

Full Length Research Paper

Germination and regeneration dynamics of the native tree species *Guibourtia copallifera* in Kasewe Forest Reserve, Moyamba District

Jonathan Johnny^{1*}, Aiah Lebbie^{2,3} and Richard Wadsworth²

¹Department of Wildlife Management and Conservation, School of Natural Resources Management, Njala University, Njala, Sierra Leone.

²Department of Biological Sciences, School of Environmental Sciences, Njala University, Njala, Sierra Leone.

³West Africa Plant List Authority, IUCN Species Survival Commission, Gland, Switzerland.

Received 17 May, 2025; Accepted 21 July, 2025

***Guibourtia copallifera*, native to West Tropical Africa, has a restricted geographic range in Sierra Leone, being common only in the Kasawe Forest Reserve. This species faces challenges in regeneration due to human pressures such as farming, logging, and charcoal production. Despite successful growth in plantations, there is minimal natural seedling establishment. The specific objective was to determine the effect of shade, leaf litter, and planting depth on germination success. Germination was significantly higher in the forest habitat compared to *ex-situ* trials, with dark forest conditions yielding the best results. Germination success decreased with increased planting depth. Seeds on the soil surface in deep shade had the highest success. Leaf litter negatively impacted germination. Seeds in full sunlight had the lowest germination rates, and intermediate light conditions supported better seedling survival. Trials at Njala University's Gmelina plantation showed poorer germination results compared to those at Kasawe ($p < 0.001$, $df = 4$, $F = 31.7$), suggesting that light quality plays a significant role in seed germination. Overall, seedling survival was best under moderate light. Increased leaf litter hindered germination. Further research is needed to understand how seed germination and seedling growth contribute to forest regeneration and species coexistence in this ecosystem.**

Key words: Biomass, forest degradation, *Guibourtia copallifera*, light intensity, planting depth, seeds.

INTRODUCTION

Natural regeneration plays a crucial role in the persistence of native tree species and in the recovery of forests after disturbances (Crouzeilles et al., 2017). The goal of this process is to foster tree recruitment, protect biodiversity,

and enhance the stability and sustainability of forest ecosystems (Hammond et al., 2021; Latawiec et al., 2016). It is shaped by both biotic and abiotic factors, as well as their interactions (Khaine et al., 2018). In Africa, the

*Corresponding author: Jonathan.johnny@njala.edu.sl.

successful natural regeneration of logged forests can be attributed to the seed production of old remnant trees that are left unharvested during logging (Wiafe, 2014). *Guibourtia copallifera* Benn., an endangered species of the Fabaceae family, is found in the subtropical forests of Africa (Tosso et al., 2018). The Kasewe Forest Reserve in the Moyamba district of southern Sierra Leone is dominated by a population of *G. copallifera* (Johnny et al., 2023). This population is a rare natural community with the highest area and purity of *G. copallifera* in Kasewe Forest Reserve. *G. copallifera* is an iconic tree species due to the fact that Sierra Leone is home to two species of trees from the genus *Guibourtia*, that is *copallifera* and *leoneansis*. *G. leoneansis* appears to be the more widely distributed of the two. *G. copallifera* has a very restricted distribution in Sierra Leone, and Kasewe Forest Reserve holds the highest single population. It is known as a species of incredible socio-cultural and economic significance. In the past, sap harvested from *G. copallifera* was called Gum Copal. This gum copal serves as a foreign exchange earner for Sierra Leone, and it was exported to Europe and America mostly as an ingredient for varnish. Kasewe Forest Reserve is 1,224 km² of natural forest, of which *G. copallifera* trees dominate 70% of this reserve. Plantations of *G. copallifera* were established along main streets or roads in provincial towns such as Moyamba, Mano, Blama, and Kenema, which are less than 2 ha. The use of biomass remains the main source of fuel for cooking and heating in rural and urban communities in Sierra Leone. This excessive dependence on biomass as a primary source of energy has significantly contributed to deforestation and loss of forest cover, as well as increased black carbon emissions, with corresponding consequences for Sierra Leonean society, including increased natural disasters and loss of biodiversity (Fayiah et al., 2018). Charcoal gradually replaced firewood and is now the fuel of choice for most city dwellers.

Despite its popularity, the coal and furnace subsector remains informal, unregulated, and fragmented, plagued by an inefficient production system based on non-renewable sources supported by inconsistent and often contradictory policy statements (Arevalo et al., 2016; McCarthy, 2017). Kasewe Forest Reserve was not spared from this saga of deforestation in Sierra Leone, and wildfires occur every year. Agricultural activity is constantly growing year after year. The forest is endangered due to illegal activity, coercion, and illegal exploitation, and the forest has disappeared due to illegal logging. The communities surrounding Kasewe relied on the use of forests through logging, collection of non-timber forest products (NTFPs), firewood collection, pole harvesting, harvesting of plant parts and fruits, hunting, and charcoal burning (Koroma et al., 2021). The reuse of locally valuable native species is also limited because there are no nurseries interested in their propagation. Therefore, there is a limited number of native species distributed nationally. Accurate historical

records of the species' occurrence are scarce, so there is considerable uncertainty about where they historically occurred in the Sierra Leonean vegetation continuum.

Hence, this research aims to investigate the seed germination patterns of *G. copallifera* in its range. Specific objectives include: (1) To determine the effect of litter and planting depth on the germination success of *G. copallifera*, and (2) to establish the effects of light on the germination process of the species. In order to achieve this aim, a critical analysis of the following hypotheses was conducted:

H1: The density of mature *G. copallifera* trees positively correlates with the density of naturally regenerating seedlings in the forest reserve.

H2: Human activities (for example, logging, agriculture) negatively impact the regeneration dynamics of *G. copallifera* in Kasewe Forest Reserve.

Very little is known about the germination and seedling development of forest plants in central Sierra Leone, and it is uncertain whether there were significant differences in seed germination between the different microhabitats in which this restricted species occurs. Germination dynamics of this species are scarce, and nurseries are undocumented without basic materials. The country's current forests cannot meet the current human demand for forest products due to overexploitation of resources, deforestation, lack of quality seeds and planting, rising costs of planting, and lack of proper research and engineering. There is almost no long-term monitoring of forest and species composition in a manner useful for a satisfactory understanding of vegetation dynamics; therefore, population development and species status cannot be predicted. Current research on seed germination and plant growth is limited, and most studies (Eisah et al., 2021; Fayiah et al., 2022; Mattia and Sesay, 2020; Koroma et al., 2021) are limited to economic species. Integrated knowledge of seed collection, storage, germination requirements, and plant growth performance of native tree species is critical to regional biodiversity conservation and restoration plans. *G. copallifera* is the most iconic tree species in the Kasewe Forest Reserve (Eisah, 2020). So information about these species is useful for ecological studies and restoration. *G. copallifera* is vulnerable in the wild and is a key species in its community. Information about its distribution is important for conservation biologists. Considering the operating costs of a nursery, nursery managers prefer species with high germination and rapid seedling growth that produce high-quality seedlings in a reasonable time. Therefore, the urgent need for this research cannot be overemphasized.

MATERIALS AND METHODS

Study area

The study was carried out in the Kasewe Forest Reserve, situated on

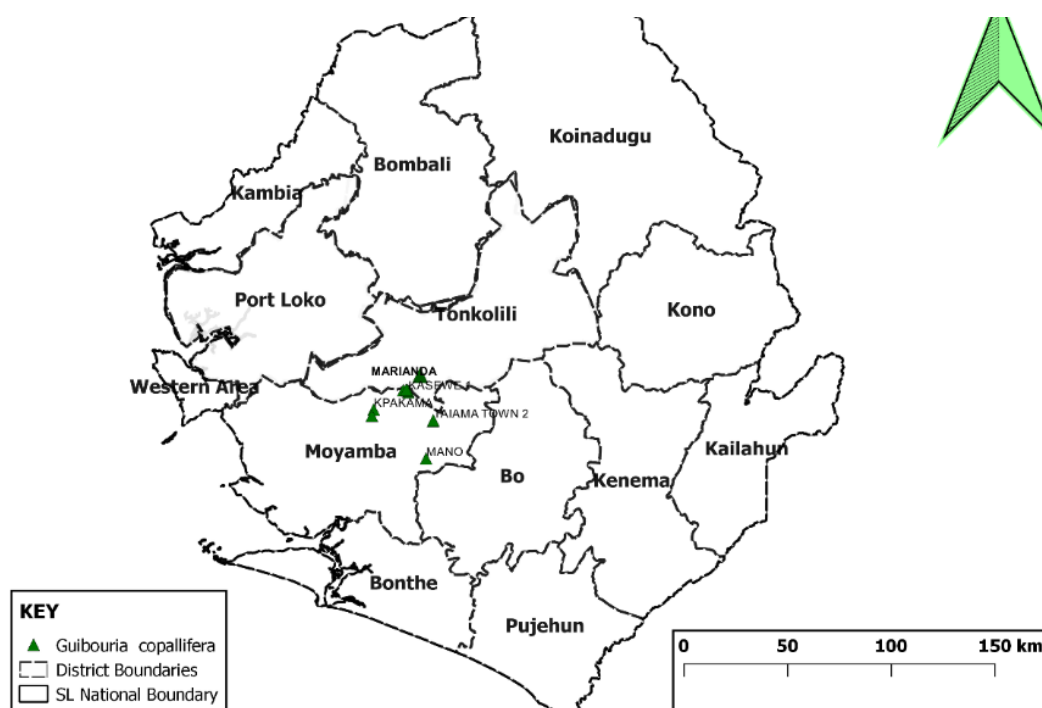


Figure 1. Map of Sierra Leone showing distribution of the species in the districts.
Source: Author compilation.

the border between Tonkolili and Moyamba Districts in south-central Sierra Leone, approximately 170 km east of Freetown and next to the Bo-Freetown highway (Figure 1). This reserve features lowland forests that transition into medium-altitude forests along the slopes and peaks of the Kasewe Hill ridges, with elevations ranging from about 100 to 500 m. Covering an area of roughly 2,331 ha, the Kasewe Forest Reserve is primarily dominated by tropical forest vegetation, but it also includes a mix of moist semi-deciduous forests, evergreen forests, and savanna (United Nations Environment Programme [UNEP], 2008). The climate of Kasewe Forest Reserve is tropical and humid, with distinct wet and dry seasons. The Inter-Tropical Convergence Zone (ITCZ) influences the wet season, which normally lasts from May to October and has average temperatures between 22 and 25°C. The dry season, which lasts from November to April, brings cooler, drier winds from the Sahara and temperatures that can reach 25 to 27°C. The average annual rainfall in the reserve is 2135 mm, which is a significant amount. The terrain is hilly, with elevations ranging from 100 to 645 masl (Statistic Sierra Leone (SSL), 2022). The hills, formed by volcanic intrusions, rise up to approximately 500 m above the surrounding plains, and are an essential water catchment for the local communities near the reserve (Bowden, 1997; Lytwyna et al., 2006).

Ecological and economic relevance

G. copallifera, as the dominant species in the forest areas, contributes to biodiversity and provides habitat and resources for a wide range of animals. The seeds of these trees are dispersed by the wind, contributing to their regeneration and forest maintenance, but their population is vulnerable to human activities, such as deforestation and excessive exploitation of the wood and timber. Historically, *G.*

copallifera Kobo grew naturally across a few chiefdoms in only one district in Sierra Leone. However, the current distribution has changed from the historic areas in terms of densities. The distribution of the species, as recorded in the historical records, floras, herbarium specimens, and government reports, was limited to Moyamba town, Taiama, Mano, Blama town, Kenema town, and Moyamba.

When compared to the distribution of current remnant populations of the species, it is now recorded (sighted) in Yoni in Tonkolili District (one village) and several villages in Moyamba District. Taiama and Mano have fewer trees remaining on what used to be plantation sites, with the remaining trees largely used for charcoal making. Plantations in Blama and the environs of Kenema are no longer in existence. Despite the fact that the species was recorded in the district of Tonkolili, which seems like an extension of its original range, its population density is under serious threat. In all of the sightings observed in various communities, it is used for charcoal production irrespective of its density and population growth trends.

Overexploitation of this species for charcoal production is on the increase in every community where it was recorded. In Sierra Leone, the most preferred species for charcoal production by the exploiters is *G. copallifera*, a species of tree that was heavily exploited for gum copal during the colonial period, but is no longer being exploited at present. It was one of the commodities that was a foreign exchange earner for Sierra Leone in the colonial period.

The high quality of charcoal produced from this species and the increased exploitation it currently faces in this unprotected reserve could predispose this limited geographical range species to extirpation. Communities around the reserve still use the leaves, stems, and roots for traditional medicine in healing several ailments. At the same time, the gum extracted from the tree is used as a lighting source for the home at night and for sealing leaking plastics and metal containers.

Table 1. Germination trials on pre-treated seeds (soaking and not soaking seeds in water).

Trials	Pre-treatment	Planting media	Planting depth (cm)	Shade (%)
T.1.1	Soaked 24 h	Soil	3	75
T1.2	Soaked 24 h	Sand	3	75
T1.3	None	Soil	3	75
T1.4	None	Sand	3	75
T2.1	Soaked 24 h	Sawdust	3	75
T2.2	None	Sawdust	3	75
T3.1	Testa chipped	Sand/Soil	3	75
T3.2	None	Sand/Soil	3	75

Seed collection

Mature fruits of *G. copallifera* were collected from underneath parent trees within the Kasewe Forest Reserve. The seeds were collected in bags from the forest floor and from seed traps installed along a transect line. Seeds from seed traps were properly checked to remove rotten seeds or partly germinated seeds from the lot. Seeds collected were washed, sun-dried, placed, and stored in a safe place to prevent insect invasion and moisture from affecting the seeds. Seeds of *G. copallifera* were stored for six months to a year before germination commenced. Seeds can still be viable after a year if they are properly preserved and stored.

Germination trials

Phase 1: Ex-situ germination trials

Seed pre-treatments: Seeds collected from the forest floor were washed with water and sun dried to clean them of sand, filth, and other debris, are sorted out to eliminate those already infested by insects. All seeds with holes, which were an indication of insect infestation, were separated and not included in the seeds to be planted (30% of all seeds collected). After the sorting, seeds that were not insect-infected were removed from the fruit. Seeds removed from the fruits were placed in water to determine the viable and non-viable seeds. Seeds that floated on the water were considered non-viable; thus, not suitable for planting. Seeds that settled at the base of the container were considered proper for planting. These seeds were used in the germination trials.

Planting trials: Germination trials were done in two phases: phase 1 was *ex-situ*, in which seeds collected from Kasewe Forest Reserve were planted outside the forest environment; and phase 2 was *in-situ*, seeds collected from Kasewe Forest Reserve were planted within the reserve itself. In the *ex-situ* trials, two sets of trials were conducted on the Njala University campus. For this *ex-situ* trial, a total of 360 seeds were planted in all of the polythene bags. Three individual seeds were planted in each polythene bag in a triangular pattern. Replication of trials was done with the same number of polythene bags, but with different growth medium using seeds treated either with water soaking, or with the seed coat chipped (Table 1). Control conditions for these trials were seeds not soaked in water and seed coats not chipped.

Trial descriptions: Trials of 15 polythene bags were used to examine the effect of soaking or not soaking the seeds, and on the growth media (Table 1). Growing media were sterilised in an autoclave at 45°C. The steps were:

- 1) T 1.1 contained 15 polythene bags with soil in them, in which seeds were soaked in water for 24 h prior to being planted.
- 2) T 1.2 also contained 15 polythene bags with sand in them, in which seeds were not soaked in water prior to being planted.
- 3) T 1.3 also contained 15 polythene bags with soil in them, in which seeds were not soaked in water prior to being planted.
- 4) T1.4 also contained 15 polythene bags with sand in them, in which seeds were not soaked in water prior to being planted.
- 5) T 2.1 contained 15 polythene bags with sawdust in them, in which seeds were soaked in water for 24 h prior to being planted.
- 6) T 2.2 also contained 15 polythene bags with sawdust in them, in which seeds were not soaked in water prior to being planted.
- 7) T 3.1 contained 15 polythene bags with a mixture of soil and sand (equal amount) in them, in which the seed's testa/coat was chipped prior to being planted.
- 8) T 3.2 contained 15 polythene bags with a mixture of soil and sand (equal amount) in them, in which the seed's testa/coat was not chipped prior to being planted.

Phase 2: In situ germination trials

Site preparation: Reconnaissance survey of the study area was undertaken to determine the needed habitats within the forest. Phase two of the germination trial (in situ) was conducted in the Kasewe Forest Reserve, where the seeds were collected. Sampling sites and plots were all located within the forest patch. Sampling sites were selected based on the amount of sunlight available to the sites. Three habitat types were selected with reference to the availability of sunlight in the forest environment. These include:

- (1) Gaps or openings in the forest canopy where sunlight penetrated and reach forest floor;
- (2) where canopy cover is dense that sunlight cannot reach the forest floor, and
- (3) in a degraded patch where sunlight is in abundance or an open field in the forest where the force of the sun light has no limit. Each sampling area has three plots in the order P1, P2, and P3. Each of these plots was measured, cleared, pegged, and soil was prepared for planting seeds.

Canopy openness/cover was characterized on each plot with a Type A convex spherical densiometer. Densiometer measurements were acquired by the same observer for all plots. To standardize the densiometer measurements, standard recommended operating procedures were followed, and the field team completed intensive training prior to field data collection to calibrate their measurements. Four densiometer measurements were taken at each plot (once with the observer facing each cardinal direction) and averaged to minimize

Table 2. Germination trials on Njala University Campus.

Trials	Conditions	Planting media	Planting depth (cm)
T4.1	Full shade	Soil	0-4
T4.2	partial shade	Soil	0-4
T4.3	full sun	Soil	0-4
T5.1	surface	Soil	0
T5.2	Depth	soil	2
T5.3	Depth	Soil	3
T5.4	Depth	Soil	4
T5.5	Depth	Soil	5
T5.6	Leaf litters	Soil	2
T5.7	Leaf litters	Soil	3
T5.8	Leaf litters	Soil	4

observer errors (Baudry et al., 2014). For densiometer measurements, it was assumed that four equi-spaced dots were in each square of the grid, and systematically counting dots equivalent to quarter-square canopy openings. The total counts were multiplied by 1.04 to obtain the percentage of overhead area not occupied by the canopy. The difference between this and 100 is an estimation of over-story canopy density in percent (Stumpf, 1993).

Trial description: The trial descriptions are as follows:

- 1) T4.1 Full shade (Seeds were planted in the part of the forest where sunlight doesn't reach the forest floor).
- 2) T4.2 partial shade (Seeds were planted in the part of the forest where sunlight does not reach the forest floor).
- 3) T4.3 full sun (Seeds were planted at the edge of the forest where sunlight is at its full strength).
- 4) T5.1 surface (Seeds were just scattered on the soil surface).
- 5) T5.2 depth of 2 cm (Seeds planted at 2 cm depth in the soil).
- 6) T5.3 depth of 3 cm (Seeds planted at 3 cm depth in the soil).
- 7) T5.4 depth of 4 cm (Seeds planted at 4 cm depth in the soil).
- 8) T5.5 depth of 5 cm (Seeds planted at 5 cm depth in the soil).
- 9) T5.6 seeds planted on the soil surface and covered with 2 cm of leaf litter.
- 10) T5.7 seeds planted on the soil surface and covered with 3 cm of leaf litter.
- 11) T5.8 seeds planted on the soil surface and covered with 4 cm of leaf litter.

Germination trials conducted at Njala Campus under the various conditions observed in Kasewe Forest Reserve are shown in Table 2.

In-situ seed sowing in the Kasewe forest: Each sampling area consisted of three sampling units designated as plots: P1, P2, and P3. Each plot measured 8 m × 5 m, which was further subdivided into 8 subplots measuring 1 m × 5 m. These subplots were labelled 1 to 8 for planting, but each of these subplots was treated differently from the others with regard to seed sowing method (Table 2).

Trial description: The trial description is as follows:

- 1) Subplot 1, seeds were scattered on the ground surface.
- 2) Subplot 2, seeds planted at a depth of 2 cm.
- 3) Subplot 3, seeds planted at a depth of 3 cm.
- 4) Subplot 4, seeds planted at a depth of 4 cm.

5) Subplot 5, seeds planted at a depth of 5 cm.

6) Subplot 6, seeds scattered on the surface and covered with 2 cm of leaf litter.

7) Subplot 7, seeds scattered on the surface and covered with 3 cm of leaf litter.

8) Subplot 8, seeds scattered on the surface and covered with 4 cm of leaf litter.

These were the methods adopted for seed sowing in the plots inside and outside the reserves' boundaries. All of the subplots in the different habitats were planted on the same day so that the recording of data could be done in order. Each of the sub-plots was planted with 200 seeds, after which seed holes were closed and subplots 6 to 8 were packed with leaf litter to the specific limits as described in the protocol. Germination sites were monitored every day to record the date, number of germinating seeds, and sites where they started. The data collation continued until the time that the last seeds germinated.

This germination protocol employed in Kasewe Forest Reserve was also repeated at Njala University campus under similar light conditions with the same three plots as in Kasewe Forest Reserve. The availability of suitable sites on campus with the necessary light conditions, for very thick/closed canopy cover to avoid penetration of light to the floor of the experimental site, was of utmost concern.

Methodological restrictions

Although this study offers insightful information about the germination and regeneration dynamics of *G. copallifera*, there are a number of methodological limitations to take into account when interpreting the data. First, during field trials, seed predation was not completely controlled, which would have resulted in an underestimation of the germination potential since rodents, insects, or other animals may have damaged or removed seeds. Future studies could isolate the impacts of predation by using exclusion techniques like barriers or seed cages. Second, rather than being tracked continuously, soil moisture levels (a crucial component affecting seed germination and seedling survival) were checked periodically. This restriction might have made the correlation between moisture availability and regeneration success less accurate. To better understand the moisture requirements of *G. copallifera* seedlings, automated soil moisture sensors would offer more precise and reliable environmental data. Lastly, there may have been variation in germination and growth results due to the incomplete measurement of other environmental

Table 3. Status of seeds harvested from the various traps.

Seed conditions	Forest floor (%)	Seed traps (%)
Infested seeds	20	12
Rotten seeds	15	13
Germinated seeds	13	05
Good seeds	52	70

Table 4. Germination in relation to light intensity.

Sampling site condition	Germination percentages	
	Kasewe	Njala
Full shade	66.1	28.6
Partial shade	48.1	24.3
Full sun	31.5	19.7

parameters, such as light availability, temperature swings, and soil nutrient status. Future research addressing these issues will enhance the formulation of conservation strategies and contribute to a more comprehensive understanding of the regenerative ecology of the species.

Data analysis

The majority of the analyses were done using R version 3.6.2 (R Core 2020). To determine the assemblages/communities that exist in such a collection of data, multi-dimensional scaling (MDS) using the cmd scale package in R was used to visualize the relationship between plants. Analysis of variance (ANOVA), single-factor analysis, paired t-tests, and linear regression were used to determine the effectiveness of the different types of plots, dispersal, and germination in the different environments, during changes over time.

RESULTS

Seed quality or seed content

Significant differences were found between seed collected from the traps and those from the forest floor for germination. About 40 to 60% of seeds collected from the forest floor were infested or compromised, while 45 to 85% of seeds from the traps were in good condition (viable). The seeds collected were detected to be infested when evaluating seed fill using visual estimates, using a scale ranging from 0 to 100%. Based on pooled data of all harvests, 30% of all seeds collected directly from the seed traps were compromised in some respects (Table 3). While 48% of all seeds collected from the forest floor were compromised. From the compromised seeds, the percentages are as follows: infested or predated (73.2%), immature (20%), and empty (6.8%).

Prior studies indicate that dormancy is not an issue with *G. copallifera* species, and seeds can maintain viability for 12 months under dry storage conditions (Matthew, 2020).

In the field, seedling emergence was reduced by 50 to 72% at peak emergence times after a single year, indicating the seed bank might be short-lived (<3 years) under existing forest conditions.

Germination percentage with light and planting depth

The germination percentage rate appears to be very sensitive to different light conditions at Njala Campus and Kasewe Reserve Forest (Table 4).

The percent germination of *G. copallifera* in the forest habitat was approximately three times greater, and maximum germination occurred in half the time used in *ex-situ* germination (Table 4). Differences in germination with location were expected because *G. copallifera* was rare everywhere, except at Kasewe.

The cumulative plot for the seeds that germinated indicates that there is a considerable difference in germination depending on the light conditions, with better germination in full shade and worse in full sun. The significant difference is that germination percentage is higher in a shaded habitat than in full sunlight. The cumulative plots for Njala indicate the same general trend as that of Kasewe, but at about half the success. It would appear that this species requires a good canopy cover to successfully germinate (Table 5).

Germination of seeds based on the depth of soil and leaf litter

The seeds are relatively light and wind-dispersed. Seeds allowed to germinate on the soil surface had the highest success in germination, while those buried deeply did poorly (Table 6 and Figure 2).

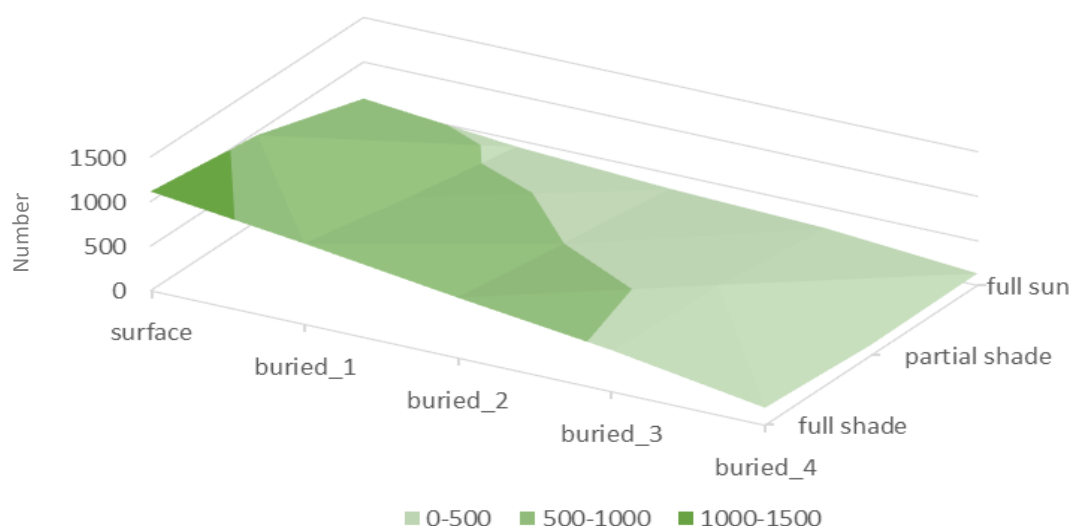
With increased sowing depth, seed germination

Table 5. Cumulative germination in relation to shade and light.

Day	Kasawe			Njala		
	Full shade	Partial shade	Full sun	Full shade	Partial shade	Full sun
1	84	74	58	34	39	35
2	214	168	127	90	89	75
3	396	314	230	178	175	134
4	653	507	353	328	291	211
5	1002	793	549	550	464	346
6	1474	1187	811	828	692	520
7	1821	1505	981	1002	851	629
8	2050	1694	1078	1117	939	693
9	2184	1796	1114	1181	973	716

Table 6. Summary of impacts of planting depth and shade on germination.

Condition	Surface	Buried_1	Buried_2	Buried_3	Buried_4
Full Shade	1113	907	677	467	197
Partial Shade	962	650	500	413	120
Full Sun	590	425	330	270	135

**Figure 2.** Germination number in relationship to shade and depth.
Source: Author compilation.

decreased and reached the minimum at depth 3 or 4 cm. Burying seeds affects germination or emergence. Putting the seed in leaf litter has a similar effect to burying the seed; that is, germination is reduced (Table 7 and Figure 3).

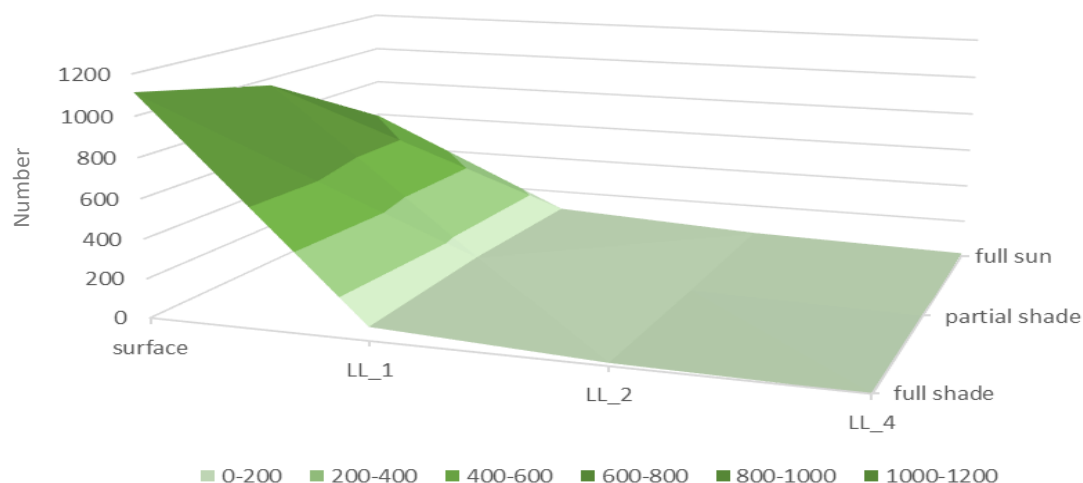
The best conditions for germination are seeds falling on bare ground in full shade. Burying the seed in the presence of leaf litter is detrimental to germination, as is full sun.

Germination of seeds based on the sites/location of the trial ANOVA: Two-factor with replication (Summary)

Germination showed a highly significant relationship between geographical location and shade ($p < 0.001$, $df = 4$, $F = 31.7$) and the planting depth ($p < 0.001$, $df = 7$, $F = 251.7$). There is also a highly significant interaction

Table 7. Summary effect of leaf litter on germination.

Condition	Surface	LL_1	LL_2	LL_4
Full Shade	1113	69	15	0
Partial Shade	962	101	23	0
Full Sun	590	96	40	16

**Figure 3.** Leaf litter effects, light levels, and seed germination.
Source: Author compilation.**Table 8.** Total ANOVA (95% confidence interval).

Source of variation	SS	df	MS	F	P-value	F crit
Sample	32,020.62	4	8005.1	31.8	8E-16	2.485
Columns	444,787.7	7	63541.1	251.8	9.82E-52	2.126
Interaction	45,032.3	28	1608.3	6.4	3.38E-11	1.617
Within	20,191.3	80	252.4	-	-	-
Total	542,031.9	119	-	-	-	-

SS: Sum of squares, DF: degrees of freedom, MS: mean sum, F: the ratio of between-group variation and within-group variation, P-value: statistical significance, and F crit = F critical value.

between location and planting depth ($p < 0.001$, $df = 28$, $F = 1608.3$). Germination time and germination rate are related to light conditions, seed sowing depth, and leaf litter (Table 8).

In the first trials where seeds were planted at a depth of 3 cm or more in plastic bags with various media, namely, soil, sand, sawdust, and mixtures of the three at equal proportions. Germinating seeds observed in this trial were less than 5% of the total number of seeds planted at the start of the trial. Only 0.65% of the seeds of *G. copallifera* germinated within the first 15 days and gradually approached an overall level of $< 5\%$ germination success toward the end of the trial. In the forested trials, success

was up to 60% with a short germination time of 6 days after planting.

The results of the one-way ANOVA for the various light conditions in the forest indicated a statistically significant relationship ($p < 0.01$, $df = 2$, $F = 11.4$), implying that the germination of the seeds was affected by the light conditions of the forest (Table 9).

Interaction effect between depth, shade, light, and site (two-way ANOVA without replication)

The result of the two-way ANOVA indicated that there was

Table 9. Amount of light and germination rate ANOVA (95% confidence interval).

Source of variation	ANOVA					
	SS	DF	MS	F	P-value (95% CI)	F crit
Between Groups	28,980.9	2	14490.4	11.45	0.001653	3.88
Within Groups	15,188.4	12	1265.7	-	-	-
Total	44,169.3	14	-	-	-	-

SS: Sum of squares, DF: degrees of Freedom, MS: mean sum, F: the ratio of between-group variation and within-group variation, P-value: statistical significance, F crit: F critical value, and CI: confidence interval.

Table 10. Interaction between shade and depth on germination rate at Njala (95% confidence interval).

Source of variation	ANOVA					
	SS	DF	MS	F	P-value (95 % CI)	F crit
Regression	360968.2	4	90242.06	49.30301	0.001563	4.28 E-24
Residual	210491	115	1830.356	-	-	-
Total	571459.2	119	-	-	-	-

SS: Sum of squares, DF: degrees of Freedom, MS: mean sum, F: the ratio of between-group variation and within-group variation, P-value: statistical significance, F crit: F critical value, and CI: confidence interval.

a significant effect between shade and germination of the plant ($p < 0.001$, $df = 4$, $F = 49.3$), but there was no significant change over the eight trials of the experiment ($p > 0.05$, $df = 9$, $F = 1.62$) (Table 10).

The result of the two-way ANOVA indicated that there was a significant effect among depth, litter, and germination of the plant ($p < 0.001$, $df = 4$, $F = 74.7$), for both depth and shade. There were also very significant effects that leaf litter had on the germination of the species, but there was no significant change among the trials of the experiment ($p > 0.05$, $df = 9$, $F = 1.66$).

Plants in deeper soils or deeper water may rely on higher light levels to maintain photosynthesis; that is, deeper environments can be more limiting. If shade increases with depth, it might create a synergistic negative effect, that is, less light availability where it is already limited. Species adapted to low light (shade-tolerant) may dominate in deeper or more shaded areas. Root or shoot elongation might be observed as adaptive traits. While seemingly redundant, shade can affect light quality (for example, more far-red light in forest understory), while light intensity refers to quantity. Species may respond differently to spectral quality than intensity; for example, shade-grown plants might increase chlorophyll *b* to optimize absorption. Phenotypic plasticity (ability to adjust morphology/physiology) becomes crucial for survival. Soil or water depth can vary across sites, leading to different resource availability or stress gradients (for example, oxygen, nutrients, root penetration limits). Site-specific depth effects may drive local adaptation, or species sorting, across a landscape. Sites may vary in canopy cover, aspect, or

altitude, affecting light regimes. Interaction implies that shade effects or light-driven productivity are not uniform across sites; it depends on how the environment shapes microclimates. Management strategies (for example, for reforestation or conservation) must be site-specific.

A linear regression of median seed germination per trial for the sites gives a t-stat value of only -0.140, which is not significant ($p > 0.05$, $df = 8$, $F = 0.017$), indicating that there are no significant differences between the sites where the experiment was conducted (Table 11).

Implications for restoration activities at Kasewe forest reserve

Seedling mortality for this species, based on the results obtained, was around 30 to 38% when planted in the proper conditions and environment (Shaded Forest, high humidity, and shallow planting depth). Reasons for mortality were not always evident, but observations revealed that waterlogged soil, excess water, fire, and fungal attack are causal factors. Herbivory by insects, beetles, grasshoppers, and ants was observed for this species, and was evident in all the sites and plots.

The germination results prove that this species can be used for restoration purposes, since its germination percentage in the nursery is significantly high and the number of seeds produced by the individual trees is numerous. Limited dispersal and stringent requirements for germination could explain the very restricted range of this species in Sierra Leone. It is a species for which there were

Table 11. t-Test: two-sample assuming unequal variances.

Parameter	Variable 1 (Njala)	Variable 2 (Kasewe)
Mean	69.64583	71.40278
Variance	3891.468	5471.427
Observations	48	72
Hypothesized Mean Difference	0	-
df	112	-
t Stat	-0.14019	-
P(T<=t) one-tail	0.444381	-
t Critical one-tail	1.658573	-
P(T<=t) two-tail	0.888761	-
t Critical two-tail	1.981372	-

no known nursery protocols prior to this study.

DISCUSSION

Seed quality

Seed quality encompasses various dimensions (genetic, physical, physiological, and sanitary) that collectively influence both how seeds perform in the field and how well they endure during storage (Pires and Baute, 2022). High-quality seeds are associated with improved germination rates, robust seedling development, superior crop quality, and increased yields (Singh and Raia, 2020). In the current research, it was found that 30% of seeds collected from traps and 38% of those from the forest floor were degraded. Seed degradation over time leads to diminished vigor, heightened susceptibility to environmental stress, and ultimately failure to germinate (Rajjou and Debeaujon, 2008). Both genetic and environmental elements—especially storage temperature and moisture levels—play crucial roles in determining how long seeds can be effectively stored (Walters et al., 2005).

The primary cause of the rapid deterioration of seed quality during storage is moisture from ambient relative humidity (Afzal, 2018; Bakhtavar et al., 2019a). Nonetheless, seed quality can be maintained by keeping the seeds dry while being stored (Afzal et al., 2017; Bakhtavar et al., 2019b). High humidity, particularly during the monsoon season, causes seeds to acclimate to the relative humidity (RH), increasing the moisture content of seeds kept in traditional porous packaging materials (Afzal et al., 2017; Williams et al., 2017). In a related study, an increase in moisture up to 1.04% in wheat and 1.43% in maize caused a considerable loss in germination of seeds in polypropylene bags (14%) and 22% in maize. According to Roberts (1972), the moisture content and storage temperature of seeds mostly affect how long they last. Elevated storage temperatures hasten the decomposition

of seeds, leading to a reduction in seed quality and, consequently, a reduced percentage of seeds that germinate (Genes and Nyomora, 2018).

Light and shade effects on germination

Environmental variables like light, temperature, seasons, and water availability affect the germination of seeds and the establishment of plant species in natural forest ecosystems (Leal et al., 2013). Over the course of the experiment, shade levels had a substantial impact on seed germination in this investigation. According to other research, invasive plants do badly in low light but thrive and grow more quickly in high light (Ioana et al., 2015; Cai et al., 2021). According to this research, *G. copallifera* seeds germinate best when they are shaded to a maximum degree (60%) during the rainy season. While seeds with more than 50% shade levels took longer to sprout, the bulk of *G. copallifera* seeds (95% ultimate germination) in this study's experiment germinated after five days. However, when soil moisture is sufficient and tree seed dispersers are present, for other species, such as *Maesopsis eminii*, seed populations have high germination rates, particularly in big canopy gaps and forest margins (Epila et al., 2017).

Seasonal variation impacted *G. copallifera* seed germination and development in this study. Light and humidity had a stronger inhibitory effect on seed germination during the dry season than during the wet one. As demonstrated in this study, adequate moisture availability during the rainy season also increased *G. copallifera* seed germination to the degree that light effects were mitigated.

Seedlings may suffer in the shade until they reach the gap when the rainy season ensues and new leaves arrive, raising the shade level (Kilawe et al., 2018). In a similar vein, Epila et al. (2017) reported that 97% of mapped *M. eminii* species were located in regions with mean annual rainfall over 1000 mm, indicating that water availability is a

limiting factor for *M. eminii* distribution. According to Ye and Wen (2017), seed germination is a crucial developmental stage that is essential to invasive ecology in terms of seedling establishment and overall environmental adaptation.

Planting or sowing depth and germination

The ultimate germination rate seems to be influenced by seed depth. In contrast, seeds that fall on bare soil in full shade are the most conducive to germination for *G. copallifera*. According to a related study by Uniyal et al. (2007), *A. indica* seeds buried 5 cm below the soil surface grew at a higher proportion and produced seedlings earlier. In trials involving *Chamaesyce hirta* seeds, Freitas et al. (2021) discovered that, in comparison to other depths, a seed depth of 0 cm demonstrated the best germination, independent of the plant cover. The findings of this investigation align with those of this earlier study. Similarly, *Gossypium hirsutum* cotton seed data revealed that no germination took place above 9.2 cm and that germination declined with increasing seed depth (Nabi et al., 2001). However, *Boundial shea* had the highest ultimate germination (84.60%) and the shortest latency duration (51 days) at 5 cm planting depth, according to Martial et al. (2021). Bamboo seeds (*Oxytenanthera abyssinica*) sown to a depth of 2.5 mm also exhibited faster germination with a higher percentage of germination than seeds seeded to a depth of 5 and 10 mm, according to similar findings reported by Embaye et al. (2003).

Islam et al. (2020) discovered that 15 universal trees in Bakphuli, Sadakoroi, Ipilipili, Akashmon, Sonalu, Babla, Kalokroi, and Raintree had a germination percentage ranging from 30 to 60% with a maximum germination depth of less than 1.5 and 2.5 to 4.5 cm depths of 11, 21, 22, 16, 44, and 30 days, and the germination percentage varied from 30 to 60%. Compared to the current study, which lasted two weeks or fewer than fourteen days, these germination durations are significantly greater. Following germination, the vegetative vigor of burned seedlings was positively impacted by the horizontal orientation of seeds in the lateral direction (HL). Embaye et al. (2003) found similar effects for bamboo and beans, whose seedlings only look better when the seeds are placed horizontally.

Singh et al. (2017) reported that *Cinnamomum tamala* seedlings emerged most readily in shallow burial (3 cm) and least readily in deep burial (7 cm). While many seeds buried 3 cm deep did not sprout, John and Sullivan (2013) observed that seeds buried deeply tended to sprout later than seeds buried shallowly. Additionally, Ali and Idris (2015) found that when seed depth decreased, *Vicia faba* seed germination increased with other factors. According to Guo et al. (2010), seeds buried deep in the ground may rot, because deeper soil has more moisture than shallower soil. According to Ahirwar et al. (2015), *Butea frondosa* seeds

germinated more readily at a depth of 2 cm, and as seed depth increased, the germination percentage progressively dropped.

Leaf litter effects on germination

Increases in litter depth or volume significantly reduced the germination of *G. copallifera* seeds, which peaked at a depth of 3 to 4 cm. Burying seeds prevents or postpones emergence or germination. The impact of placing seeds in leaf litter is comparable to that of burying them in soil (germination is reduced). In contrast to grassland habitats, where litter cover had no discernible impact on seedling emergence, this study's findings demonstrated that the presence of litter had a detrimental influence on seedling emergence in forest ecosystems, consistent with findings of Xiong and Nilsson (1999). Another significant factor influencing the impact of litter on seedling establishment, in addition to litter type, is litter amount (Hata et al., 2010; Cavieres et al., 2007; Hovstad and Ohlson, 2008; Kremer et al., 2019; Facelli and Ladd, 1996; Kai and Gutekunst, 2003). Similarly, Gavinet et al. (2018) discovered that seedling emergence was aided by a thin layer of litter cover ($< 200 \text{ g m}^{-2}$). In contrast, a meta-analysis revealed that thick litter has a detrimental influence on seedling emergence in forest ecosystems, whereas low ($\leq 250 \text{ g m}^{-2}$) and medium ($250\text{--}500 \text{ g m}^{-2}$) litter thickness had no effect on seedling emergence.

According to this study's results, seedling survival was adversely impacted by all levels of litter cover, but particularly by high levels. According to these findings, even while seedlings successfully emerge under litter cover, physical interception that prevents them from obtaining light before stored reserves run out makes seedling survival doubtful (Liu et al., 2017; Azquez-Yanes et al., 1990). According to earlier research, seeds may sprout under heavy litter cover but are unable to pierce the litter layer (Ruprecht et al., 2010; Kremer et al., 2019). Leaf litter significantly reduced the germination of *Boechera constancei*, and the effects on all populations were comparable. Germination was lower in the median and maximum litter treatments than in the control treatment, suggesting that litter buildup may result in decreased germination in *B. constancei* populations.

Implications for forest management and conservation

A strong basis for sustainable forest management and conservation in Sierra Leone is established by the knowledge gathered from the germination and regeneration dynamics of *G. copallifera* in Kasewe Forest Reserve. Forest managers can create focused treatments that improve population recruitment and long-term viability by knowing the species' unique needs for seed germination,

seedling survival, and natural regeneration. Important uses include reforestation. Success rates can be increased by using the findings in this study to help choose the best microhabitats and times to plant *G. copallifera* seedlings or seeds. Critical regeneration niches can be protected from human disturbances like logging and agricultural encroachment by identifying them. By assuring the availability of high-quality planting materials for restoration, strategies for seed collecting and storage can be informed by knowledge of seed viability and dormancy. By educating local communities about the species' requirements for regeneration, agroforestry projects that incorporate native plants are supported, and sustainable harvesting methods are encouraged. By highlighting the preservation of native tree species that support biodiversity, carbon sequestration, and ecosystem resilience, the findings can help shape national forestry strategies. Sierra Leone can improve forest restoration initiatives, protect indigenous biodiversity, and fortify ecosystem services that support local livelihoods and the environment by integrating these scientific findings into management plans.

Conclusion

This study found that *G. copallifera* seed germination was higher under high shade levels, especially during its favorable season. This ability to germinate under low light and varied environmental conditions allows the species to exploit niches with low competition. However, high shade levels may limit its distribution and colonization success, particularly at the germination stage, suggesting that light availability could restrict its spread in forest ecosystems. This has significant implications for predicting ecological niches and managing *G. copallifera* in the Kasewe Forest Reserve.

The germination of *G. copallifera* seeds is influenced by planting depth and shade. Seeds planted at depths greater than 3.0 cm germinated more slowly and at lower rates, suggesting that shallow planting or surface planting is optimal. Germination is faster in forested conditions compared to non-forested environments, with the highest germination percentages occurring in shaded forest habitats. Seedling survival is generally higher at intermediate light levels and lowest at full irradiance. Additionally, the presence of leaf litter, regardless of irradiance levels, significantly reduces germination rates, with increased litter leading to lower germination percentages.

Litter cover significantly impacts *G. copallifera* seed germination, with thick litter having a negative effect on both germination and establishment, while thin litter cover has minimal impact. Smaller seeds are more affected by litter than larger ones. Litter weight negatively influences germination, regardless of light availability, suggesting that litter reduction (for example, through prescribed fires) could

enhance germination success. Litter depth should be considered in conservation planning, especially in seed planting or relocation efforts, as it affects germination rates. Prescribed fire can increase seed germination rates, reduce understory vegetation competition, and preserve ecosystem dynamics by breaking hard seed coatings and changing soil conditions. This also helps *G. copallifera* seedlings establish favorable microhabitats and reduce fuel accumulation, thereby preserving the species composition and forest structure of the Kasewe Forest Reserve. Small gaps in *G. copallifera* seedlings promote ideal microhabitats, prevent canopy loss and soil erosion, and support natural regeneration dynamics. They ensure wet, moderate sunshine exposure and minimize soil exposure, preserving ideal conditions for root development and seed germination. This study provides valuable insights for the regeneration and cultivation of *G. copallifera* and emphasizes the need for further research on seed handling and management, particularly for endangered and economically important species. Future management should consider light and water availability, focusing on early detection during the wet season when germination rates are highest and minimizing forest gaps that create favorable light conditions for the species. Given the deforestation pressures on Kasewe Forest Reserve and climate change issues, understanding the germination behavior of this species is essential for predicting plant community dynamics. Additional research is crucial to support restoration programs and species conservation.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors thank the local personnel, community authorities, and the Ministry of Forestry and Food Security for enabling research in the Kasewe Forest Reserve. They also appreciate the Sierra Leone National Herbarium staff for their technical support, with special acknowledgment to Mr. Jonathan Musa, Mr. Kinnie Jarawallay, Mr. Josephus Jauna, and Mr. Andrew Kamanda for their key roles in field data collection.

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