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Adaptation potential of *Opuntia ficus-indica* along altitudinal gradient of Gullele Botanical Garden, Addis Ababa

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Abstract

Ethiopia's diverse agro-climatic zones host a rich variety of endemic and introduced flowering plants, among which is Opuntia ficus-indica, an introduced species prized for its nutritional benefits for both humans and animals. This research aims to evaluate the adaptability of Opuntia ficus-indica across different altitudinal ranges within the Gullele Botanical Garden, located in the central plateaus of Ethiopia. Approximately 45 cladodes were sourced from the Gurage zone to analyze the species' adaptation and growth performance at varying altitudes in the Gullele Botanical Garden, Addis Ababa. The cladodes were planted at three distinct altitudinal levels, with their survival rates, growth metrics, and developmental timelines closely monitored over a period of 30 months. The results indicated that while initial survival rates were modest, the species demonstrated resilience across altitudes ranging from 2,559 to 3,000 meters above sea level. Notable differences were observed in growth duration, cladode height, and flowering periods. Lower altitudes facilitated quicker growth and larger cladodes, whereas higher elevations led to delayed growth and flowering, likely due to cooler temperatures. These findings suggest that Opuntia ficus-indica can be successfully cultivated in highland ecosystems, contributing to ecological restoration, enhancing food security, and promoting sustainable agriculture in Ethiopia's drought-prone areas. It is recommended that further long-term studies be conducted to refine cultivation techniques and assess reproductive and yield potentials. Integrating Opuntia into restoration programs and farming systems could provide a reliable source of food and fodder, improve soil stability, and serve as a climate-resilient crop option for local communities.

Keywords/Phrases: Adaptation, Altitude, Botanical garden, Ecological restoration, *Opuntia ficus-indica*

1 Introduction

Opuntia ficus-indica, commonly known as the cactus pear, is a perennial succulent characterized by a robust woody trunk that can grow to heights of 3 to 5 meters. Its thick, oblong to spatula-shaped stems, known as cladodes, feature a waxy, water-repellent, and reflective epidermis (Giraldo-Silva *et al*., 2023). Cladodes aged between one and two years produce flowers, with fruits that can range in color from pale green to deep red. The plant's flowers come in three distinct colors: white, yellow, and red (Barbera *et al*., 1995). Typically, the fruits are enjoyed after the thick outer skin is removed and they are chilled for a few hours. Their flavor is reminiscent of sweet watermelon, and the flesh, which can be bright red, purple, white, or yellowish, contains numerous tiny hard seeds. While these seeds are generally swallowed, individuals with digestive issues are advised to avoid them (Aruwa, 2019).

Opuntia ficus-indica thrives in semi-arid and arid environments and is cultivated globally for its edible fruit. It is well adapted to desert conditions marked by irregular rainfall and erosion-prone soils, making it increasingly valued for its resilience (Inglese *et al*., 2017). During drought periods, it provides sustenance for both people and livestock, rendering it a crucial crop in fragile agricultural systems (Ben Salem & Louhaichi, 2014).

Interest in Opuntia has surged in recent decades due to its contributions to sustainable agriculture in semi-arid and moderately humid regions (Fonseca *et al*., 2019). Once viewed as a wild plant, it is now widely cultivated for both subsistence and commercial purposes, bolstering food security in marginalized areas (Barbera *et al*., 1995). In times of severe water scarcity, the cactus has re-emerged as a critical source of food, forage, and water for rural communities and their livestock, underscoring its role in climate resilience (Kumar *et al*., 2018). Its pads can store up to 180 tons of water per hectare, acting as a "botanical well" that supports more livestock than traditional rangelands (Zinabu, 2020). Commercial yields vary by environment and management, reaching over 20 tons of fruit per hectare in Italy and up to 50 tons under irrigation in Mexico, though production is generally lower in rain-fed systems (Caloggero & Parera, 2004).

The species' adaptability is attributed to its unique morphology and physiology. Its crassulacean acid metabolism (CAM) allows for nocturnal water absorption and conservation, while its deep root system stabilizes soil, reduces erosion, and controls sand movement (Kumar *et al*., 2018). These traits make Opuntia an effective tool against drought, soil degradation, and rising temperatures, while also providing food, fodder, and ecological benefits in drylands (Aruwa, 2019).

The Ethiopian Highlands represent a complex agro-ecological zone influenced by altitude, climate, and soil diversity, presenting both challenges and opportunities for crop adaptation (Gorfu & Ahmed, 2012). In these environments, cacti could help mitigate erratic rainfall, erosion, and water scarcity while enhancing food security and income generation (Zemu & Berhanu, 2015). However, despite their widespread distribution in lowlands and degraded landscapes, cactus cultivation in highland plateau areas remains limited (Hailemariam *et al*., 2024). Expanding cultivation into these regions could therefore yield significant agricultural and ecological benefits.

Previous studies have highlighted the multifunctional value of *Opuntia ficus-indica*. In Ethiopia, it serves multiple roles, including food, fuel, livestock feed, income generation, and soil conservation (Shushay, 2014). Research in Mexico, its center of origin, demonstrates its ability to thrive in rocky, mountainous terrain (Griffith, 2004). Meanwhile, Ethiopian pastoral systems are increasingly vulnerable to recurrent droughts and climate change, which are pushing suitable habitats from lowlands to montane ecosystems (Berhanu & Fekadu, 2014; Razgour *et al*., 2020). In this context, resilient crops such as cactus pear present a strategic option for adaptation.

Despite its potential, cactus farming remains limited in the highland regions of Ethiopia, including the Gullele Botanical Garden, which lies at altitudes between 2,559 and 3,000 meters above sea level. The presence of sandy silicic rocks such as Trachyte and Rhyolite suggests that these soils could support the growth of *Opuntia ficus-indica*. However, its adaptation is hindered by a lack of knowledge regarding optimal growth conditions and cultivation practices suited to plateau regions. This shortfall impedes efforts to harness the plant's benefits for sustainable agriculture, food security, and environmental restoration. Therefore, assessing the plant's adaptability and growth performance under the specific environmental conditions of Gullele is essential. Such research will provide insights necessary for developing effective cultivation strategies across different altitudinal gradients, ultimately facilitating the integration of *Opuntia ficus-indica* into local agricultural systems and enhancing resilience in drought-affected areas.

This study aims to evaluate the growth performance and adaptability of the species in relation to varying altitudinal gradients, as well as to identify which altitude class best supports its growth.

The research addresses the following questions:

1. What is the growth and adaptation performance of *Opuntia ficus-indica* in the mountainous and plateau areas of Gullele Botanical Garden?
2. What are the survival and growth durations of

the species' cladodes across different altitudinal classes?

3. Can Opuntia focus-indica be effectively cultivated in highland and plateau ecosystems to enhance food security and support ecological restoration?

The hypothesis posits that there is a significant difference in the growth performance and adaptability of *Opuntia ficus-indica* across the altitudinal gradients of Gullele Botanical Garden, with certain altitude classes being more conducive to its cultivation.

The objectives of the study are to:

1. Cultivate *Opuntia ficus-indica* in Gullele Botanical Garden.
2. Evaluate its growth performance across different altitudinal strata.
3. Identify the most suitable altitudinal zones for sustainable cultivation.
4. Assess its potential ecological and production benefits.
5. Provide baseline information for future adaptation research on *Opuntia ficus-indica* under changing climatic conditions.

2 Methods and Materials

2.1 Study Area

The Gullele Botanic Garden (GBG) is located on the outskirts of Addis Ababa, at elevations ranging from 2,559 to 3,000 meters above sea level. Covering an area of 705 hectares, it lies between latitudes 9°1'30" N and 9°5'35" N, and longitudes 38°41'30" E and 38°44'20" E, forming part of Ethiopia's central plateau. The climate in this region can exhibit both warm and cold conditions simultaneously, with high precipitation occurring in August (1,300 mm). February is the warmest month, averaging 20.7°C, followed closely by March and May with averages of 20.2°C and 20°C, respectively. Conversely, August is the coldest month, with an average temperature of 7.5°C. The dry season occurs from March to May, with an average annual rainfall of 1,215.4 mm (Argaw, 2015; Mehair *et al.*, 2024).

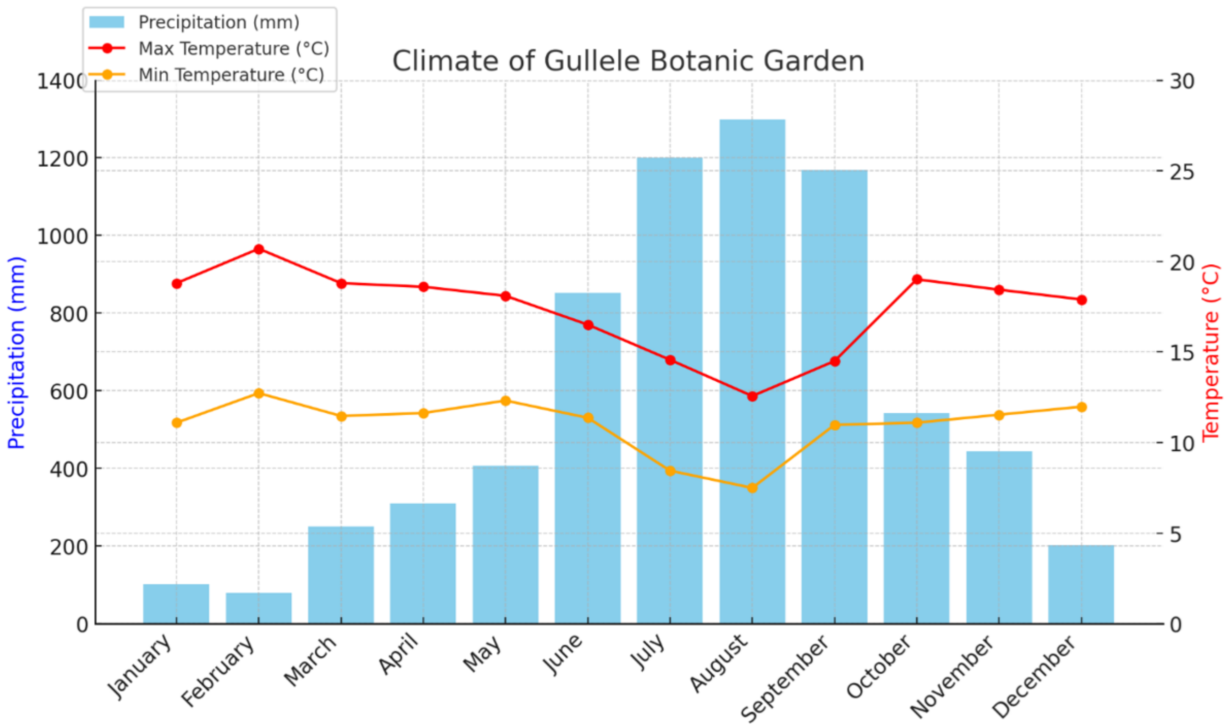

Figure 1. Climate diagram of Gullele Botanical Garden

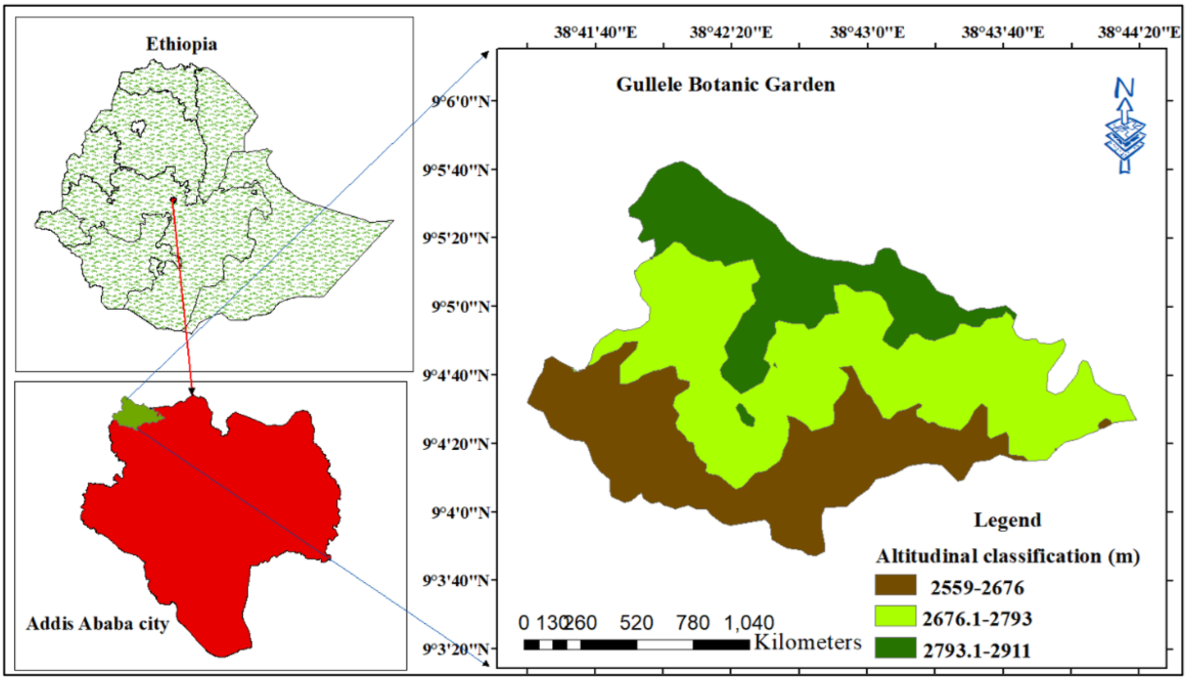

Figure 2. Location map of the study area showing Gullele botanic garden

The vegetation in the area predominantly consists of dry afro-montane and, to a lesser extent, afro-alpine structures, with Juniperus procera being the most prevalent species. Other notable species include Olinia rochetiana, Jasminum abyssinicum, Erythrina africana, Sideroxylon oxyacanthum, Maesa lanceolata, various Maytenus species, and Rosa abyssinica, along with a range of herbaceous plants that coexist with Juniperus procera. At higher elevations, different species of Helichrysum and Erica arborea can also be found alongside Juniperus procera. Historically, the garden was dominated by Eucalyptus species, but efforts are currently underway to remove these in favor of prioritizing indigenous species.

2.2 Planting Material Collection

The one-year-old cladodes, harvested from the top of the mother plant, were collected in late December 2022 from the Gurage zone near Welkite (1,910 meters above sea level). These cladodes were subsequently planted at three garden sites differentiated by altitudinal classes: lower (2,600 meters), middle (2,700–2,800 meters), and higher altitude (2,960 meters), following the technique outlined by Alemu *et al.* (2017).

Prior to collection, the cultivars underwent a thorough physical inspection to assess their health and ensure uniformity in size and age. Selection criteria focused on identifying cladodes that were unpaired or non-flowered (single) and sufficiently developed for planting. Each cladode's initial size was measured before being cut with a sterilized knife, and they were then placed on cardboard for transportation. After planting, data were recorded every two weeks to monitor progress and development.

2.3 Treatments and Experimental Design

Three separate planting zones were established for the collected cladodes, accounting for the elevation differences within the Gullele Botanical Garden. The elevation stratification, with a variation of 150 meters, was divided into three categories: lower (2,600 m), middle (2,750 m), and upper (2,900 m). In each of these zones, 15 cladodes were planted, totaling 45 pads.

During the planting process, the flat edges of the cladodes were oriented east and west, while the thin sides faced north and south. This orientation helps prevent burning and desiccation when the sun shines on the narrowest part of the cladodes during peak heat. Planting was scheduled to occur within three days after collection. Mature cactus pads were placed 1 meter apart in holes approximately 30 cm

Figure 3. Partial view of *Opuntia ficus-indica* cladode growth performance

2.4 Method of Analysis

deep, ensuring that one-third of their surface area was buried while two-thirds remained above ground. The planting took place at the beginning of the dry season in December 2022 to promote optimal establishment.

Across all elevation ranges, the planting was conducted on rocky, fallow, and bare land with uniform treatment to avoid significant variations. Prior to planting, obstacles were cleared, holes were dug, and preparations were made one month in advance to facilitate successful establishment. Monitoring and watering were performed twice a week following planting. Data monitoring and recording occurred bimonthly during the first six months to closely track survival rates and the growth of new cladodes, with all growth performance data documented in an Excel spreadsheet.

Data collected over a 30-month period were analyzed using SPSS version 22 statistical software. To examine the growth performance of different cladodes across various altitudinal classes, a stacked bar plot was generated in R. This visualization illustrated the variation in growth metrics along the altitudinal gradients. Additionally, R was used to analyze the time taken for growth performance in relation to the classified altitudinal gradients for this study.

For the analysis of altitudinal classes and parameters such as cladode survival, height of mother cladodes, developmental stages (first, second, third), and flowering time, one-way ANOVA tests were conducted using IBM SPSS Statistics version 30. These analyses aimed to determine whether significant differences exist in these variables across the different altitudinal classes.

The mean growth performance of the experimental species at each altitude was computed using the following formula:

$$Overall\,Mean = \frac{\sum Mean\,Growth\,of\,All\,Species\,in\,Altitude\,A}{Number\,of\,Species\,in\,Altitude\,A}$$

3 Result and Discussion

3.1 Survival rate in the first three months

After planting 15 mother cladodes (primary cuttings) in each altitudinal class, the survival and growth patterns varied across the different elevation levels over time (Figure 4). During the initial two months following planting, all species exhibited wilting symptoms and showed no immediate signs of survival. However, some previously wilted cladodes later began to sprout new growth. By the third month, the

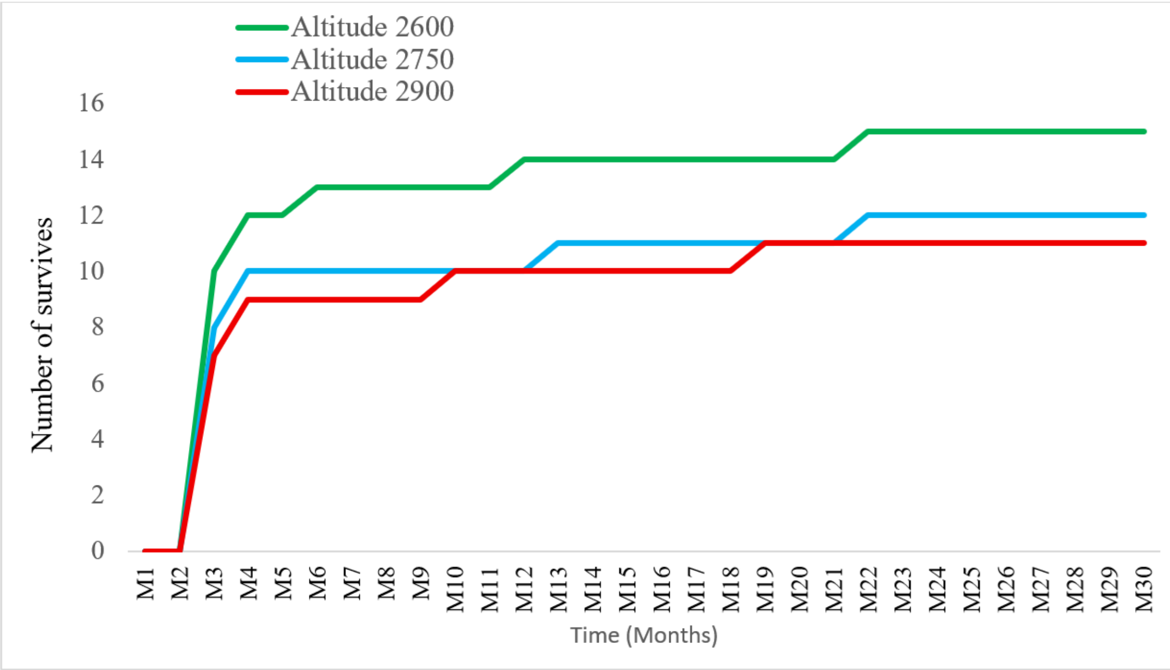

Figure 4. Number of *Opuntia ficus-indica* cladode survives vs time (months) along altitudinal classes

number of surviving cladodes differed by altitude: 12 in the lower altitude, 10 in the middle altitude, and 9 in the higher altitude. The status of each cladode, whether alive or dead, was assessed and recorded over a six-month period.

Despite most of the planted cladodes of *Opuntia ficus-indica* surviving through the monitoring period, the survival rate was low and uncertain during the first two months after planting. Many of the cladodes exhibited wilting signs due to transplant shock, environmental stress, or suboptimal microclimatic conditions. By the third month, however, survival rates improved considerably; the best results were observed in the lower altitudinal class, where 12 out of the 15 cladodes survived. The middle altitude zone followed with 10 survivors, while 9 cladodes survived in the higher altitudinal class. This trend suggests that lower elevations may provide better conditions for initial growth, likely due to relatively warmer temperatures and favorable air conditions that support growth and establishment. These results align with findings by Aruwa (2019) and Prisa (2023).

3.2 Final total survives

Once the mother cladodes have survived, it typically takes around six months for a new generation of cladodes to develop within each altitude category (Table 1).

Table 1. Growth performance of *Opuntia ficus-indica* cladode along altitudinal classes at GBG

Altitude classes	1st generation cladode		2nd generation cladode		3rd generation cladode	
	Time taken to Emerge (months)	Time taken to Cladode complete (months)	Time taken to Emerge (months)	Time taken to Cladode complete (months)	Time taken to Emerge (months)	Time taken to Cladode complete (months)
Lower (2600)	6	10	11	16	17	25
Middle (2750)	6	11	12	18	20	28
Higher (2900)	6	13	14	21	22	30

Thirty-eight *Opuntia ficus-indica* cladodes, all representing the third generation, survived the experimental conditions and exhibited diverse growth performances. Notably, survival rates varied significantly by altitude. The initial fifteen cladodes established in the lower altitude class achieved complete survival, while the middle and higher altitude classes yielded 12 and 11 surviving cladodes, respectively (Figure 5).

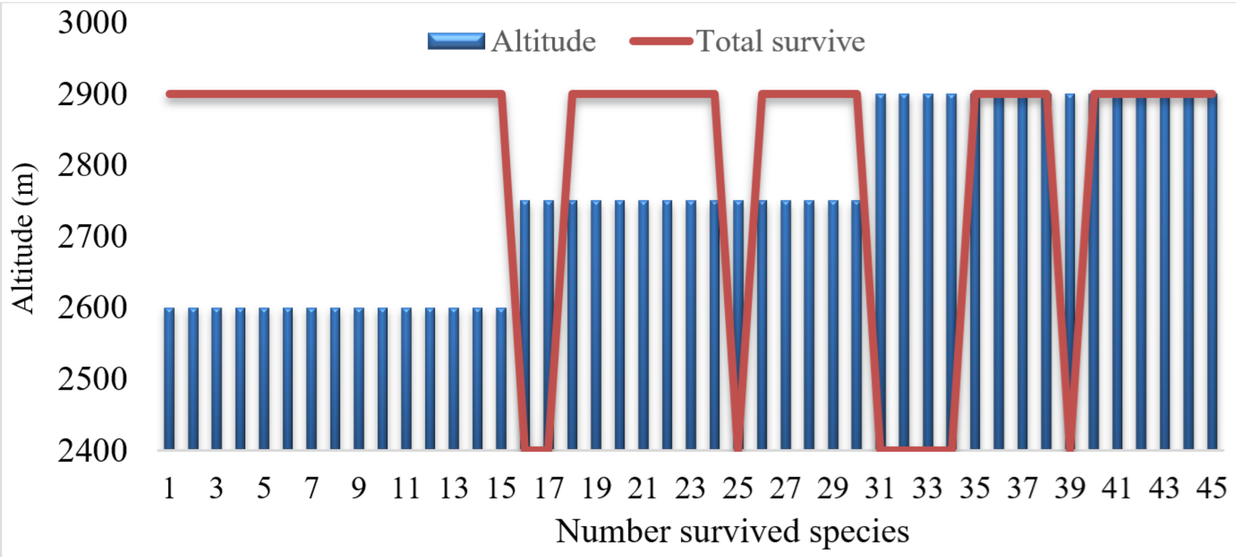

Figure 5. Relationship between altitude (m) and total mother cladodes survive

3.3 Growth performance versus altitude

The growth duration for the initial cladodes varied by altitude: approximately 10 months for lower altitudes, 11 months for middle altitudes, and 13 months for higher altitudes (Figure 6). The second cladode emerged around the 11th month in the lower altitude zone, while it took 12 months in the middle altitude and 14 months in the higher altitude. The total time to complete the growth of the second generation of cladodes is roughly 16 months for lower altitudes, 18 months for middle altitudes, and 21 months for higher altitudes. The development of the third cladode spans 17 to 25 months for lower altitudes, 20 to 28 months for middle altitudes, and 22 to 30 months for higher altitudes. By the 30th month, only two cladodes (the fourth cladode and a flower) had emerged, with no additional development noted in the other altitude classes.

Key: T1C: Time taken for the first cladode; TC1C: Time taken to complete the first cladode; T2C: Time taken for the 2nd cladode; TC2C: Time taken to complete the 2nd cladode; T3C: Time taken for the 3rd cladode; TC3C: Time taken to complete the 3nd cladode, T4C/f: time take for the 4th cladode or/and flower.

The results of the study indicated that the time from emergence to the completion of growth for successive cladodes increased with altitude. For instance, the first cladodes emerged after six months in all zones, but the time required to develop each successive cladode grew longer from lower to higher altitudes. Specifically, the third cladode took approximately 17, 20, and 22 months to emerge at lower, middle, and higher altitudes, respectively. The slower development at higher elevations may be attributed to cooler temperatures, lower solar radiation, and reduced soil nutrients, confirming previous research that altitude affects the phenological development of cacti (Shushay, 2014; Khandelwal *et al.*, 2019).

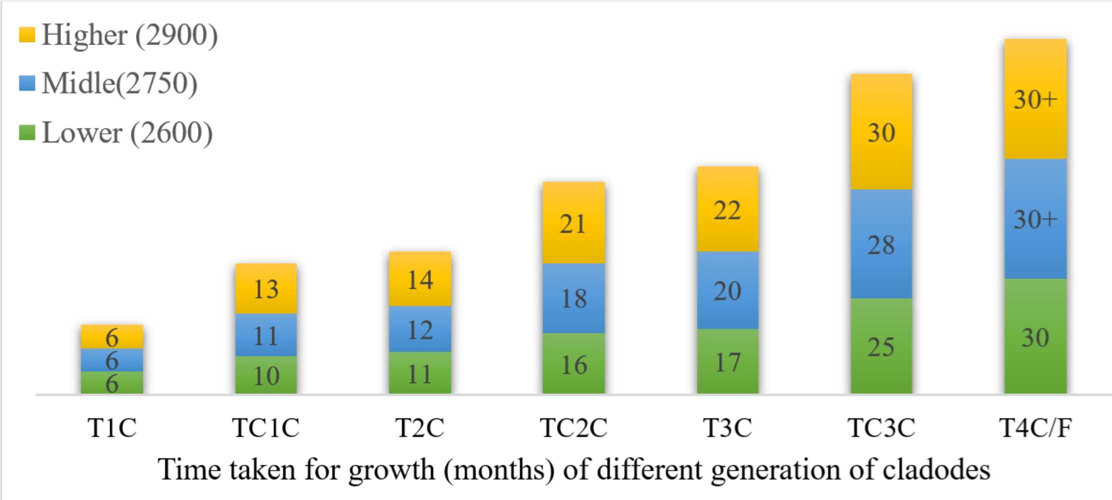

Figure 6. *Opuntia ficus-indica* cladode growth performance versus time

3.4 The impact of altitude in survival and height of cladode

The altitudinal gradient does not significantly affect the height of the mother cladode (p = 0.668) or the height after survival (p = 0.454). However, altitude significantly influences the height of the first, second, and third cladodes, as well as flowering time, with significant values of 0.045, 0.027, 0.004, and 0.001, respectively (Table 2). The average height of cladodes shows the highest mean square (114.311) in the lower altitude class (2,600 m), followed by the middle altitude class (2,750 m). In contrast, the higher altitude class (2,900 m) exhibits a relatively lower mean square (62.178) in height compared to the other altitudinal classes.

Table 2. Results of ANOVA analysis regarding the effects of altitude on the height of cladodes

ANOVA						
	Altitudinal class	Sum of Squares	df	Mean square ± SD	F	Sig.
Primary height	Lower	114.311	44	3.09 ± 2.1		
	Middle	112.133	42	2.67 ± 1.78	0.41	0.67
	Higher	62.178	24	1.81 ± 1.1		
Height after survive	Lower	101.2	22	1.87 ± 1.1		
	Middle	97.467	42	2.321 ± 2.04	0.8	0.45
	Higher	58.733	44	4.00 ± 2.6		
Height of 1st cladode	Lower	80.578	38	4.62 ± 2.8		
	Middle	61.333	18	1.70 ± 0.33	2.72	0.05
	Higher	19.244	14	0.88 ± 0.25		
Height of 2nd cladode	Lower	134.978	42	10.69 ± 3.01		0.03
	Middle	103.6	22	2.71 ± 0.2.05	3.95	
	Higher	21.378	14	1.23 ± 0.66		
Height of 3rd cladode	Lower	32.844	44	16.422 ± 3.7		
	Middle	107.067	12	2.549 ± 2.1	6.44	0
	Higher	139.911	2	1.12 ± 0.12		
Flowering time	Lower	124.061	24	0.422 ± 0.1		
	Middle	42.184	12	0 ± 0.05	6.44	0
	Higher	38.311	2	0 ± 001		

NB: Lower altitude= 2600 meters above sea level; Middle altitude =2750 meters above sea level

The ANOVA results indicated that altitude significantly affected the heights of the first, second, and third cladodes, as well as flowering time ($p < 0.05$), but not the initial or post-survival height of the mother cladode (Table 2). The greatest cladode heights were observed at lower altitudes, suggesting that the environmental conditions in these areas were more favorable for robust growth compared to higher altitudes. The decline in size with increasing altitude may be attributed to decreasing temperatures and shorter growing seasons, which influence the amount of biomass accumulation. This finding is consistent with previous observations of altitude-related differences in cactus growth (Gouhis *et al.*, 2017; Naorem *et al.*, 2024).

Interestingly, flowering time was significantly delayed at higher altitudes ($p = 0.001$), likely driven by cooler temperatures and photoperiodic effects. Delayed flowering can impact reproductive success and yield, which should be considered when planning cultivation strategies (Song *et al.*, 2020).

3.5 Implications for Cultivation and Ecological Restoration

The demonstrated adaptability of *Opuntia ficus-indica* across different altitudinal classes suggests potential for cultivation beyond conventional arid environments. The evidence of its resilience, as shown in the study, includes moisture-stress survival rates and overall growth performance at higher elevation sites, which align with observations by Griffith (2004) and Prisa (2023), who noted similar resilience under rocky and resource-scarce conditions. The ability of *Opuntia ficus-indica* to thrive in rocky soils, as seen in the Gullele Botanical Garden, and to withstand adverse conditions highlights its remarkable flexibility. This adaptability reinforces its potential as a candidate for ecological restoration and sustainable agricultural practices in the Ethiopian highlands (Dejene, 2003).

The delayed yet continued growth at higher elevations indicates that environmental constraints, such as lower temperatures, limited oxygen availability, and reduced nutrient levels, initially inhibit faster growth rates. However, once the species adapt, they can exhibit consistent growth processes over time (Ranjan *et al.*, 2016). This evidence supports the notion that, despite immediate physiological limitations at high elevations, these species may adapt to sustain growth capacity in the long run, emphasizing the importance of acclimatization and evolutionary adaptation (Körner, 2007).

4 Conclusion

This study demonstrated that *Opuntia ficus-indica* is thriving and adapting well across various altitudes in the Gullele Botanical Garden, suggesting it could be an excellent candidate for cultivation in Ethiopia's highland and plateau ecosystems. While initial survival rates were somewhat low in the early planting months, this resilient species rebounded, with survival rates improving over time, particularly in the lower altitude regions. Elevation played a significant role in its growth cycle and physical characteristics, such as the height of the cladodes and the timing of flowering. Lower elevations appeared to promote quicker growth and larger cladodes, while the cooler temperatures and environmental challenges at higher elevations slowed growth, though they did not prevent the plant from surviving and establishing itself.

These findings highlight that *Opuntia ficus-indica* could thrive beyond arid areas, potentially leading the way in ecological restoration, enhancing food security, and promoting sustainable agriculture in the Ethiopian highlands. Its ability to grow in rocky, nutrient-poor soils and withstand environmental stress underscores its potential for revitalizing degraded and drought-affected lands. However, to fully understand its capabilities, further long-term research is needed on its reproductive success, fruiting, and ecological effects.

Limitations and Recommendations

This study is limited to 30 months of activity and the environmental conditions at Gullele Botanical Garden. Long-term monitoring of reproductive performance, fruit yield, and ecological impacts would provide a more comprehensive understanding of the cultivation potential. Additionally, exploring cultivar variability and soil amendments could enhance growth to optimal levels in highland environments.

Based on the study's findings, it is recommended to prioritize the cultivation of *Opuntia ficus-indica* in lower altitudes (2,600 m), as this zone demonstrated the highest survival rates, faster growth, and larger cladode development. However, with proper management and acclimatization, the species can also be established at middle and higher altitudes, although growth and flowering may be slower.

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Data Availability Statement

Data are contained within the article.

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Conflicts of Interest

The authors declare no conflict of interest.

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