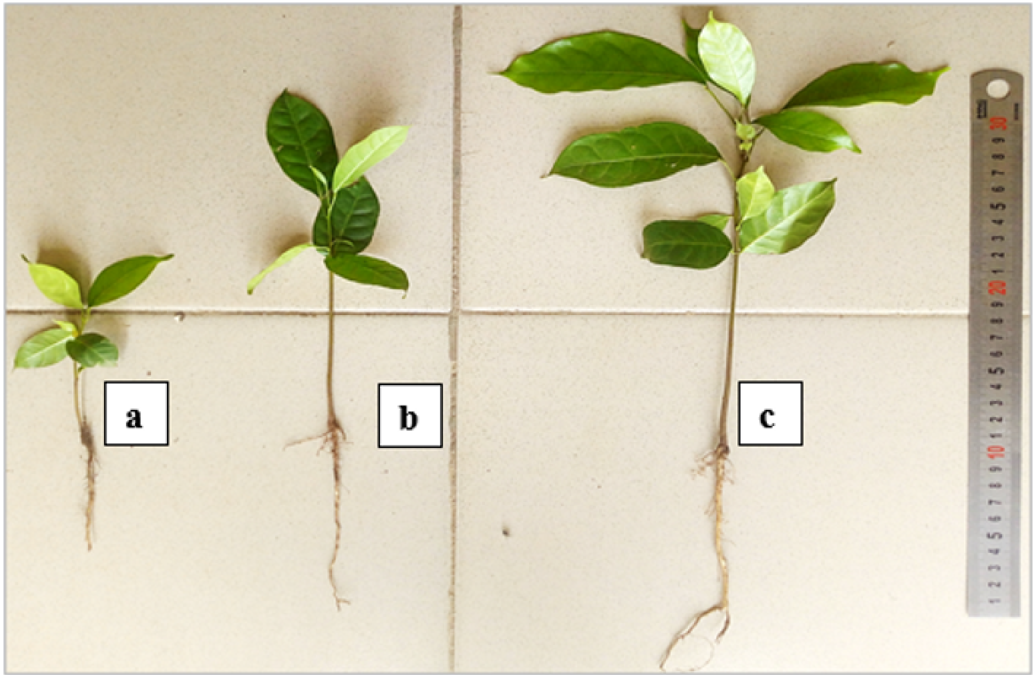


Figure 8

Vigour of 4-month-old seedlings from germination of small (a), medium (b) and large (c) seeds in *Khaya senegalensis*

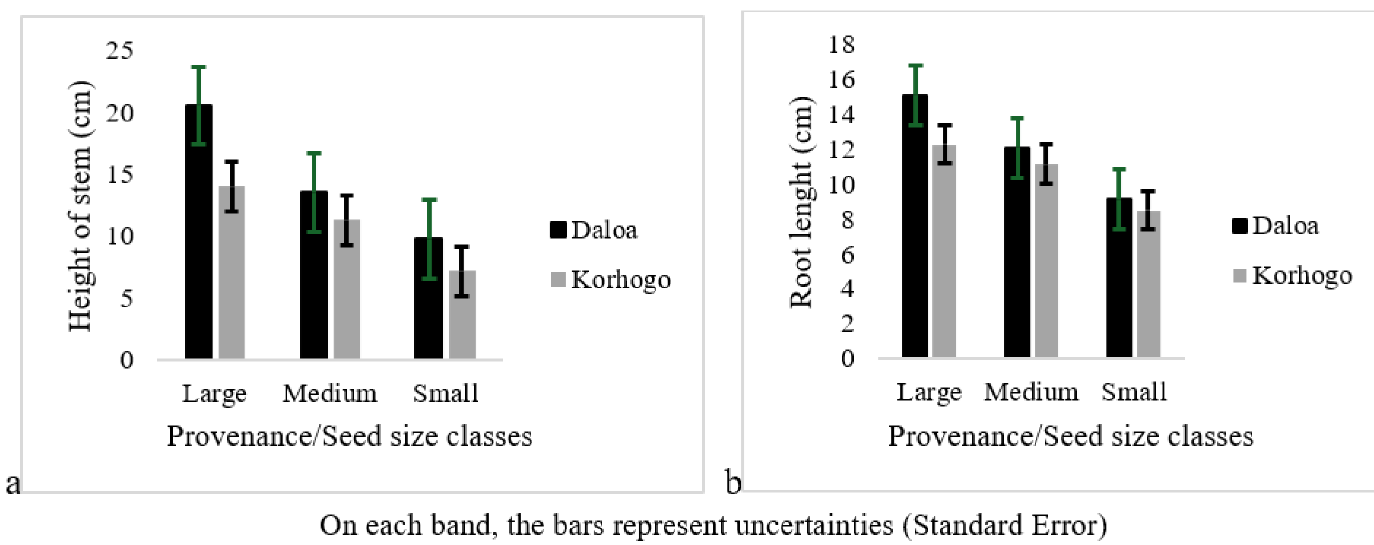


Figure 9

Average stem height (a) and average root length of seedlings by seed size category and study site in *Khaya senegalensis*.

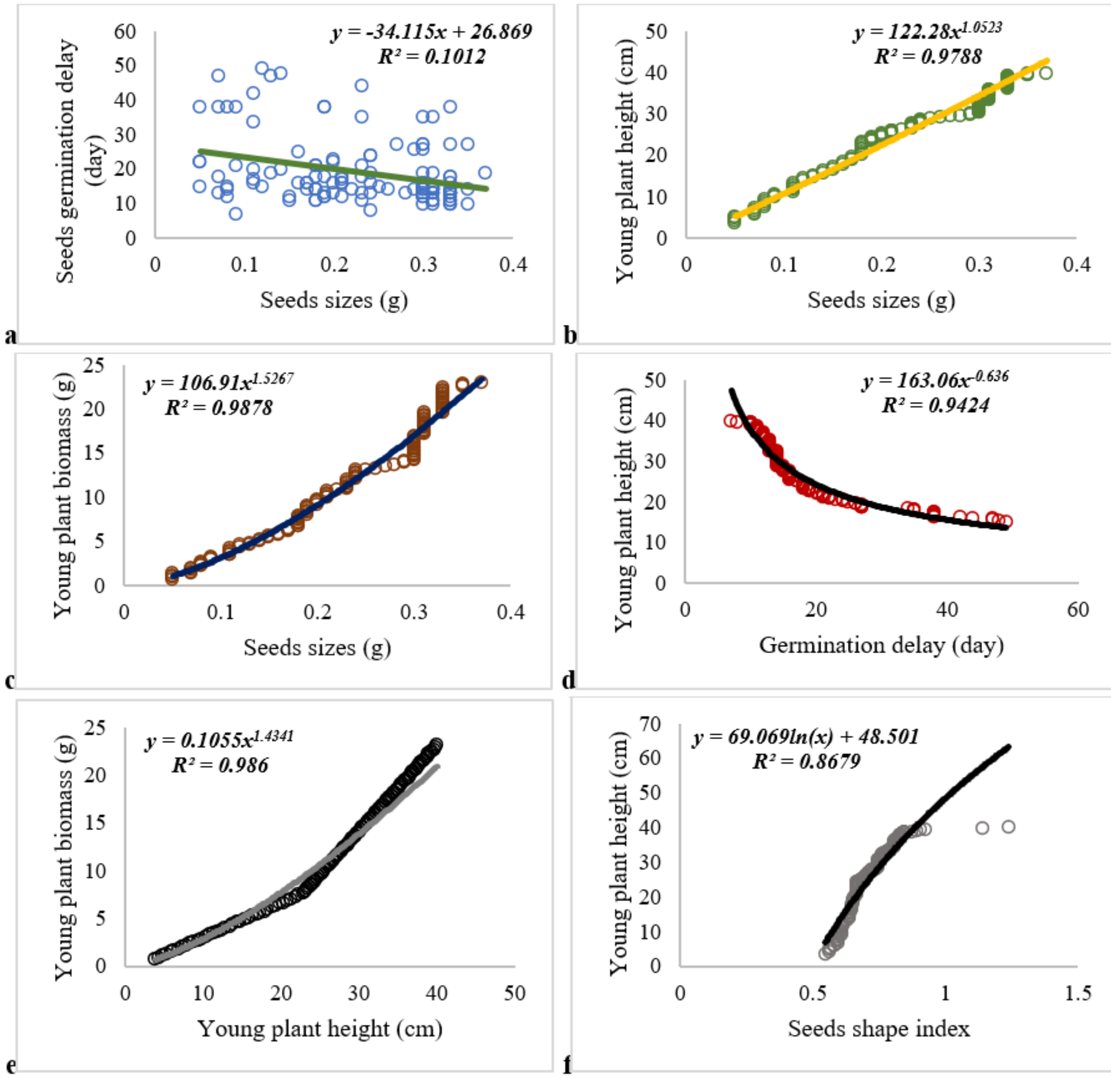


Figure 10

Relationships and regressions between seed size and parameters assessed in *Khaya senegalensis*.

Figure 11

Vigour of seedlings from germination of large (a), medium (b) and small (c) seeds in Parkia biglobosa

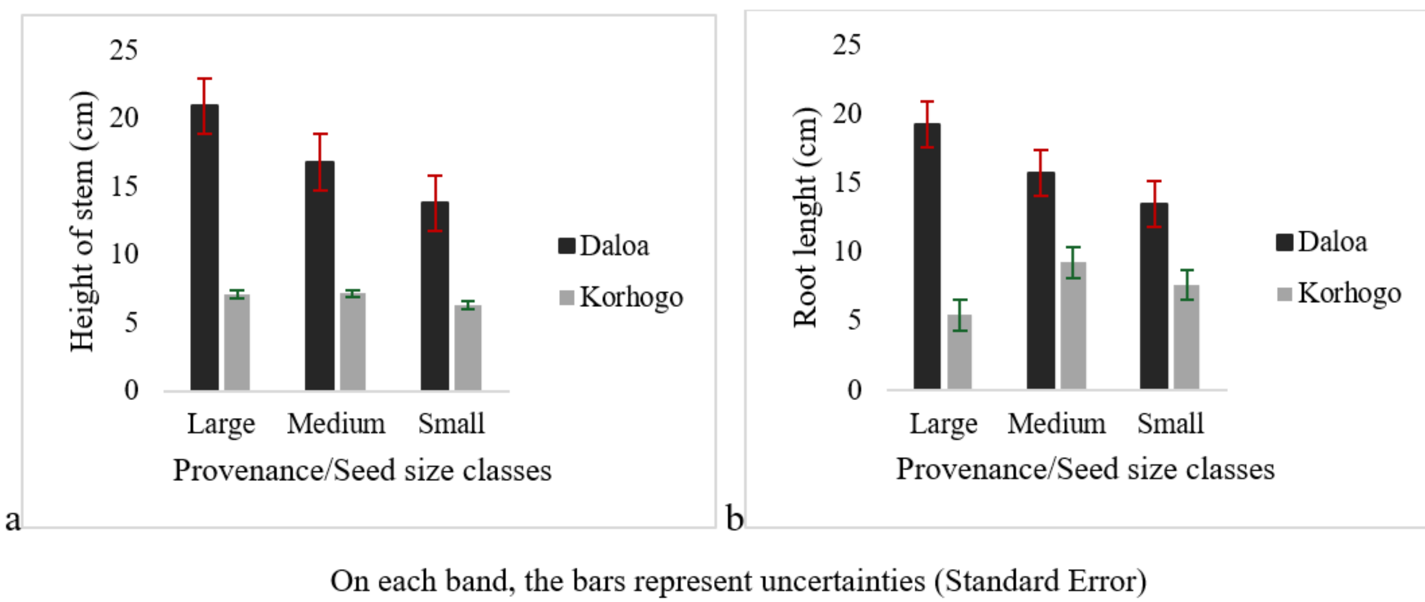


Figure 12

Average stem height (a) and average root length (b) of seedlings by seed size category and study site in *Parkia biglobosa*.

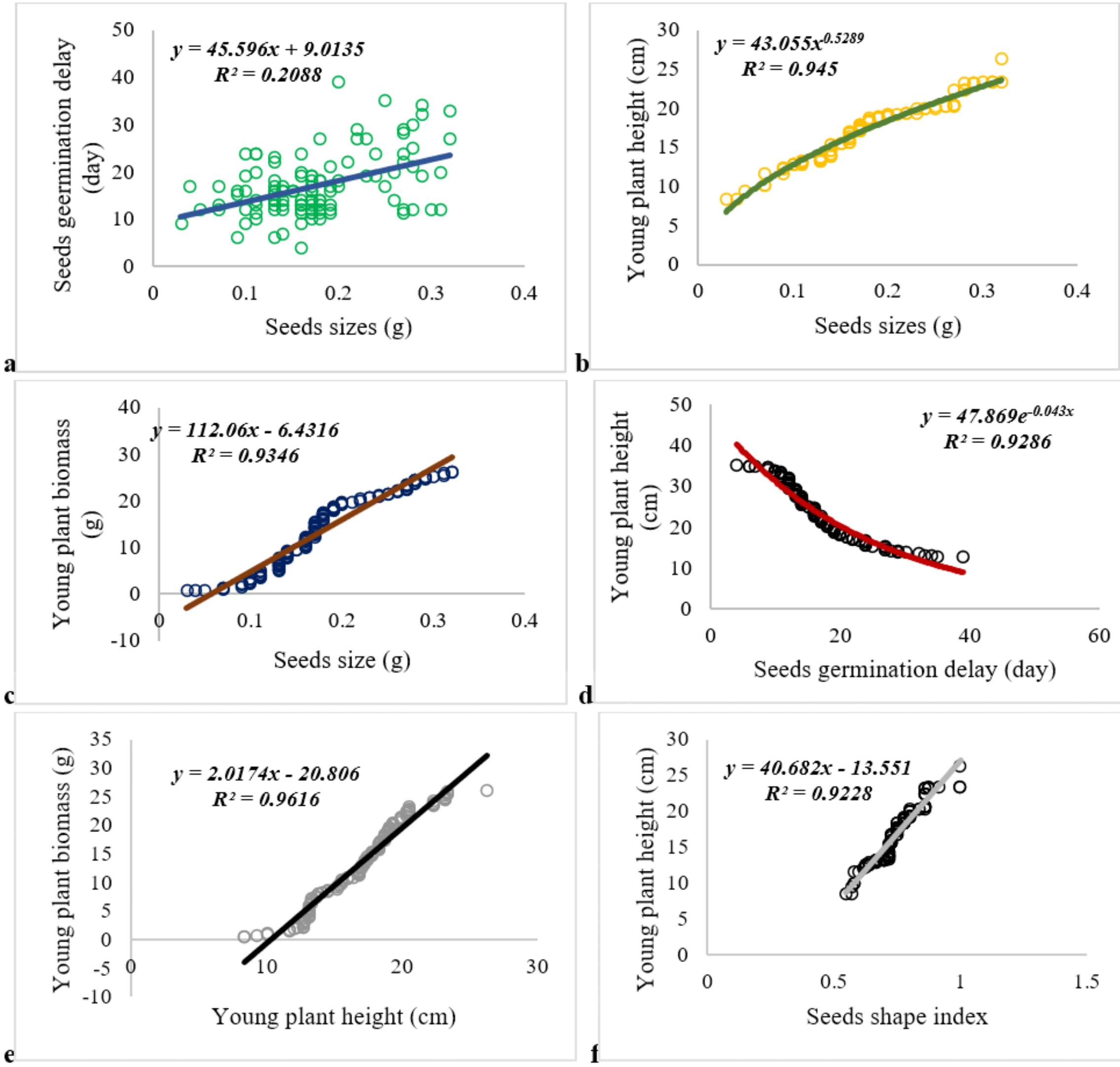


Figure 13

Relationships and regressions between seed size and parameters assessed in *Parkia biglobosa*.