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Research Article

Effect of Spacing on Survival and Growth Performance of *Eucalyptus grandis* Hill ex Maiden at Holeta Research Site, Central Ethiopia

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Application of optimum initial plant spacing is one of the most important silvicultural practices to maximize the survival and growth performance of established plants at field. A field experiment was conducted to evaluate the effect of different plant spacing on survival and growth parameters of *E. grandis* at the ages of 4, 17, 34, 56, 66, and 79 months after establishment at Holeta Research Site. The experimental trail was planted at the initial plant spacings of 1.5 m × 1.5 m, 2 m × 2 m, 2.5 m × 2.5 m, and 3 m × 3 m using a randomized complete block design (RCBD) in three replicates. Other than regular management intervention including regular spot hoeing, weeding, and cleaning, the experiment did not receive any other treatment applications. Evaluation was made on survival and growth performance (plant RCD, height, and DBH) at different ages from 4 to 79 months after planting. Except survival percentage, all other variables (plant RCD, height, and DBH) were significantly affected by initial plant spacing. At the age of 56, 66, and 79 months after planting, the closer plant spacing (2 m × 2 m) was most promising in producing optimum plant height and DBH. Overall, our finding confirmed that initial plant spacing has a significant effect on growth performance of *E. grandis* at Holeta trail site. Evaluation of basic wood properties in relation with spacing or stand density management for quality wood and wood-based production and clear bole formation is suggested.

1. Introduction

Eucalyptus species particularly *Eucalyptus globulus* was introduced to Ethiopia during the reign of Emperor Menelik II [1–3] in 1895 [2, 3]. At that time, the main purpose of introducing the species was to satisfy the high demand of construction and fuelwood supply in and around Addis Ababa [1–3]. Since then, *Eucalyptus camaldulensis, Eucalyptus grandis, Eucalyptus saligna,* and other *Eucalyptus* species have been introduced to Ethiopia, which might yield better timber products particularly more suitable for construction and industrial purposes than *E. globulus* [2]. However, most of the interest of people concentrated on *E. globulus* and *E. camaldulensis* due to their easy propagation and fast growth rate [2]. Nowadays, 55 *Eucalyptus* species are reported in Ethiopia [4], while over 500 species are found across the world [5]. Thus, *Eucalyptus* species are the most widely planted species in Ethiopia and elsewhere across the globe because of their fast growth, higher adaptability, and utilization potential.

Of these, *Eucalyptus grandis* Hill ex Maiden is a fast-growing indigenous species in Queensland and New South Wales of Australia, belonging to the family *Myrtaceae* [2, 4, 6, 7]. The species is commonly known as flooded gum or rose gum [4, 6–8] and *Key Bahir Zaf* in Amharic [6, 7]. It is a very tall tree with a height of up to 55 m tall [4, 7] and a diameter of 2 m [6]. The species name *E. grandis* is related to its large size [8]. *Eucalyptus grandis* is commonly planted in trail plots, woodlots, and large-scale plantations throughout Ethiopia [4] in Shewa, Arsi, Harerge, and Keffa floral regions within altitudinal ranges of 1,700–2,500 m above sea level [4, 6, 7]. But the species also has a wider altitudinal range elsewhere from sea level to 2,700 m a.s.l. [8]. According to the Bekele [6] report, the species grows successfully in moist and wet midland (*Weyna Dega*) agro-climatic zones of Ethiopia. Some of these planted sites are Asella, Holeta, Ambo, Wondo Genet, Alemaya, Munessa, Menagesha, and Belete [4]. Regarding plantation sites, Hunde et al. [9] reported that 13 provenances of *E. grandis* were introduced (i.e., 12 from Australia and one from Zambia) and established in 1991 at Wondo Genet trial site. However, *E. grandis* is also widely introduced and planted in Africa including Cameroon, Democratic Republic of Congo, Ghana, Nigeria, Malawi, Mozambique, Namibia [7], Angola, Kenya, Tanzania, Uganda, Zambia, Zimbabwe, and South Africa as well as elsewhere such as Argentina, Brazil, Uruguay, and India [7, 8]. The species performs well on moist, light, and medium neutral to acidic soils with free drainage capacity [6]. In addition, Orwa et al. [8] described that it requires deep, free draining and fertile loam or clay loam soils besides lighter sandy soils. Alem et al. [10] found out that there were no significance differences between *E. grandis* plantation and adjacent natural forest in the level of major soil nutrients including total nitrogen, available phosphorus, exchangeable potassium calcium, and magnesium except the percentage of clay particles and exchangeable sodium content. However, *E. grandis* shows poor survival and growth performance on calcareous soils in arid climates as opposed to successful growth performance in higher humidity [2]. At the same time, Gezahgne et al. [11] reported that *E. grandis* is commonly affected by the *Botryosphaeria* stem canker fungal disease, which is observed on both coppice stems and first generation stands on plantation located at Wondo Genet. The species also grows from −1 up to 4°C temperature range with a mean annual rainfall of 100–1,800 mm [8]. *E. grandis* does not form lignotubers, unlike well-developed lignotubers in *E. saligna*, and is hence a better producer of coppice [4]. *Eucalyptus grandis* has an excellent straight trunk with white, grey white, or blue-grey smooth bark and some rough flaky bark at the base [4, 7]. It has a good all-round red, light, and durable timber and yields 0.26% oil [2].

The species has multipurpose uses including fuelwood production (firewood collection and charcoal making), timber harvesting for heavy and light construction, making furniture and boxes, poles for building purposes and electricity transmission, posts, veneer, and plywood supply [6]. The same author further listed other uses such as bee forage, shade, ornamental, windbreak, and short-fiber pulp for paper making. In line with this, *E. grandis* has an ample potential for timber production due to its key wood qualities including an average released strain of surface growth stress (−0.0726%), average xylem density (0.664 g·cm^{-3}), average microfibril angle (13.9°), and average fiber length (1.125 mm) [12]. Consequently, planting *E. grandis* closer to the equator will produce higher quality wood [13]. Furthermore, the wood density of *E. grandis*, which is the harvesting age for pulp and paper industry, was attained at the age of 3 years old despite its fiber length increased consistently with age from 3 to 9 years [14]. According to Dejene et al. [15], *E. grandis* was the 2nd fast-growing species for fuelwood production at Diksis District of Arsi Zone, which accounted for 89% of the survival rate [15]. Likewise, *E. grandis* was the 2nd in survival rate after 36 months and the 4th in average DBH after 6 years among the 11 fast-growing fuelwood species at Diksis District of Arsi Zone [15]. By contrast, its poor survival rate and the least growth performance (RCD and height increment) among the four fast-growing *Eucalyptus* species in Lasta-Lalibela District is an indication of limited adaptation at higher altitude, *i.e.*, around 3,600 m a.s.l. [16]. Overall, *E. grandis* uses are similar to those of *E. camaldulensis* and *E. globulus* [15].

On the other hand, frequent critical criticism against *Eucalyptus* species is reported on depletion of water and soil nutrients, removal of too much water from underground water supplies, and inhibition of the growth of other species by its allelopathic effect and hence suppression and replacing native species [5]. However, *E. grandis* plantation favors the natural regeneration of indigenous woody plants much better than the adjacent natural forest [17]. Similarly, according to the findings of Bekele and Abebe [18], *E. camaldulensis* plantation has higher species composition, diversity, and richness as well as better indigenous woody species regeneration than under the canopy of *Cupressus lusitanica* plantation. Likewise, the number of naturally regenerated native woody species in the coppiced stands of *E. saligna* and *E. globulus* was also almost comparable to that of the adjacent natural forest at Munessa-Shashemene Forest [19]. Regarding the working properties of *E. grandis* wood, it works easily and well and finishes satisfactorily and is hence appropriate to make tables and chairs compared to other selected *Eucalyptus* species for lumber production [20]. Its straight and clear tree boles appearance of *E. grandis* lumber is comparable with *E. globulus, E. camaldulensis,* and *E. saligna* clear lumber appearance [7, 20]. At the same time, *E. grandis* had been seasoned very rapidly and fairly as compared to *E. globulus* and *E. saligna* [20]. By contrast, *E. grandis* has lower density, modulus of rupture (MOR), modulus of elasticity (MOE), and compression parallel to grain than *E. camaldulensis*, *E. globulus* and *E. saligna* [7, 20]. These wood properties, in turn, have considerable influence on species growth performance including tall height; long, straight, and cylindrical clear bole; large diameter; and high-volume increment potential as well as high lumber quality [20]. Research conducted in Zambia by Hardie [21] further found out that despite its rapid growth, *E. grandis* has certain natural defects in the wood that limit sustainable utilization including longitudinal growth stresses, stem form, impermeable heart wood, dead knots, brittle heart, and wood decay. This most probably attributed to the limited stand density management intervention, particularly the lack of optimum spacing management during early establishment of the species and intensity of thinning during the later stage. At the same time, according to the Sibomana et al. [22] finding, the wood properties of teak grown at Tanzania mainly basic density, modulus of elasticity (MOE), modulus of rupture (MOR), compression parallel to grain, and shear parallel to grain all increased progressively with an increasing plant spacing from 2 to 2.5 and then 3 m. By contrast, its basal area and wood volume ha^{-1} progressively decreased with increasing the corresponding teak initial plant spacing [22]. Similar to this study, cleavage parallel (tangential) to grain in teak progressively increased from the closest (2 m ×2 m) to widest (4 m × 4 m) spacing, while shear parallel to grain and cleavage perpendicular (radial) to grain progressively decreased from the closest (2 m × 2 m) to widest (4 m × 4 m) spacing [23]. Furthermore, Rocha et al. [24] found out that *Eucalyptus* clones planted with wider spacing produced higher wood density and insoluble lignin content of the wood, resulting in higher yield in charcoal. Hence, application of various appropriate silvicultural measures should be undertaken to remove or reduce these defects and thereby to improve the quality and productivity of its wood and wood-based products for timber harvesting, electric transmission poles, and pulp and paper production. With this understanding, the primary purpose of this experimental trial was to evaluate, identify, and recommend the suitable initial plant spacing for further successful field establishment, well-adapted to the experimental site and/or other areas of similar ecological conditions in Ethiopia, enhance plantation development for timber harvesting and fuelwood production, and serve as industrial input.

Therefore, the present investigation was aimed at evaluating the four initial plant spacings for improving the survival and growth performance of *E. grandis* at Holeta trial site.

2. Materials and Methods

2.1. Description of the Study Area

2.1.1. Location. Holeta Research Site is located in Holeta town in Walmara District, West Shewa Zone of Oromia National Regional State, Ethiopia. The site is situated in a north-facing direction with a 3% slope of land inclination. It is geographically located at 9.25° north latitude and 38.53° east longitude within an altitude of 2,390 m a.s.l. [3]. Holeta town is situated along Addis Ababa to Nekemte town main asphalt road. The town is the capital of Walmara Administrative District, which is about 45 km far away from Addis Ababa. The area is found in the central part of Ethiopia within the western plateau of highland (*Dega*) agroecology. The 2007 National population Census conducted by the CSA reported that Holeta town has a total population of 24,030, out of whom 11,921 are men and 12,109 are women [25].

2.1.2. Climate of the Area. Holeta town is classified under the highland (*Dega*) climate. The area is characterized by bimodal rainfall with the long rainy season (*Meher*) extending from the mid of June to the end of September, while the short rainy season (*Belg*) lasts from the mid of March to the mid of May. Its mean annual rainfall ranges from 1,200 to 1,300 mm [3], and the mean monthly temperature ranges from 10°C to 15°C. The average minimum and maximum temperatures are 7.9°C and 20.4°C, respectively [3]. The dry season extends from October to February. It is characterized by an average day light of almost 12 hours. A remarkable climatic difference influencing plant growth and development is observed during the drought period [2]. Holeta is characterized by higher relative air humidity (45%) and frost nights in January compared to Ambo, which is about 40% humidity [2].

2.1.3. Soils of the Area. The trial site has usually reddish brown to dark reddish brown clay soil [3]. However, according to von Breitenbach [2], the soil of the study area is prevailed by grey, brown, and black capillary clays, i.e., black soil. According to this investigator, this type of soil desiccates, becomes compact during the dry time, and superficially silts up during rains. Calcium and potassium availability is very high in the calcareous soils of the study area [2]. But the soil is low in phosphorus availability, and 3.5–5.5% content of organic matter with soil acidity varies from 5.5 to 6.5 pH ranges [2]. Mamo et al. [3] described that about 70% of the soil is low, around 11% is medium, and 19% is high in available phosphorus. As a result, these authors stated that available phosphorus creates soil acidity in the site.

2.2. Experimental Design and Treatment Application. The field layout was established at Holeta Research Site in May 2016 during the dry season. Following this, the experimental design was arranged using a randomized complete block design (RCBD) with three replications [26]. The experimental treatments consisted of four initial plant spacing levels, namely, closest spacing (1.5 m × 1.5 m), closer spacing (2 m × 2 m), wider spacing (2.5 m × 2.5 m), and widest spacing (3 m × 3 m). The four levels of spacings were considered based on previous experiences and research findings related to diverse uses of various *Eucalyptus* species [3, 8, 9, 15, 16]. The four plant spacings were randomly distributed in each of the three blocks. Each spacing treatment was used as an experimental plot, and each plot had 36 seedlings. The distance between plots and blocks was 2 and 3 m. The plot layout in each experimental block was established east-to-west direction. On the other hand, *E. grandis* seeds were brought from fresh seeds collected at the Asela permanent seed source stand and stored at cold room in +5°C. Thereafter, the required *E. grandis* seedlings were raised at the Central Ethiopia Forestry Development Center (CEFDC) nursery on polythene pots and placed under shade. The required silvicultural practices including watering, weeding, soil loosening, and insect pest and disease inspection were carried out regularly during the entire seedlings' nursery lifespan. Following this, circular pits (holes) of 50 cm wide and 60 cm deep [27] were dug up and prepared following the field layout designed before the rainy season in May 2016. During the beginning of the main rainy season, *E. grandis* seedlings were planted in the experimental site in the mid of July 2016. After seedling establishment, beating up with dead seedlings was carried out in July 2017 and 2018. Replaced seedlings in each treatment were proportional (12–20 seedlings) so that it was assumed that no significant difference occurred in the collected data. Proper silvicultural management intervention such as weeding, clearing, mulching, and soil loosening was conducted equally for all the treatments regularly during the entire experimental period despite some free-grazing effects during the early stage before fencing the site. At the same time, illegal cutting of some experimental trees and coppicing thereafter were observed during supervision and data collection.

2.3. Data Collection and Statistical Analysis. Field data collection on survival and growth performance of *E. grandis* was conducted at the end of 4, 17, 34, 56, 66, and 79 months after seedlings were established (planted) in the site. Of course, the actual field data collection period was set with a fixed regular interval, which is commonly applied to other related forestry research. But due to different unforeseen reasons, data collection was not carried out as per the plan. Counting the survival percentage was recorded at the age of 4, 17, and 34 months. Accordingly, the survival rate was calculated as the proportion of survived seedlings in relation to the total planted seedlings and expressed as a percentage. Similarly, measuring the root collar diameter (RCD) at the surface of the soil level using a digital caliper in centimeter (cm) was conducted at the age of 4, 17, and 34 months. On the other hand, diameter at breast height (DBH) or stem diameter was recorded at 1.30 m from the soil level using a tree caliper in cm at the age of 56, 66, and 79 months after seedlings were planted. Plant height was measured at 4, 17, 34, 56, 66, and 79 months after seedlings were established. The height was measured from the soil surface to the top of each tree using a range pole or a Vertex IV hypsometer in meter (m). Finally, the collected data were summarized and analyzed by using descriptive statistics such as percentages, tables, and figures. Data were further subjected to analysis of variance (ANOVA) using the generalized linear model (GLM) to determine whether initial plant spacing had any influence on survival and growth of *E. grandis* using SPSS Software version 27. One-way ANOVA was also employed to test the effect of each parameter (survival percentage, RCD, height, or DBH) among the four initial plant spacings. The sources of variation (plant spacings, age of planting months, and their interaction effect) was presented in each survival and growth parameters in means ± standard deviation (SD) of the three replicates of each group. Treatment means comparison was carried out using the least significance difference (LSD) test to show a real significance difference in survival and growth parameters among treatments at a $p < 0.05$ significance level.

3. Results

3.1. Effect of Plant Spacing on Survival Percentage. The present study showed that the survival rate did not differ significantly ($p < 0.05$) among the four initial plant spacings, planting ages, and their interaction effect in *E. grandis* at Holeta Research Site despite considerable numerical differences (Table 1).

Notably, the 2 m × 2 m initial plant spacing had the highest survival percentage both at the 4th months (87 ± 0.34%) and 34 months (88 ± 0.33%) after seedlings were planted, while it was ranked 3rd (80.6 ± 0.40%) at the age of 17 months (Figure 1). On the other hand, the 2.5 m × 2.5 m plant spacing had the highest survival (85.2 ± 0.40%) 17 months after seedlings were planted, while the 2.5 m × 2.5 m plant spacing had recorded the 3rd survival rate after the age of 4 months (77.8 ± 0.42%). At the age of 34 months, both 2.5 m × 2.5 m and 3 m × 3 m plant spacings had an equal survival count, which accounted for 84.3 ± 0.37%. Likewise, 85.2 ± 0.36% survival in the closest spacing (1.5 m × 1.5 m) and 84.3 ± 0.37% survival in the widest spacing (3 m × 3 m) were recorded at the age of 4 and 17 months, respectively. By contrast, the least survival percentage was noted at the age of 4 months (76.9 ± 0.42%) for the widest spacing (3 m × 3 m), whereas it was noted at the end of 17 months (79.6 ± 0.41%) and 34 months (77.8 ± 0.42%) for the closest initial spacing (1.5 m × 1.5 m). In general, the highest total mean survival percentage (0.85 ± 0.36%) was observed in the 2 m × 2 m plant spacing, whereas the lowest mean survival (0.81 ± 0.39%) was counted in the closest spacing (1.5 m × 1.5 m). However, the LSD test confirmed that *E. grandis* survival did not vary ($p < 0.05$) among the four initial spacing treatments.

On the other hand, statistical analysis using one-way ANOVA showed that survival percentage significantly varied ($F = 4.74$; $p < 0.01$) among the given plant spacings (Table 2). In conclusion, our finding verified that the 2 m × 2 m initial plant spacing was the most suitable application for the highest survival of *E. grandis* plantation at Holeta Research Site.

3.2. Effect of Spacing on Plant RCD Growth. Statistical comparison of means showed that recorded plant RCD significantly varied among the initial plant spacing ($F = 5.95$; $p = 0.001$), months after seedlings were established ($F = 351.83$; $p < 0.001$), and their interaction effect between them ($F = 3.31$; $p < 0.01$) as indicated in Table 1. In this particular experiment, the largest average RCD was recorded for the 2 m × 2 m plant spacing after 4 months (0.42 ± 0.22 cm) and 17 months (0.64 ± 0.63 cm), while it was recorded for the 2.5 m × 2.5 m plant spacing at the end of 34 months (2.56 ± 2.03 cm) as shown in Figure 2. This was followed by 1.5 m × 1.5 m plant spacing at the end of 4 months (0.41 ± 0.23 cm), 2.5 m × 2.5 m plant spacing at the end of 17 months (0.57 ± 0.48 cm), and 2 m × 2 m spacing at the age of 34 months (2.34 ± 1.65 cm). Similarly, 2.5 m × 2.5 m plant spacing, the widest plant spacing (3 m × 3 m), and the closest spacing (1.5 m × 1.5 m) had 0.40 ± 0.25 cm (after 4 months), 0.49 ± 0.24 cm (after 17 months), and 1.95 ± 0.24 cm (after 34 months) average RCD, respectively. In contrast, the smallest average plant RCD was measured in the widest plant spacing (3 m × 3 m) at the age of 4 months (0.37 ± 0.24 cm) and 34 months (1.77 ± 1.41 cm), whereas it was measured in the closest spacing (1.5 m × 1.5 m) at the end of 17 months (0.47 ± 0.41 cm). Consequently, the 2 m × 2 m spacing differed significantly in the average RCD with 1.5 m × 1.5 m ($p < 0.05$) and 3 m × 3 m spacing ($p < 0.0.01$) but nonsignificant with the 2.5 m × 2.5 m plant spacing ($p < 0.05$). Nevertheless, the largest total mean RCD (1.18 ± 1.56 cm) was recorded in the 2.5 m × 2.5 m initial plant spacing, followed by 2 m × 2 m spacing (1.13 ± 1.34 cm).

Table 1: Effect of four different initial plant spacings, planting ages, and their interaction effect on survival percentage, RCD, plant height, and DBH of *E. grandis* at Holeta Research Site.

Source of variation	Survival rate (%)	RCD (cm)	Height (m)	DBH (cm)
Initial plant spacing	0.78^{ns}	5.95^{***}	10.11^{***}	8.37^{***}
Planting ages	0.26^{ns}	351.83^{***}	525.38^{***}	49.52^{***}
Plant spacing ∗ planting ages	1.56^{ns}	3.31^{**}	2.07^{**}	0.40^{ns}
R^2	0.009	0.366	0.512	0.090
Adjusted R^2	0.001	0.361	0.507	0.082

$F^{p\,\text{value}}$; significance levels were $^{***}p < 0.001$, $^{**}p < 0.01$, and $^{*}p < 0.05$; ^{ns}nonsignificant.

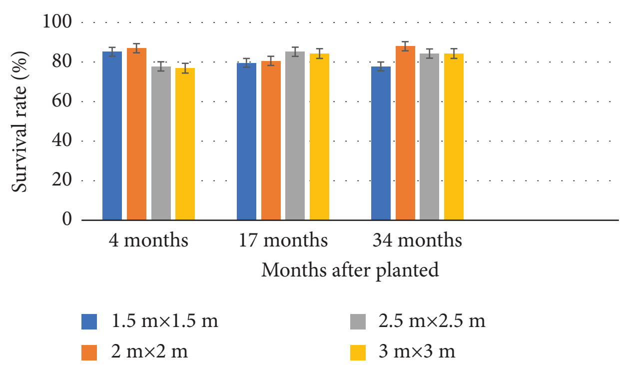

Figure 1: Effect of four different initial plant spacings and planting ages on survival percentage of *E. grandis* at Holeta Research Site. Error bars on the top of each graph represent standard deviations.

Table 2: Effect of survival percentage among different initial plant spacings of *E. grandis* at Holeta Research Site.

Source of variation	Initial plant spacing: Closest spacing (1.5 m × 1.5 m)	Closer spacing (2 m × 2 m)	Wider spacing (2.5 m × 2.5 m)	Widest spacing (3 m ×3 m)
Survival rate (%)	0.77 ± 0.42^{a}	0.86 ± 0.35^{b}	0.80 ± 0.40^{ab}	0.81 ± 0.40^{ab}
Sig.		4.74^{**}		
R^2		0.007		
Adjusted R^2		0.005		

$F^{p\,\text{value}}$; significance levels were $^{***}p < 0.001$, $^{**}p < 0.01$, and $^{*}p < 0.05$; ^{ns}nonsignificant. Means with the same letters are not significantly different using Tukey HSD.

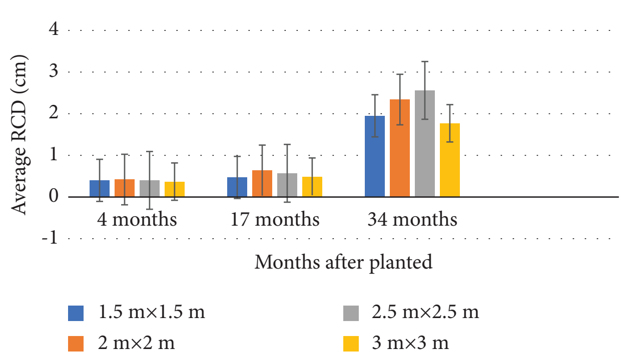

Figure 2: Effect of four different initial plant spacings and planting ages on average RCD of *E. grandis* at Holeta Research Site. Error bars on the top of each graph represent standard deviations.

In the same way, one-way ANOVA also confirmed that plant RCD differed ($F = 4.08$; $p < 0.01$) among the given plant spacings (Table 3). As a conclusion, this result affirmed that the 2 m × 2 m plant spacing was suggested for producing the highest average RCD of *E. grandis* plantation at Holeta Research Site, followed by 2.5 m × 2.5 m spacing.

3.3. Effect of Spacing on Plant Height Growth. Our statistical result (refer Table 1) indicated that the average plant height of *E. grandis* strongly differed by plant spacing ($F = 10.11$; $p < 0.001$) and months after seedlings were planted ($F = 525.38$; $p < 0.001$) as well as their interaction effect between factors ($F = 2.07$; $p < 0.01$). The tallest plant height measurement was observed in closer spacing (2 m × 2 m) among all the data collected months except at the age of 34 months (2.35 ± 0.63 m), which was the 2nd height record (Figure 3). These were at the end of 4 months (0.17 ± 0.63 m), 17 months (0.92 ± 0.63 m), 56 months (8.43 ± 0.63 m), 66 months (10.82 ± 0.63 m), and 79 months (11.45 ± 0.63 m). Overall, the tallest total mean plant height (5.67 ± 6.01 m) was measured in the closer spacing (2 m × 2 m), while the shortest mean height (4.52 ± 5.32 m) was recorded in the widest plant spacing (3 m × 3 m).

Table 3: Effect of plant RCD among different initial plant spacings of *E. grandis* at Holeta Research Site.

Source of variation	Initial plant spacing: Closest spacing (1.5 m × 1.5 m)	Closer spacing (2 m × 2 m)	Wider spacing (2.5 m × 2.5 m)	Widest spacing (3 m × 3 m)
RCD (cm)	3.23 ± 4.79^{a}	4.23 ± 5.18^{b}	3.91 ± 5.16^{ab}	3.55 ± 4.77^{ab}
Sig.		4.08**		
R^2		0.006		
Adjusted R^2		0.004		

$F^{p\,\text{value}}$; significance levels were $^{***}p < 0.001$, $^{**}p < 0.01$, and $^{*}p < 0.05$; [ns]nonsignificant.

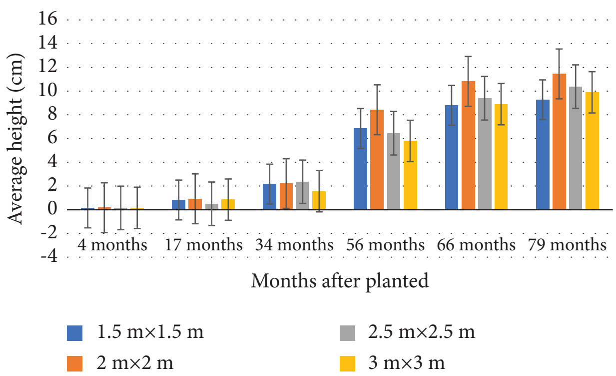

Figure 3: Effect of four different initial plant spacings and planting ages on average height of *E. grandis* at Holeta Research Site. Error bars on the top of each graph represent standard deviations.

In the same manner, the LSD test confirmed that closer spacing (2 m × 2 m) differed significantly ($p < 0.05$) in average plant height with the rest of the initial plant spacings (1.5 m × 1.5 m, 2.5 m × 2.5 m, and 3 m × 3 m). Likewise, the one-way analysis of variance further asserted that plant height varied ($F = 14.47$; $p < 0.01$) among the plant spacings (Table 4). Therefore, the current finding suggested closer spacing (2 m × 2 m) should be the best plant spacing management for improved height growth of *E. grandis* plantation in Holeta.

3.4. Effect of Spacing on Stem Diameter Growth. The statistical analysis of variance (ANOVA) revealed that the average DBH of *E. grandis* strongly varied by initial plant spacing ($F = 8.37$; $p < 0.001$) and months after seedlings were planted ($F = 49.52$; $p < 0.001$) as indicated in Table 1. However, the interaction effect of plant spacing and planting months on average DBH size was insignificant ($F = 0.40$; $p < 0.05$). The largest plant DBH (see Figure 4) was measured in closer spacing (2 m × 2 m) at the end of 56 months (6.19 ± 3.62 cm), 66 months (8.23 ± 4.82 cm), and 79 months (9.64 ± 5.77 cm). This figure was succeeded by the 2.5 m × 2.5 m and 3 m × 3 m spacings at the end of 56 and 66 months but reversed by the age of 79 months. By contrast, the smallest average DBH (4.68 ± 4.14 cm, 6.19 ± 4.00 cm, and 7.31 ± 6.33 cm) was recorded for the closest plant spacing (1.5 m × 1.5 m) in the respective order of planted months. Overall, the largest total mean DBH (8.02 ± 5.01 cm) was measured in the 2 m × 2 m spacing, while the smallest mean DBH (6.06 ± 5.45 cm) was recorded in the closest plant spacing (1.5 m × 1.5 m).

Further analysis on the LSD test among spacing treatments confirmed that except between 2.5 m × 2.5 m and 3 m × 3 m spacing treatments, all the remaining treatments significantly varied ($p < 0.05$) with each other. In line with this, the one-way analysis of variance also revealed that plant height varied ($F = 6.19$; $p < 0.01$) among the *E. grandis* spacings (Table 5). As a conclusion, our finding asserted that the 2 m × 2 m initial plant spacing was the most optimum silvicultural treatment to produce the largest average tree DBH for *E. grandis* plantation at Holeta Research Site.

4. Discussion

The optimum spacing management of *E. grandis* plantation established at Holeta Research Site contributes for intensive short rotation management and thereby to satisfy the high demand of wood and wood-based products mainly timber harvesting as well as pulp and paper products for industrial purposes. In this study, the nonsignificant variation despite considerable numerical differences between the survival of *E. grandis* spacing trial in Holeta is consistent with the result of the tree-spacing effect on *E. urophylla* in India as reported by Clara Manasa et al. [28].

In spite of this, a relatively higher survival count in the closer (2 m × 2 m) and closest (1.5 m × 1.5 m) plant spacings was recorded than in wider (2.5 m × 2.5 m) and widest (3 m × 3 m) spacings at the age of 4 months after planting. Similarly, comparatively higher average plant RCD was measured in closer (2 m × 2 m) spacing, followed by the closest (1.5 m × 1.5 m) and wider (2.5 m × 2.5 m) plant spacings, whereas higher growth performance in plant height was recorded in closer (2 m × 2 m) and the widest (3 m × 3 m) spacings in the same period. This is because during the early stage (i.e., at the age of 4 months) of seedling establishment in fields, seedlings could not be in a position to be more competent enough to efficiently exploit the available resources in the surrounding soil until they start to establish well-developed root systems and shoot parts such as branches and leaves. As a result, initial plant spacing is unlikely during early stages to affect the survival rate, plant RCD, and height growth in closest (1.5 m × 1.5 m) and closer (2 m × 2 m) spacings as opposed to wider (2.5 m × 2.5 m) and widest (3 m × 3 m) spacings. Instead of this, other external factors including limited silvicultural practices (spot hoeing, weeding, cleaning, disease and insect pest infestation, and free-grazing effect), environmental factors (drought, moisture stress during dry seasons, frost incidence during cold seasons, limited resources availability, soil factors, etc.), or other factors not yet identified might contribute to such

Table 4: Effect of plant height among different initial plant spacings of *E. grandis* at Holeta Research Site.

Source of variation	Initial plant spacing: Closest spacing (1.5 m × 1.5 m)	Closer spacing (2 m × 2 m)	Wider spacing (2.5 m × 2.5 m)	Widest spacing (3 m × 3 m)
Plant height (m)	39.15 ± 51.09^{b}	44.43 ± 55.47^{b}	26.09 ± 38.96^{a}	40.49 ± 47.36^{b}
Sig.		14.47^{**}		
R^2		0.020		
Adjusted R^2		0.018		

$F^{p\ \text{value}}$; significance levels were $^{***}p < 0.001$, $^{**}p < 0.01$, and $^{*}p < 0.05$; ^{ns}nonsignificant.

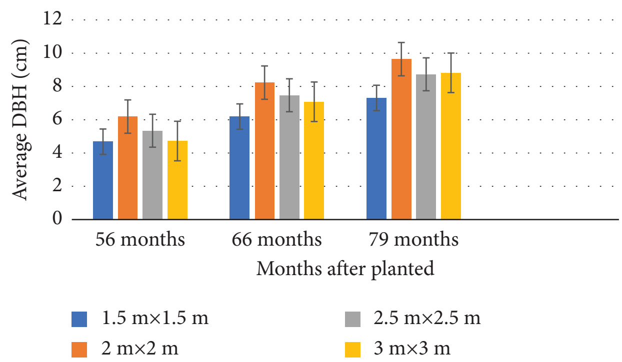

Figure 4: Effect of four different initial plant spacing on average DBH of *E. grandis* at Holeta Research Site. Error bars on the top of each graph represent standard deviations.

Table 5: Effect of plant DBH among different initial plant spacings of *E. grandis* at Holeta Research Site.

Source of variation	Initial plant spacing: Closest spacing (1.5 m × 1.5 m)	Closer spacing (2 m × 2 m)	Wider spacing (2.5 m × 2.5 m)	Widest spacing (3 m × 3 m)
Plant DBH (m)	5.44 ± 4.86^{a}	7.25 ± 4.40^{b}	6.42 ± 4.79^{ab}	5.90 ± 4.23^{a}
Sig.		6.19^{**}		
R^2		0.021		
Adjusted R^2		0.018		

$F^{p\ \text{value}}$; significance levels were $^{***}p < 0.001$, $^{**}p < 0.01$, and $^{*}p < 0.05$; ^{ns}non significant.

variations. In consistent with our finding, Kasaye et al. [16] found out that the fast and slow height and diameter growth dynamics within 4 years during dry seasons of different *Eucalyptus* species in Lasta-Lalibela District, which is due to the moisture stress in the area. Similarly, von Breitenbach [2] confirmed that *E. grandis* shows poor survival and growth performance on calcareous soils in arid climates as opposed to successful growth performance in higher humidity. The present result was further supported by the finding of Hunde et al. [9] who explained that mortality in *E. grandis* plantation was subjectively attributable to abiotic factors such as drought occurrence and debarking of the stem besides biotic problems such as disease incidence. Regarding disease and insect pest infestation, termite and/or insect pest attacks reduce the survival rate of *Eucalyptus* species including *E. grandis* in Lasta-Lalibela District [16]. In the same way, Orwa et al. [8] reported that browsing by wallabies, termite attack, insect borers, leaves defoliation by beetle, fungal infestation, and others cause a series damage or even death to *E. grandis* plantation at various stages across the world.

On the other hand, higher survival in the wider (2.5 m × 2.5 m) and widest (3 m × 3 m) plant spacings was observed than in closer (2 m × 2 m) and/or closest (1.5 m × 1.5 m) initial plant spacings at the age of 17 and 34 months. Larger plant RCD (at the age of 17 and 34 months) and larger plant DBH (at the ages of 56, 66, and 79 months) were measured in wider (2.5 m × 2.5 m) and/or widest (3 m × 3 m) spacing compared to the closer (2 m × 2 m) and/or closest (1.5 m × 1.5 m) spacings. All these results are most likely related to the limited or minimal competition over available resources, or the resources are found in enough amounts so that they are easily available at the required level. Consequently, this favors a higher chance of efficient resource utilization ability without the possibility of competition in wider (2.5 m × 2.5 m) and widest (3 m × 3 m) plant spacings over the closer (2 m × 2 m) and closest (1.5 m × 1.5 m) spacings. On the contrary, the intensive competition developed by individual plants in the closer (2 m × 2 m) and closest (1.5 m × 1.5 m) spacings might impose strong competitive ability over limited resources, or available resources might have been reduced during adverse conditions (e.g., extreme drought, severe moisture stress, limited light interception, and extreme saline and or acidic soils,) so that resources are not easily accessible to all individual plants in a particular spacing level. This, in turn, causes superior performed plants out compete and eliminate inferior performed plants, which results in a lower survival rate or relatively higher mortality as well as reduced or stunted RCD, plant height, and DBH sizes. This finding on *E. grandis* was in agreement with the result of Resquin et al. [29] who reported that the highest survival, tallest plant height, and largest DBH after 57 months later were found in the widest plant spacing (3 m × 1.5 m), while the lowest survival count and smallest plant DBH were noted in the closer spacing (3 m × 0.75 m). According to the Chapola et al. [30] report, the highest survival percentage in *E. tereticornis* was counted in the wider spacing (2.4 m × 2.4 m), whereas the lowest survival was noted in the closest spacing (1.2 m × 1.2 m) in unthinned plots in addition to insignificant difference and absence of a uniform trend between spacing levels (1.2, 1.5, 1.8, 2.1, 2.4, and 2.7 m). In the same way, Ferraz Filho et al. [31] further approved that *Eucalyptus* plantations planted under higher density (1,111 trees ha^{-1}) had a higher mortality rate than those under lower density (667 trees ha^{-1}). Regarding growth performance, Eshete et al. [32] found out that the largest RCD was recorded in the widest spacing (2 m × 2 m) as opposed to the closest spacing (0.5 m × 0.5 m), which had the smallest RCD at 6, 9, 12, and 15 months after planting. In line with our finding, Nayak et al. [33] further reported that the largest and smallest plant DBH was measured in the widest (3 m × 3 m) and closest (3 m × 1 m) *E. camaldulensis* plant spacings, respectively, and the DBH size progressively increased among spacings in different growth periods. Similarly, the largest and smallest DBH size was recorded in the widest (4 m × 3 m) and closest (3 m × 1.5 m) spacings, respectively, with a progressive increase at the age of 31 and 41 months for *E. camaldulensis* and *E. urophylla* and at the age of 15, 31, and 41 months for *E. pellita* [34]. At the same time, the largest and smallest DBH over bark at the age of 4 years was seen in the lowest (1,250 stems ha^{-1}) and the highest (3,333 stems ha^{-1}) stand density, respectively, and progressively decreased in *Eucalyptus pilularis* and *Eucalyptus cloeziana* [35]. Still, the largest DBH was recorded in the widest spacing (2.7 m × 2.7 m), whereas the smallest was noted in the closest spacing (1.2 m × 1.2 m) in unthinned *E. tereticornis* plots, and the size increased with the progressive increasing of spacing except at 2.1 m spacing [30]. The largest DBH was also measured in the wider spacing (2 m × 4 m), while the smallest DBH was noted at the closest spacing (1 m × 1 m) [36]. Research conducted by Ramalho et al. [37] found out that the largest tree wood diameter and bark thickness were measured in the widest plant spacing (3 m × 4 m) or the lowest stand density, while the smallest was recorded in the closest spacing (3 m × 1 m) or highest density, and furthermore, the wood diameter and bark thickness increase proportionally as plant spacing increases in *Eucalyptus* clones. Our result is further in agreement with other plant species by earlier studies such as Sibomana et al. [22] who confirmed that the *Tectona grandis* survival percentage progressively increased with increasing plant spacing (1.5, 2, 2.5, and 3 m) at the age of 9 years of planting despite insignificant differences between spacing treatments. In the same way, Khan and Chaudhry [38] investigated that the largest poplar tree DBH was noted in the widest spacing (3.7 m × 12.1 m); i.e., the lowest planting density compared to the smallest tree DBH was observed in the closest plant spacing (3.7 m × 6.1 m) or the highest poplar tree density. Furthermore, our result supports the finding of Sibomana et al. [22] who confirmed an increase in *T. grandis* plant spacing (1.5, 2, 2.5, and 3 m) accompanied by a corresponding increase in its plant DBH. At the age of 14 years, the largest and smallest *T. grandis* DBH was observed in the widest (4 m × 4 m) and closest (2 m × 2 m) plant spacings, respectively, with a progressive increase in size [23]. Our finding is further in accordance with other previous investigations on onion bulb [39] and *Eucalyptus* clones [37], in which the biggest diameter was recorded in the widest spacing, while the smallest diameter was noted in the closest spacing.

On the contrary, the tallest plant height was observed in the closer (2 m × 2 m) plant spacing compared to the wider (2.5 m × 2.5 m) and widest (3 m × 3 m) spacings at the age of 17, 56, 66, and 79 months after planting. This might be attributed to the intensive intraspecific competition developed by individual plants in the closer (2 m × 2 m) spacing over the limited resources particularly light interception to the plant canopy and easy access of carbon dioxide to plant leaves. Other available resources including essential nutrients, water, or moisture and the required existing space also contributed to individual plant competition. Nevertheless, after 17 months of planting at the trial site, individual plants most likely established well-developed root systems and above ground parts (stems, branches, and leaves) so that they are more competent enough to exploit limited resources and thereby able to survive, grow faster, and more adaptive to even extreme conditions. At the same time, over competition for limited resources urges a shift of vegetative growth from plant RCD and DBH growth towards faster growth in plant height that all individual plants are more competent enough for absorption of light source and carbon dioxide. The faster growth rate in plant height further promotes rapid canopy closure, which again creates suitable condition for canopy architecture. This, in turn, increases the leaf area and the number of leaves and then maximizes the leaf area index (LAI) in a closed canopy. This further enables more light interception to plant canopy. Eventually, all these processes enhance the light use efficiency of leaves, thereby resulting in a higher growth rate and development in plants, *i.e.*, taller plant height. The present finding supported far more previous studies reported as mentioned below. Accordingly, this justification was stated by Timlin et al. [40], in which the largest mean LAI was recorded in high density (closer spacing) and favored increased light interception by the canopy, which enhances the light use efficiency of leaves and finally improved the rate and efficiency of photosynthesis. This finding also supported by Wu et al. [41] who reported that high plant density (1,450 plants m^{-2}) significantly increased content of total chlorophyll, net photosynthesis rate, and finally perilla yield [41]. Likewise, the highest LAI was recorded during flowering, pod formation, and harvesting periods in the closest spacing (25 cm × 15 cm) or the highest plant density (45 plants m^{-2}), while the lowest was noted in the widest (25 cm × 35 cm) or the lowest plant density (25 plants m^{-2}) [42]. In the same way, various earlier studies further by Streck et al. [43] for the cassava plant, Grigg et al. [36] for *E. marginata*, and Zibelo et al. [44] for the okra plant found that that the closest spacing had the highest LAI, while the widest plant spacing showed the lowest LAI. Similarly, higher stand density (6,707 culms ha^{-1}) in *Dendrocalamus brandisii* resulted in higher LAI and hence larger annual litter production compared to lower (5,177 culms·ha^{-1}) stand density [45]. Maboko and Du Plooy [46] also reported that the tallest lettuce plant height, highest number of leaves, and leaf area, as well as leaf fresh and dry mass, were observed in the closest spacing (10 cm × 20 cm) as compared to the widest spacing (20 cm × 25 cm) with the smallest one. This result was in agreement with the finding reported by Baw et al. [47] who revealed that the highest number of leaves per plant was counted in the closest spacing (45 cm × 20 cm) compared to the widest spacing (60 cm × 40 cm), which had the smallest number of leaves. Likewise, according to Khan et al. [39], the highest onion leaf length and the number of leaves were recorded in the widest spacing (20 cm × 10 cm) as opposed to the lowest leaf length and the number of leaves in the closest spacing (7.5 cm × 7.5 cm). Consequently, the highest and the lowest average total tree weight ha^{-1} was observed in the closest (3 m × 1.5 m) and widest (4 m × 3 m) spacings with a corresponding increase in biomass with increasing plant spacing for both *E. camaldulensis* and *E. pellita* at age 41 months [34]. Other similar findings of Khan et al. [39] for onion and Streck et al. [43] for cassava and Neri et al. [48] for pineapple also confirmed that the closest spacing or the highest planting density produced the highest yield, while the widest plant spacing or the lowest planting density had the lowest yield. In general, the present result is consistent with the report of Minh et al. [42] that showed the tallest peanut height was measured in the closest spacing (25 cm × 15 cm) or the highest plant density (45 plants m^{-2}), while the shortest was noted in the widest (25 cm × 35 cm) or the lowest plant density (25 plants m^{-2}). In line with our finding and the aforementioned results, Zibelo et al. [44] for okra plants and Wu et al. [41] for perilla sprouts reported similar findings related to spacing or planting density.

On the other side, a lower survival value (at the age of 17 months), smaller RCD (at the age of 17 and 34 months), and smaller plant DBH (at the age of 56 and 66 months) were observed in the widest (3 m × 3 m) compared to wider (2.5 m × 2.5 m) plant spacing. In the same manner, shorter plant height was measured in the closest (1.5 m × 1.5 m) spacing than in closer (2 m × 2 m) spacing 17, 34, 56, 66, and 79 months after planting. These findings clearly suggest that initial plant spacing management has a considerable influence on survival and growth performance (RCD, plant height, and DBH) of plants, and hence, closer spacing is the optimum spacing management compared to the closest spacing. The present finding corroborated to other studies conducted by Bernardo et al. [34] who reported that the tallest and shortest plant height was recorded in the widest (4 m × 3 m) and closest (3 m × 1.5 m) spacings, respectively, with a progressive increase at the age of 31 and 41 months for *E. camaldulensis* and at the age of 15 and 41 months for *E. pellita*. In a similar way, the tallest tree height was measured in the lowest planting density (1,250 stems ha^{-1}), whereas the shortest height was seen in the highest (3,333 stems ha^{-1}) stand density at the age of 4 years and progressively decreased in *Eucalyptus cloeziana* [35]. In addition, this particular research is in agreement with various plant spacing and stand density management interventions such as *T. grandis* [22], cassava plant [43], *T. grandis* [23], pineapple cultivars [48], and *E. camaldulensis* [33], in which the tallest plant height was demonstrated in the widest plant spacing or lowest planting density, while the shortest height was noted in the closest spacing or highest planting density. In relation to this, the largest and smallest jack pine tree DBH, stem volume, live crown ration, and largest branch diameter were recorded in the highest (1,111 trees ha^{-1}) and lowest (4,444 trees ha^{-1}) stand density, respectively, despite lack of uniformity at the age of 25 years [49]. Likewise, the largest and smallest *D. brandisii* shoot yield in Simao District, China, was weighed in the highest (4 standing culms $clump^{-1}$) and lowest (1 standing culms $clump^{-1}$) stand density, respectively [50]. On the basis of our overall results obtained, it is concluded that at the age of 56, 66, and 79 months after planting, closer plant spacing (2 m × 2 m) was most promising in producing optimum plant height and DBH in *E. grandis* at Holeta Research Site. At the same time, plant RCD at the age of 17 months and the survival count at the age of 34 months further showed the same result in closer spacing (2 m × 2 m).

5. Conclusion and Recommendation

Overall, the initial plant spacing of *E. grandis* was evaluated to identify the suitable silvicultural practice for producing wood and wood-based products. The present finding indicated that *E. grandis* plant spacing had a significant ($p < 0.01$) effect on RCD, plant height, and DBH despite insignificant difference in the survival rate ($p < 0.05$) at Holeta Research Site. The tallest plant height and the largest DBH size of *E. grandis* were recorded in closer initial plant spacing (2 m × 2 m) among all the given planting ages except at the age of 34 months (for plant height). At the same time, the highest survival rate was counted in the same spacing level (2 m × 2 m) at the age of 4 and 34 planting months. Similarly, the largest RCD was recorded in closer spacing (2 m × 2 m) at the age of 4 and 17 months after planting although slightly smaller than the wider spacing (2.5 m × 2.5 m) at the age of 34 months. Therefore, our findings clearly confirmed that closer spacing (2 m × 2 m) is the optimum silvicultural management intervention for *E. grandis* early seedling establishment and plantation development at Holeta Research Site or other areas of similar agroecology at the age of 79 months. On the other hand, 10.82 ± 0.63 m and 11.45 ± 0.63 m plant heights are obtained for a closer plant spacing (2 m × 2 m) at the age of 66 and 79 months, respectively, in rotation periods. Likewise, the same spacing level (2 m × 2 m) produced 8.23 ± 4.82 cm and 9.64 ± 5.77 cm plant DBH at the ages of 66 and 79 months, respectively. Hence, harvesting properly managed *E. grandis* by closer plant spacing (2 m × 2 m) is suggested at a given rotation period for quality timber and pole harvesting with a clear bole as well as paper and pulp production. But further research should be strongly recommended to evaluate its suitability for timber and pole harvesting or paper and pulp production by considering its basic wood properties in relation to spacing or stand density management.

Data Availability

The collected field data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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