DOI: https://doi.org/10.59983/s2024020204
AgroEnvironmental Sustainability, 2024, 2(2), 94-103

RESEARCH

Exploring Genetic Diversity and Variability of Tamarind (*Tamarindus indica* L.): A Comprehensive Study in the Bilaspur Region of Chhattisgarh, India

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ARTICLE HISTORY
Received: 30 April 2024
Revised: 03 June 2024
Accepted: 04 June 2024
Published: 26 June 2024

KEYWORDS
genetic diversity
variability
Tamarindus indica

EDITOR
Pankaj Kumar

Abstract

The genetic diversity and variability of *Tamarindus indica* L., a valuable multipurpose tree species, was investigated through a comprehensive study conducted in the Bilaspur region. This research aimed to assess the morphological variations and growth responses of *T. indica* under contrasting environments, specifically agroforestry and natural forest systems. The study employed a rigorous scientific approach, encompassing field surveys, statistical analyses, and morphological assessments. The results indicated pronounced morphological differences between *T. indica* trees in the agroforestry and natural forest systems. *T. indica* trees in the natural forest exhibited significantly greater average height and diameter at the breast height (DBH) compared to those in agroforestry settings, highlighting the influence of the environment on growth parameters. Here, the crown diameter displayed homogeneity across both environments, suggesting a potential level of adaptability in this trait. The findings show the importance of considering environmental conditions when assessing the growth and development of *T. indica*, providing valuable insights for both scientific research and practical applications in agroforestry and conservation efforts.

Citation: Ojha, A., Dhuria, S. S., Shukla, A. K., & Chandrakar, A. K. (2024). Exploring Genetic Diversity and Variability of Tamarind (*Tamarindus indica* L.): A Comprehensive Study in the Bilaspur Region of Chhattisgarh, India. *AgroEnvironmental Sustainability*, 2(2), 94-103. https://doi.org/10.59983/s2024020204

Statement of Sustainability: The present investigation can significantly contribute to several Sustainable Development Goals (SDGs). By studying the genetic diversity of *T. indica*, we advance SDG 15 (Life on Land) through biodiversity conservation and ecosystem resilience. Our research supports SDG 2 (Zero Hunger) by identifying robust genotypes that enhance food security and sustainable agriculture. Through collaboration with local communities, we promote SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth) by fostering sustainable livelihoods and empowering local economies. Also, our paper aligns with SDG 13 (Climate Action) by preserving native species that mitigate climate change impacts. Engaging in community education and capacity-building ensures that our efforts support SDG 4 (Quality Education), promoting knowledge transfer and environmental stewardship. Ultimately, our work integrates scientific research with community engagement to drive sustainable development and environmental conservation.

1. Introduction

Genetic diversity is the amount of genetic variability present among individuals of a variety or a population within a species (Chandrakar, 2012; Chandrakar et al., 2016). Genetic diversity serves several important purposes: (a) as a resource for tree breeding and improvement programs to develop well-adapted tree species varieties and to enhance the genetic gain for a multitude of useful traits; (b) to ensure the vitality of forests as a whole by their capacity to withstand diverse biotic and abiotic stressors under changing and unpredictable environmental conditions; and (c) the livelihoods of indigenous and local communities that use traditional knowledge (FAO, 2013). Rich genetic diversity within and among forest tree species thus provides an opportunity to improve the silvicultural and economic value of a species by identifying the best wild seed sources; and, selecting individuals within these to develop varieties that are considerably better than the wild material (Tiwari and Dhuria, 2018).

Tamarindus indica (Linn.) is a significant multipurpose tree belonging to the Fabaceae (Leguminosae) family. It plays an important role in ecological and economic functions (Das and Alam, 2001; Fandohan et al., 2010a; Sidibe et al., 2012; Azad et al., 2013; Azad et al., 2014). Tamarind has a wide geographical distribution in the subtropics and Southeast Asian nations including India, Sri Lanka, Nepal, Pakistan, and Bangladesh have made significant progress in domesticating this species (Sidibe et al., 2012; Azad et al., 2013; Fandohan et al., 2011). It is mostly used for its fruits, which are either turned into juices, consumed immediately, or used as ingredients in recipes and preservatives (Gullipalli and Kasiviswanatham, 2013; Kidaha et al., 2019). The tamarind tree plays a significant part in the regional economy, complements the food, and is utilized in both conventional and cutting-edge medicines (Fandohan et al., 2011; El-Siddig et al., 2006). According to Kidaha et al. (2019), *T. indica* trees differ morphologically in terms of their fruit, crown, leaf, trunk, seed, and flower traits. Morphological descriptors have been used as fundamental elements in plant identification, breeding, commercialization, preservation of plant resources, cluster analysis, and understanding of genetic similarities and differences (Santos et al., 2012; Cervantes and Diego, 2010). In ethnobotany, the leaves, bark, and pulp have all been extensively exploited (Gupta et al., 2014). Due to its availability and widespread use, the tree is frequently utilized as an ornamental tree (Doughari, 2006). It is crucial to the paints, varnishes, and cosmetics industry (Santos et al., 2012). Its pulp is highly valued in condiments and juice production, and it is a good source of proteins, lipids, and carbs that could be utilized to treat childhood malnutrition. *Tamarind* fruit consumption may be beneficial for diabetes and heart patients due to its sugar and dietary fiber content (Adeola and Aworh, 2010). Despite its many advantages, *T. indica* is primarily found in the wild, is purposefully planted in home gardens, or is left alone on farmland during land cultivation. Burning charcoal, over-harvesting food and timber, gathering firewood, gathering animal feed, and increasing conversion of land into farms are examples of anthropogenic activities that have severely eroded species' genetic diversity and damaged habitat (Masette et al., 2015; Lakor et al., 2016; Sobola et al., 2023). Morphological trait information would guide the selection of *T. indica* for various uses, such as domestication and breeding improvement (Sobola et al., 2023).

Previous research on tamarind has predominantly focused on its agronomic traits, chemical composition, and various uses in traditional practices. Studies investigating genetic diversity have been carried out in different parts of India and other countries (Fandohan et al., 2011; Rajamanickam, 2023). There is a lack of region-specific data that could reveal unique genetic traits adapted to local environmental conditions. Moreover, there has been a lack of focus on the Bilaspur region specifically, which has unique environmental conditions and local tamarind varieties that may possess distinct genetic traits. This gap hinders the development of targeted conservation strategies and sustainable agricultural practices for the region. Studying the genetic diversity and variability of *T. indica* is crucial for conservation and sustainable utilization. *Tamarind*, a significant source of nutrition and traditional medicine, faces threats from habitat loss and climate change. Understanding its genetic diversity helps in developing conservation strategies, enhancing crop resilience, and ensuring food security (Nyadoi et al., 2009). Moreover, it supports sustainable agricultural practices and economic growth for local communities dependent on tamarind. Enhancing its genetic diversity could lead to the discovery of varieties with superior qualities, improve yield, benefit local farmers and industries, and maintain ecosystem balance.

Our hypothesis posits that the *T. indica* populations in the Bilaspur region exhibit significant genetic diversity and variability, which can be systematically characterized and utilized for conservation and improvement programs. This genetic diversity is expected to be structured according to ecological and geographical variations within the region. The objective of this study is to evaluate morphological differences among the tamarind population in the agroforestry system and the natural forest area of Bilaspur. By addressing this objective, this study aims to fill the existing gaps in the genetic knowledge of *T. indica* in Bilaspur. The outcomes will contribute to the conservation and sustainable exploitation of tamarind, ensuring that this valuable species continues to benefit local communities and ecosystems.

2. Material and Methods

2.1. Study Area and Site Selection

The study was conducted in the Bilaspur district of Chhattisgarh state in India, to assess the morphological variation of *T. indica* in both natural forest and agriculture field environments. The district experiences a subtropical climate with hot summers and mild winters. The average annual rainfall ranges from 1,000 to 1,200 mm, primarily received during the monsoon season from June to September. Six specific sites were chosen for data collection based on their representation of natural forests and agriculture fields (Figure 1). The natural forest areas included Ratanpur, Kota, and

Kanan Pendari forest divisions, while the agriculture field sites consisted of Devagaon, Birkona, and Masturi villages. Data collection took place in various geographical locations within Bilaspur, specifically in agroforestry fields (Devagaon, Birkona, Masturi) and natural forests (Ratanpur, Kota, Kanan Pendari). The trees were observed under diverse environmental conditions and subjected to different management practices. To analyze the variability of morphological characteristics of the tree species *T. indica* were considered, including height, diameter at breast height (DBH), leaf structure, pods, bark, seeds, and other relevant traits. Additionally, the location of each tree and its historical background were documented. The research project was carried out between January 2023 and July 2023, employing a scientific approach to ensure accurate and reliable findings.

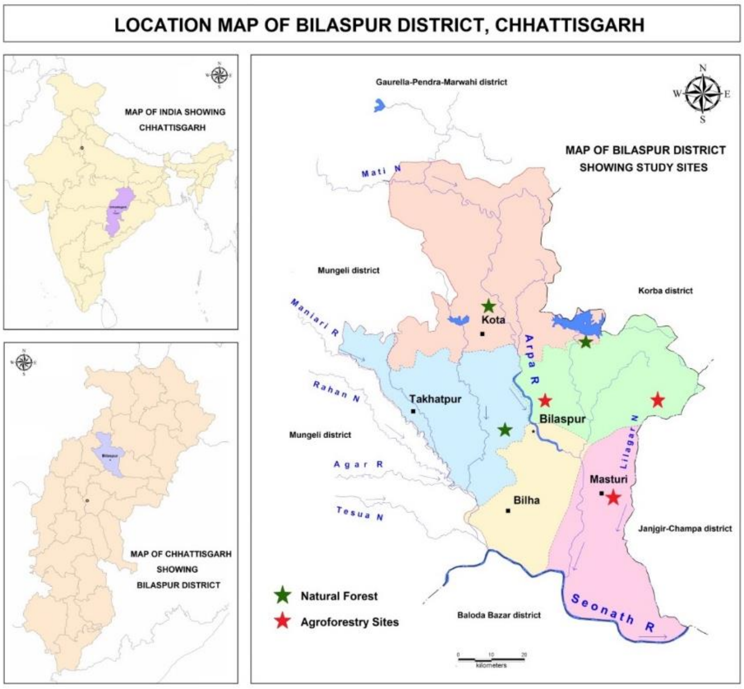

Figure 1. Location map of study sites (green stars indicate Natural forests and red stars indicate agroforestry sites).

Table 1. Selected locations of *T. indica* with their specific latitude and longitude.

Sample	Location Name	Latitude	Longitude
Agroforestry field			
A1	Devagaon	22.0900N	81.6706E
A2	Birkona	22.1399N	82.1636E
A3	Masturi	21.9924N	82.2683E
Natural forest			
F1	Ratanpur	22.2859N	82.1652E
F2	Kota	22.2945N	82.0246E
F3	Kananpendari	22.1172N	82.0601E

2.2. Data Collection and Analysis

As part of the research data collection process, open-pollinated seeds were carefully collected from each of the six selected sites (Table 1) (Mamo et al., 2006). A total of five trees were sampled from each location to ensure a representative seed collection. The fruits obtained from the selected trees (Divakara, 2008; Joukhadar et al., 2018) were collected and stored in sample bags, with proper labeling indicating their respective location and sample names (Motamayor et al., 2008). These bags were then transported to the departmental nursery at Guru Ghasidas Vishwavidyalaya (GGV) for further experimental procedures. The collection and storage of the fruits in sample bags with appropriate labeling were conducted in a scientifically rigorous manner to maintain the integrity of the collected seeds. By following standardized protocols (WHO, 2003), we ensured that the seeds remained associated with their specific location and sample identity throughout the transportation process. Further, observed morphological as well as phenotypic variations in seeds, fruits, seedlings (Kumar et al., 2018; López et al., 1996; Finch, 1986), and germination

(Thomson, et al., 1993), tree height (Singh and Tiwari, 2014), diameter at the breast height (DBH) of each tree (Gupta et al., 2019) from both systems.

3. Results and Discussion

3.1. Variation in Fruit Characteristics

3.1.1. In Agroforestry Practices

The morphological variability of *T. indica* L. in agroforestry was investigated, focusing on pod length (cm), pod width (cm), pulp weight (g), seeds per pod, and single seed weight (g) in three selected sites: Masturi, Birkona, and Devagaon (Table 2). The mean pod length in Masturi was found to be the highest at 9.464±0.90, followed closely by Birkona with 9.298±1.22. Devagaon had the shortest pod length, measuring 8.014±0.51. In terms of pod width, Masturi exhibited the widest pods at 2.084±0.12, while Devagaon and Birkona showed similar performance in pod width. When considering pulp weight, Masturi had the highest mean value of 8.242±0.41, followed by Birkona with 7.174±0.70, and Devagaon with 5.888±0.78. In terms of seeds per pod, Masturi and Birkona had the highest mean values at 6.4±1.01, while Devagaon had a slightly lower value of 6.2±0.90. Regarding seed weight, Masturi had the highest mean value at 1.032±0.15, followed by Birkona and Devagaon sites, respectively.

Table 2. Variation in parameter of *T. indica* in selected agroforestry systems.

Location	Sample	Pod Length (cm)	Pod Width (cm)	Pulp Weight (g)	No. of Seed/Pod	Single Seed Weight (g)
Devagaon	AF1	8.39	2.03	5.08	6	1.08
	AF2	8.15	2.18	6.25	6	1.01
	AF3	7.23	1.95	5.67	5	0.96
	AF4	7.65	2.05	7.23	6	0.85
	AF5	8.65	1.65	5.21	8	0.75
	Mean value	8.014±0.51	1.972±0.17	5.888±0.78	6.2±0.90	0.93±0.12
Birkona	AF1	7.1	2.01	7.65	6	1.2
	AF2	9.65	2.03	8.32	5	0.94
	AF3	8.98	1.85	6.5	8	0.65
	AF4	10.65	1.97	6.8	6	1.1
	AF5	10.11	1.99	6.6	7	1
	Mean value	9.298±1.22	1.97±0.06	7.174±0.70	6.4±0.01	0.978±0.18
Masturi	AF11	11.23	2	8.3	8	1.23
	AF12	9.36	2.2	8.5	7	1.2
	AF13	8.97	2.21	8.9	5	0.91
	AF14	9.01	2.13	8.01	6	0.99
	AF15	8.75	1.88	7.5	6	0.83
	Mean value	9.464±0.90	2.084±0.12	8.242±0.41	6.4±1.01	1.032±0.15
	Grand mean	8.93	2.01	7.10	6.33	0.98

These results indicate significant morphological variability among the studied *T. indica* populations in different agroforestry sites (Table 2). The statistical analysis performed, such as the calculation of means and standard deviations (SD), provides a quantitative understanding of the variation observed (Fandohan et al., 2011). The findings suggest that the Masturi site exhibits favorable conditions for the development of *T. indica*, as it consistently displayed the highest values in terms of pod length, pulp weight, seeds per pod, and seed weight. Birkona also showed relatively good performance in most traits, while Devagaon displayed comparatively lower values. The observed variations in morphological traits may be attributed to various factors, including genetic differences among populations, environmental conditions, and management practices (Rosenzweig et al., 2007) in the respective sites. Further investigation is warranted to determine the underlying causes of these variations and their potential implications for the cultivation and management of *T. indica* in agroforestry systems (Sanogo et al., 2023).

3.1.2. In Natural Forest System

The morphological variability of *T. indica* in natural forest areas was investigated (Fandohan et al., 2010b; Álvarez et al., 2019) focusing on pod length (cm), pod width (cm), pulp weight (g), seeds per pod, and seed weight (g) in three selected sites: Ratanpur, Kanan Pendari, and Kota (Table 3). The mean pod length in Ratanpur was found to be the highest at 10.724±1.10, followed by Kanan Pendari with 10.09±1.07, Kota had the shortest pod length, measuring 9.592±0.69. In terms of pod width, Ratanpur exhibited the widest pods at 2.082±0.16, followed by Kota with 1.97±0.18, and Kanan Pendari with 1.866±0.31. When considering pulp weight, Kota had the highest mean value of 8.514±0.45, followed by Kanan Pendari with 8.056±0.89, and Ratanpur with 7.12±1.33. In terms of seeds per pod, Kota and Kanan Pendari had the highest mean values at 7.6±1.44, while Ratanpur had a slightly lower value of 7.2±1.30. Regarding seed weight, Kanan Pendari had the highest mean value at 1.038±0.34, followed by Kota and Ratanpur sites, respectively.

Table 3. Variation in parameter of *T. indica* in selected natural forestry system.

Location	Sample	Pod Length (cm)	Pod Width (cm)	Pulp Weight (g)	No. of Seed/Pod	Single Seed Weight (g)
Ratanpur	F1	10.32	2.13	5.32	6	0.98
	F2	9.65	2.21	6.23	7	0.89
	F3	9.98	2.23	7.87	8	0.74
	F4	11.32	1.85	8.65	9	1.23
	F5	12.35	1.99	7.54	6	1.01
	Mean value	10.724±1.10	2.082±0.16	7.12±1.33	7.2±1.30	0.97±0.17
Kota	F6	9.85	2.25	8.9	7	1.05
	F7	8.65	2.02	8.65	6	1.09
	F8	9.12	1.95	7.98	8	0.85
	F9	9.98	1.85	8.09	9	0.89
	F10	10.36	1.78	8.95	8	0.99
	Mean value	9.592±0.69	1.97±0.18	8.514±0.45	7.6±1.44	0.974±0.17
Kanan Pendari	F11	11.23	2.05	8.65	7	1.09
	F12	11	2.09	9.2	7	1.5
	F13	9.45	1.87	7.45	8	0.65
	F14	10.12	1.32	6.98	9	0.75
	F15	8.65	2	8	7	1.2
	Mean value	10.09±1.07	1.866±0.31	8.056±0.89	7.6±0.89	1.038±0.34
	Grand mean	10.14	1.97	7.90	7.47	0.99

These results indicate significant morphological variability among the studied *T. indica* populations in different natural forest sites (Azad et al., 2014). The statistical analysis performed, such as the calculation of means, provides a quantitative understanding of the variation observed (Table 3). The findings suggest that the Ratanpur site displays favorable conditions for the development of *T. indica*, as it consistently showed the highest values in terms of pod length and pod width. Kota also demonstrated good performance in pod length and pulp weight, while Kanan Pendari exhibited higher values in terms of pod width, pulp weight, seeds per pod, and seed weight. The observed variations in morphological traits may be attributed to various factors, including genetic differences among populations, environmental conditions, and specific characteristics of each natural forest site. Further investigation is necessary to determine the underlying causes of these variations and their potential implications for the conservation and management of *T. indica* in natural forest ecosystems.

The morphological variability of *T. indica* was investigated in two different environments: natural forest and agroforestry systems. The mean values, standard errors (SE), and specific traits were examined (Figure 2). The standard errors indicate the precision of the mean values and reflect the variability within the collected data. Comparing the two environmental systems, it can be observed that there are variations in the measured traits between the natural forest and agroforestry systems (Okello et al., 2018). In terms of pod length, the natural forest had a higher mean value (10.14±026) compared to the agroforestry system (8.93±0.30). However, the standard errors indicate some variability within these measurements. For pod width, the agroforestry system exhibited a slightly higher mean value (2.01±0.04) compared to the natural forest (1.97±0.06). In terms of pulp weight, the natural forest had a slightly higher mean value (7.90±0.12) compared to the agroforestry system (7.10±0.31). The number of seeds per pod was higher in the natural forest (7.47±0.27) compared to the agroforestry system (6.33±0.27). Regarding single seed weight, there was no significant difference observed between the two environments, as the mean values were similar (0.99±0.06) in the natural forest and (0.98±0.04) in the agroforestry system (Figure 2). These findings suggest that the natural forest environment may contribute to larger pod sizes, higher pulp weights, and more seeds per pod compared to the agroforestry system. However, it is important to consider the standard errors, as they indicate the level of variation within the measured traits (Sanogo et al., 2023).

These correlations provide insights into the relationships among the morphological traits of *T. indica* (Table 4). The correlation coefficient ranges from -1 to +1 and indicates the strength and direction of the relationship between two variables (i.e., natural forest and agroforestry). For example, longer pods tend to have more seeds and higher pulp weight, while wider pods tend to have fewer seeds and lower pulp weight (Table 4) (Hallwachs, 1986). Understanding these correlations can contribute to a better understanding of the overall morphological variability in *T. indica* and its potential implications for seed production and quality (Okello et al., 2018).

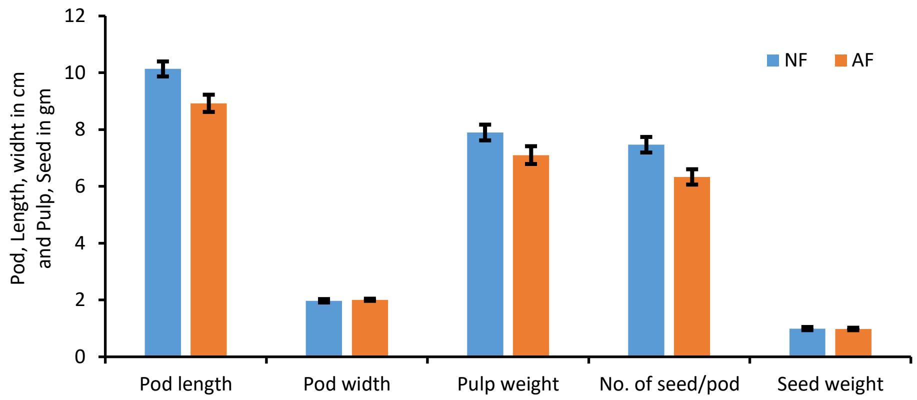

Figure 2. Morphological variation between agroforestry (AF) and natural forest (NF).

Table 4. Correlation between natural forest and agroforestry systems tree species.

Parameters	Pod Length	Pod Width	Pulp Weight	No. of Seed/Pod	Single Seed Weight
Pod Length	1*				
Pod Width	-1**	1*			
Pulp Weight	1*	-1**	1*		
No. of Seed/Pod	1*	-1**	1*	1*	
Single Seed Weight	1*	-1**	1*	1*	1*

*Positive correlation between both variables; **Negative correlations between one variable increase but other variables decrease.

3.2. Variation in Seed Characteristics

In the agroforestry system, the mean seed length was estimated to be 1.4 and the mean seed breadth was 1.08 (Table 5). On the other hand, in the natural forest, the mean seed length was 1.42, and the mean seed breadth was 1.10. The result showed seed variability data suggests slight differences in seed length and breadth between the agroforestry system and the natural forest site i.e., exhibited potential factors influencing seed variability in the two sites (Abasse et al., 2011; Dangasuk et al.,1997).

Table 5. The average value of seed characters at both sites.

System	Sites	Seed Length	Seed Breadth
Agroforestry	Devagaon	1.45	1.15
	Birkona	1.40	1.00
	Masturi	1.35	1.09
	Mean	1.40	1.08
Natural forest	Ratanpur	1.47	1.16
	Kota	1.42	1.02
	Kanan Pendari	1.37	1.13
	Mean	1.42	1.10

3.3. Variation in Seedling Characteristics

3.3.1. Germination Rate

During the investigation, it was observed that the seed germination rate of *T. indica* differed between the agroforestry system and the natural forest (Thomson et al., 1993). The seed germination rate in the agroforestry system was found to be 70%, while in the natural forest, it was 85% (Figure 3). Seed germination is a critical stage in the life cycle of plants, as it marks the initiation of growth and development. The variations in seed germination rates between the agroforestry system and the natural forest may be attributed to several factors like environmental conditions, seed quality, competition, microenvironment, and so on (Rhoades, 1996).

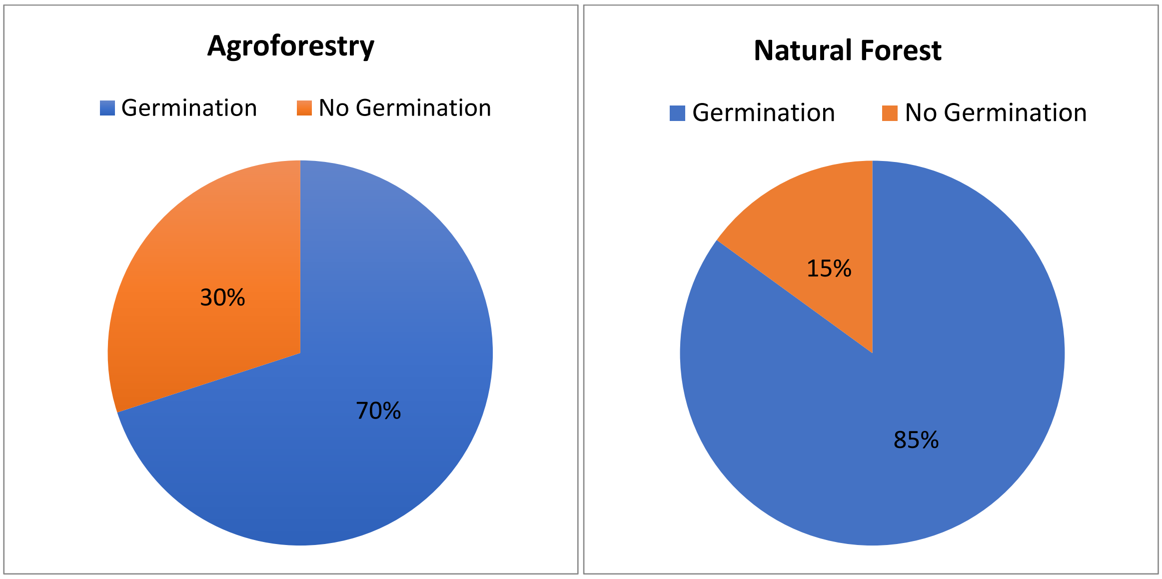

Figure 3. Germination percentage of natural forest and agroforestry systems sites.

3.3.2. Seedling Growth Performances

Significant differences were detected in seedling height after 15, 30, 45, and 60 days of growth. Seedling collar diameter showed the same scheme after growth (Fandohan et al., 2010b). For both parameters, the selected sites from the natural forest showed the highest growth speed (Figures 4a, b). Besides, larger seeds also showed higher growth speed than smaller ones. Many studies have highlighted that seed traits, particularly its mass are a determinant for seedling growth and survival during early life stages of plants (Khan, 2004; Meyer and Carlson, 2001). Rapid germination and quick growth might, in that case, be attributed to initial large food reserves in seeds (Khan, 2004; Foster, 1986; Fandohan et al., 2010b).

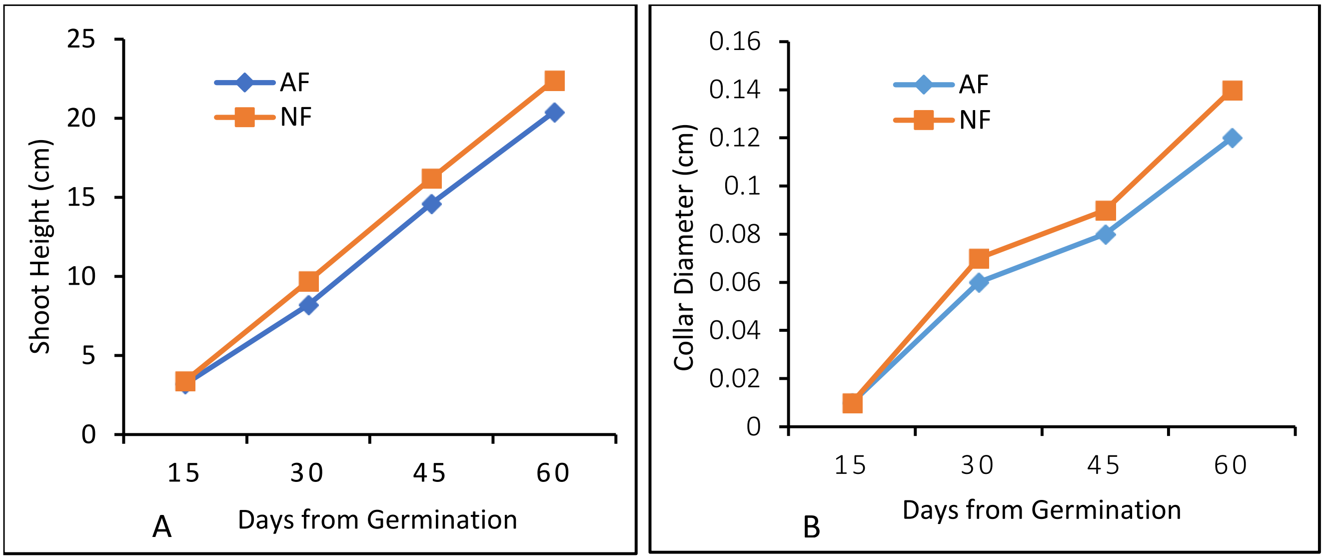

Figure 4. Evolution of mean value for A. shoot height (cm), B. collar diameter (cm), of *T. indica* according to the number of days from germination (AF: Agroforestry, NF: Natural Forest).

3.4. Enumerations of *T. indica*

Based on the measurement of a total of 30 tree species, including *T. indica*, from both agroforestry systems and natural forests. The average tree height (m) was highest in the natural forest (NF) with a value of 23.6 ± 0.32, while in the agroforestry system (AF), it was 22.8 ± 0.70 (Figure 5). The average crown diameter was found to be maximum in the natural forest. The mean value of DBH growth was higher in the natural forest (NF) with a value of 186.26 ± 3.7, compared to the agroforestry system (AF) with a value of 181.6 ± 4.8.

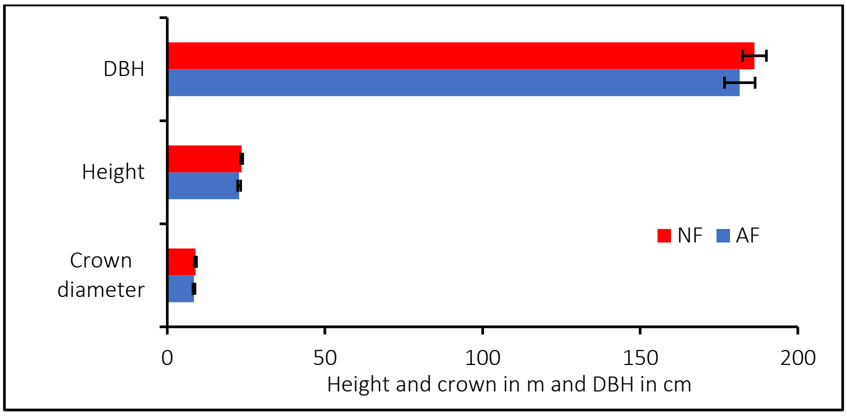

Figure 5. Encountered *T. indica* tree species parameter of Natural Forest (NF) and Agroforestry system (AF).

4. Conclusion

The research findings highlight differences in the morphological characteristics of *T. indica* between agroforestry and natural forest environments. These differences include various growth parameters and traits that were examined in the study. The study demonstrates that *T. indica* trees exhibited superior growth in natural forest conditions compared to agroforestry settings, particularly in a nursery context. This observation suggests that the natural forest environment provides more conducive conditions for the overall growth and development of *T. indica* trees. Specifically, the average height and DBH of the selected *T. indica* trees were significantly higher in the natural forest system compared to the agroforestry system. This indicates that *T. indica* trees in natural forests tend to attain greater height and exhibit thicker trunks than those grown in agroforestry settings. Interestingly, while there were pronounced differences in height and DBH between the two environments, the crown diameter of *T. indica* trees appeared to be relatively consistent and homogenous across both the natural forest and agroforestry sites. This suggests that the crown development of *T. indica* might be less influenced by the type of environment it is grown. The research findings have practical implications for agroforestry practices and conservation efforts involving *T. indica*. If agroforestry systems aim to optimize *T. indica* growth, strategies may need to be refined to replicate some of the favorable conditions found in natural forest environments. Moreover, the study contributes to the broader understanding of genetic diversity and variability within *T. indica* populations in the Bilaspur region. This study on the genetic diversity and variability of *T. indica* in the Bilaspur region sheds light on the significant morphological variations of this tree species between agroforestry and natural forest systems.

Author Contributions: Conceptualization: Ankit Ojha, Shiv Shankar Dhuria; Data curation: Ankit Ojha; Investigation: Ankit Ojha, Shiv Shankar Dhuria; Methodology: Ankit Ojha, Arun Kumar Shukla, Shiv Shankar Dhuria; Resources: Shiv Shankar Dhuria; Software: Arun Kumar Shukla, Alok Kumar Chandrakar; Supervision: Shiv Shankar Dhuria; Validation: Ankit Ojha, Arun Kumar Shukla; Visualization: Arun Kumar Shukla, Alok Kumar Chandrakar; Writing – original draft: Ankit Ojha, Arun Kumar Shukla; Writing – review & editing: Shiv Shankar Dhuria, Alok Kumar Chandrakar. All authors have read and agreed to the published version of the manuscript.

Funding: Not applicable.

Acknowledgment: The authors are grateful to Guru Ghasidas Vishwavidyalaya, Bilaspur for providing necessary facilities to conduct this research.

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: The study was approved by the National Commission for Science, Technology, and Innovation and the School Graduate Studies of Kibabii University, Kenya.

Data/Supplementary Information Availability: Not applicable.

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