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Original Article

Inosculation in *Terminalia pendula*—A Beneficial Trait for Devising Green Infrastructure to Mitigate Climate Change: A Case Study from Bundelkhand Region of Uttar Pradesh, India

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ABSTRACT

Natural connections (inosculations) by fusion of the vascular systems of two stems, branches, or roots allow trees to share water, nutrients, and photosynthesis products and influence tree growth, physiology and survival. Such inosculation may depend on tree proximity, stalk thickness, and environmental factors. How the occurrence of inosculation in *Terminalia* pendula stalk is influenced by tree girth classes, density, and topography in Akbarpur forest of Banda district, Uttar Pradesh, India was investigated. Observations were population of different tree species, girth at breast height (GBH) categorized into <30 cm, 30–60 cm, and >60 cm girth classes, number of inosculated trees, and height of inosculation joint in 20 plots of size 0.1 ha laid in pediment, hillslope, and hilltop areas. T. pendula was the dominant species with 84.5% population (286.5 tree ha^{-1} in 319.5 tree ha^{-1} total population) and IVI value 187.8 among 18 species from 13 families. This species only showed inosculation. Population of all species combined, and total and inosculated T. pendula trees, and GBH were highest ($p < .05$) in the pediment and 30–60 cm girth class. Population density and inosculation height were lowest on the hilltop, whereas GBH was lowest on the hillslope. The frequency of inosculated trees varied from 7.7 to 22.0% (hilltop-pediment) in topographical conditions and from 10.0 to 19.1% (<30 cm—30–60 cm) in girth classes and were positively influenced by tree density and GBH of T. pendula. This signifies the importance of tree density and GBH in promoting inosculation by supporting a closed canopy and rubbing the bark under wind action. Thus, inosculation appears an advantageous trait to arborists for developing green infrastructure in urban areas by promoting closed canopy plantations. However, physiological connectivity and mechanical insight of the stems/branches of this species require to be studied by conducting further research.

Keywords: Dry region, girth class, Kardhai, self-grafting, topographical condition

Introduction

Nature-based solutions are important strategies and actions for promoting biodiversity and their systematic utilization and integration in urban planning. Growing urbanization, changes in the landscapes and ecosystems, and the various challenges posed by climatic changes are foremost architects. These altogether inspire landscape designers to rely more on nature-based solutions in devising urban green infrastructure (EEA 2021; Middleton et al., 2023; Ravishankar and Ji 2021). Architects and designers throughout the globe have been involved in designing living trees by shaping or merging trees in recent decades (Arbona et al., 2003; Bowler et al., 2010; Kirsch 1996; Ludwig 2016; Reams 2005; Tan et al., 2016). Increased attention is also being paid to enhancing ecosystem services in urban areas like amelioration in environmental conditions, carbon storage, removal of air pollutants, and reduction in surface runoff through a network of high-quality natural areas such as street trees, parks, and urban forests (Aram 2019; Kuehler et al., 2017; Nowak & Crane 2002; Rahman et al., 2020; Rötzer et al., 2019; Sturiale & Scuderi 2019). Living trees have also been converted into artificial architectural structures in some urban areas while preserving their ecosystem services (Ludwig et al., 2019a; 2019b; Smolina 2020). Approaches are to design chairs and other furniture in plantations by shaping and grafting trees (Oommen, 2021). Light pruning and shaping individual trees are methods of arboriculture to prevent undesirable development in maintaining traffic safety along roads and preserving the vitality of the trees. Sometimes, stems, branches, or roots of trees join and merge into new physiological units with mechanically strong connections and are adaptations in living trees to support structural loads (Middleton et al., 2020). This phenomenon is known as 'inosculation' or self-grafting (Gaut et al., 2019; Luley 2015).

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Inosculation is a natural process among trees growing in proximity. When trunks, roots, or branches come in close contact, they gradually fuse together (Gaut et al., 2019). The cambium of the two branches touches and self-grafts after gradual abrasion due to wind action, growing conjointly as they swell in diameter (Wang et al., 2020). Such trees respond by producing callus tissue that grows outward and increases the pressure between the two trees. Inosculation is different from grafting because it is a naturally occurring phenomenon, whereas grafting is a technique used to cultivate horticultural and ornamental plants. The word is derived from the Latin word *Osculari*, which means "to union" or "to touch closely." Living root bridges are functional load-bearing structures grown from *Ficus elastica* roots by the rural people in the Khasi and Jaintia communities in Meghalaya, India. They are the best examples of inosculation (Rathnayake, 2021). Inosculation usually occurs between trees of the same species, but it also occurs between trees of different species (Ribelin, 2023). Examples of inosculations between different species include *Tamarindus indica* and *Ficus religiosa*, and between *Ficus religiosa* and *Pithecolobium dulce*/*Azadirachta indica* and in *Ficus benjamina* respectively (Fig. 1). The less common occurrence of this phenomenon between trees of different species is due to a weak union of the conductive tissues. This type of natural grafting is more common between roots compared to branches and trunks (Mylo et al., 2023). Inosculated trees reinforce mechanical support and exchange water, nutrients, and photosynthates through the extended common root system (Fraser et al., 2006; Bader & Leuzinger, 2019). Bormann and Graham (1959) have quantified the natural root grafting process in the roots of *Pinus strobus* based on physiological observation with dyed water, while Basnet et al. (1993) demonstrated the interconnection in large roots of *Dacryodes excelsa* that provided additional support and stability to the trees. Quer et al. (2020) recorded the frequency of root grafting in *Abies balsamea* (L.) Mill by measuring the number of roots and grafts per tree, and the diameter and age of all stems, roots, and grafts using dendrochronology techniques. They found connected roots that occurred early in stand development and continued throughout the life of the stands. The number of roots per tree and distance between trees were the best predictors for root grafting (Quer et al., 2020). This phenomenon facilitates the redistribution of resources between trees by a common root system, resulting in increased tree growth and delayed tree mortality (Adonsou et al., 2016; Tarroux and DesRochers, 2011). Inosculation in roots has been reported in nearly 200 perennial woody species of diverse habitats (Bormann 1966).

Slater (2018) reported above-ground inosculation in deciduous trees, i.e., 6.6% of bifurcations of similar-sized branches. Shu and Ludwig (2023) have devised a tool to forecast the relative girth growth of different segments in inosculated structures based on topological skeletons and validated the results with a set of photographs of inosculated tree structures covering 80 years of growth in Scotts Valley, USA (Katola & Goy 2015). A study was also performed on morphometric investigations of inosculation in *Salix alba* L., *Platanus* × *hispanica* auct. non-Mill. ex Münchh., nom. dub. (a hybrid of *Platanus orientalis* and *Platanus occidentalis*), *Acer platanoides* L., *Betula pendula* Roth, and *Alnus glutinosa* (L.) Gaertn. (Mylo et al., 2023). Some common species prone to inosculation are *Tsuga canadensis* (Eastern hemlock), *Pinus strobus* (eastern white pine), Acer spp. (maples), Betula spp. (birches), Fraxinus spp. (ashes), *Fagus grandifolia* (American beech), *Ficus elastica* (India rubber plant), *Hesperocyparis arizonica*, *Ficus religiosa, Azadirachta indica*. etc (Baldwin 1938; Mylo et al., 2023; Pillai & Palani 2022; Vallas & Courard 2017; Verrier 2022). Most of these species are from temperate or tropical moist regions and are rarely reported for trees of tropical dry regions like Terminalia pendula (Edgew.) Gere & Boatwr (Kala Dhaora or Kardhai), which generally grow in tropical dry deciduous forests (Singh et al., 2007; Verma & Pal 2019). Furthermore, we did not find the effects of different girth classes of the trees and topographical positions on the incidences of inosculations.

Hence, this observation on inosculation in Kardhai (*Terminalia pendula*) focused on varying topography like pediment, hillslope, and hilltop in the Akbarpur forest block in the Banda Forest Division, Uttar Pradesh, and is the first report on this species. The objectives were to quantify the occurrence of inosculation in this species influenced by hill topography and tree girth classes for utilizing its potential in creating green artificial architectural structures in urban areas of dry regions.

Material and Methods

Study Area

The study was conducted in a hilly tract of the Akbarpur forest block of the Banda Forest division, located at 25°18′27.81″ N and 80°22′02.11″ E and 170 m above mean sea level. This is a hill forest with clear topographical differentiation (strata) like pediment, hillslope, and hilltop, covering an area of about 60 ha. The pediment, hillslope, and hilltop cover about 35 ha, 14 ha, and 10 ha, respectively. The orientation of the hills is southwest to northeast, and the aspect of the study is southeast (Fig. 2). Banda district is one of the seven districts of the Bundelkhand region of Uttar Pradesh. Banda district experiences a hot and humid climate, and May is the hottest month when mercury shoots up to 47.5°C. January is the coldest month, with the lowest temperature dropping down to 5.8°C. The average annual rainfall of the district is 902 mm (https://banda.nic.in). However, most rain falls during the monsoon months of June to October. Average hourly wind speed experiences significant seasonal variation. The windier part of the year is from April to August with average wind speeds of >12.2 km h^{-1}. The windiest month of the year is June, with an average wind speed of 16.1 km h^{-1}. The lowest average hourly wind speed of 8.2 km h^{-1} is from September to April. The forest of Banda district is typically dry deciduous mixed forests covering about 600 km^2 area of the district. Main forest species found in the forests of this region are: *Tectona grandis* (Teak), *Terminalia anogiessiana* (Dhou), *Terminalia pendula* (Kardhai), *Dyospyros melanoxylon* (Tendu), *Senegalia catechu* (Khair), *Butea monosperma* (Palash), *Dendrocalamus strictus* (Bamboo), *Phyllanthus emblica* (Amla), *Terminalia belirica* (Bahera), *Aegle marmelos* (Bel), *Terminalia arjuna* (Arjun), *Madhuca longifolia var. latifolia* (Mahua), *Moringa oleifera* (Seja), *Buchanania cochinchinensis* (Chironji), etc. *T. pendula* is a medium-sized, drought-resistant, windfirm, and multipurpose tree growing widely in rocky and hilly areas (Rai & Rai 2009). It is a species of edaphic climax that comes in the form of a pure crop. Major soil types in Banda district are Rakar, Mar, Kabar, and Paduat. Black cotton soil is prominent in the central part of the district.

Observation Recording

This study was conducted during 2022–2023 after laying out sample plots of 0.1 ha (31.6 m × 31.6 m) size. The total area was stratified into three strata based on topographical conditions like pediment, hillslope, and hilltop, and sampling plots were allocated proportionally in each stratum (Kefalew et al., 2022). There were 12 sample plots in the pediment area and four plots each in the hillslope and hilltop areas. Thus, a total of 20 sample plots were laid out covering three topographical areas of the hill. All the tree species available in the plots were counted and measured for girth at breast height (GBH) and categorized further into different girth class like <30 cm, 30–60 cm and >60 cm. Observation on inosculation were recorded, and the height of the inosculation joint was also recorded for the inosculated trees, i.e., from the ground level (Fig. 3). Observations recorded were inosculation between branches or trunks of the trees, whether in the same species

Figure 1.
Inosculation in Different Species: (A) Ficus religiosa and *Tamarindus indica, (B) Ficus benjamina,* and *(C) Pithecolobium dulce/Azadirachta indica* and *Ficus religiosa.*

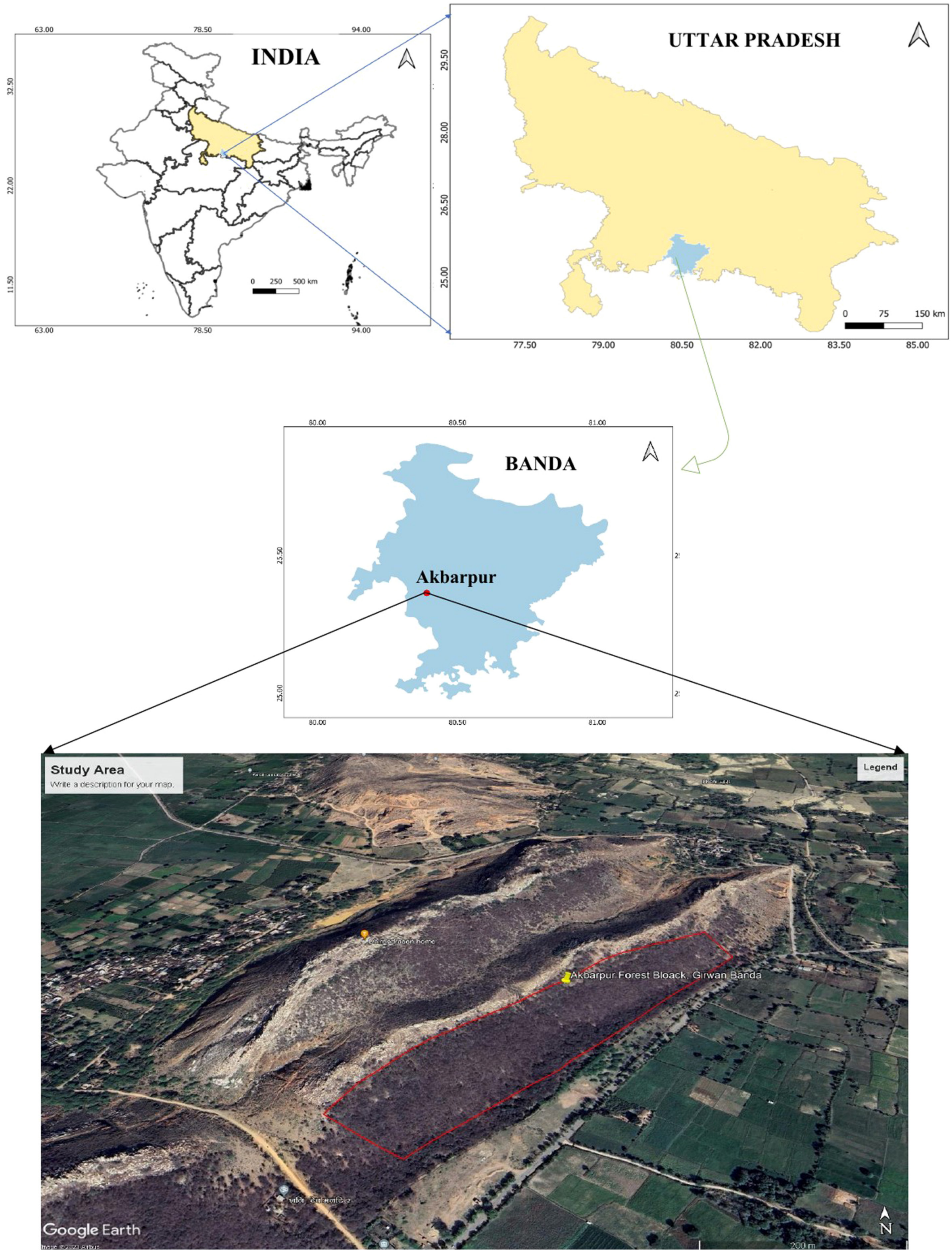

Figure 2.
Aerial View of the Study Area in the Akbarpur Forest Block of Banda district, Uttar Pradesh.

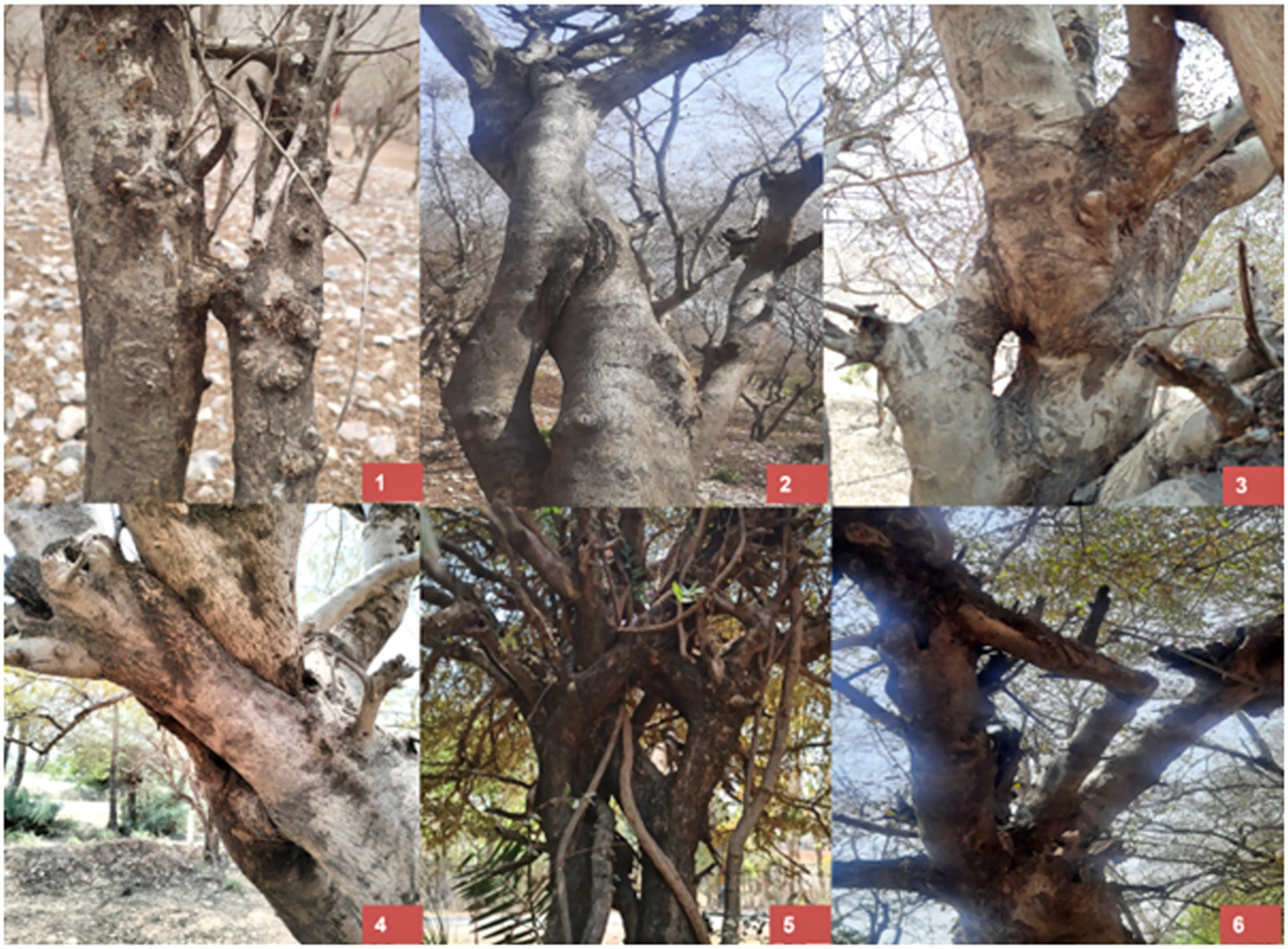

Figure 3.
Images 1–6 Show Varying Levels of Inosculation in Terminalia pendula *in Akbarpur Forest Block of Banda, Uttar Pradesh.*

or between different species. All the species observed in the sample plots were identified based on the available flora of the region (Naithani 2018; Sinha & Shukla 2004).

Data Calculation and Analysis

Populations of all species were added to make a combined population. Other data are inosculated, non-inosculated, and total population of *T. pendula* trees. These populations are presented as numbers per hectare (nos ha^{-1}) after multiplying the sum of recorded populations in all three girth classes by 10. The total population of *T. pendula* was also presented as a percent contribution to the combined population of all species, whereas the inosculated population is presented as a percent of the total population of *T. pendula*. The Importance Value Index (IVI) of each species was estimated as IVI = RD + RD + RF, where RD is relative density calculated as the number of a given species expressed as a percentage of all species per unit area, RD is relative dominance defined as the basal area per species per unit area, and RF is relative frequency (per ha) estimated as the proportion of plots in the area where the species occurred at least once. The IVI, which was developed by Curtis and McIntosh (1951), was used in this study as a proxy for the ecological importance of different species and the composition of dominant species in this hilly tract of the Bundelkhand region.

Data were analyzed using the Statistical Package for Social Sciences version 20.0 software (IBM Corp.; Armonk, NY, USA). All data such as total population, inosculated population, non-inosculated population, percent inosculation, and inosculation height of *Terminalia pendula* trees were analyzed using two-way ANOVA. Different topographical categories and girth classes were the main factors, and each data set was the dependent variable. Duncan multiple range tests (DMRT) were applied to categorize various parameters into homogeneous subsets based on topographical regions and girth classes at $p < .05$ level. Pearson correlation was also performed to determine the relationship between different variables.

Results

Phytosociology

A total of 18 tree species belonging to 13 families were recorded in the study area (Table 1). *Terminalia pendula* was the dominant species with the highest importance value index (IVI) and more than 50 in relative density, relative frequency, and relative dominance. It was followed by *Ficus religiosa* (28.51), *Madhuca longifolia* (23.30), and *Azadirachta indica* (16.04). Other species were *Vachellia leucophloea*, *Dolichandrone falcata*, *Prosopis juliflora*, *Azadirachta indica*, *Limonia acidissima*, *Vachellia nilotica*, *Aegle marmelos*, *Wrightia tinctoria*, *Zizyphus xylopyrus*, *Alangium*

Table 1.
Importance Value Index (IVI) of the Tree Species Recorded in Akbarpur Forest Block of Banda District, Uttar Pradesh

S No.	Tree Species	Family	Relative Density	Relative Dominance	Relative Frequency	IVI
1	*Aegle marmelos*	*Rutaceae*	0.07	0.03	0.03	0.13
2	*Alangium salviifolium*	*Cornaceae*	0.74	0.12	0.12	0.98
3	*Azadirachta indica*	*Meliaceae*	4.71	5.66	5.66	16.04
4	*Butea monosperma*	*Fabaceae*	4.26	2.45	2.45	9.17
5	*Diospyros melanoxylon*	*Ebenaceae*	3.24	3.25	3.25	9.74
6	*Feronia lemonia*	*Rutaceae*	0.37	2.59	2.59	5.54
7	*Ficus religiosa*	*Moraceae*	0.07	14.22	14.22	28.51
8	*Madhuca longifolia*	*Sapotaceae*	0.81	11.25	11.25	23.30
9	*Melia azedarach*	*Meliaceae*	0.07	0.27	0.27	0.61
11	*Morinda coreia*	*Rubiaceae*	0.37	0.43	0.43	1.22
12	*Phoenix sylvestris*	*Arecaceae*	0.22	3.19	3.19	6.60
13	*Prosopis juliflora*	*Fabaceae*	0.74	0.47	0.47	1.67
14	*Stereospermum chelonoides*	*Bignoniaceae*	0.59	0.66	0.66	1.90
3	*Terminalia pendula*	*Combretaceae*	79.56	54.12	54.12	187.80
15	*Vachellia leucophloea*	*Fabaceae*	0.07	0.25	0.25	0.57
16	*Vachellia nilotica*	*Fabaceae*	1.47	0.04	0.04	1.54
17	*Wrightia tinctoria*	*Apocynaceae*	2.43	0.91	0.91	4.25
18	*Zizyphus xylopyrus*	*Rhmnaceae*	0.22	0.10	0.10	0.42

salvifolium, *Morinda coreia*, etc., with IVI less than 10. The least dominant species was *Aegle marmelos,* with IVI value of 0.03. Out of these 18 tree species, inosculation was observed in *T. pendula* only.

Tree Population

The combined population of the site involving all species was 319.5 trees ha^{-1}. In this, the population of *T. pendula* was 286.5 trees ha^{-1} (i.e., 84.5%). Tree population varied significantly ($p < .01$) both due to both topographical positions and tree girth classes (Table 2). The combined population of all species across girth classes ranged from 135.0 trees ha^{-1} in hilltop to 470.0 tree ha^{-1} in pediment area. This variation for *T. pendula* trees was from 97.5 trees ha^{-1} in hilltop to 444.1 trees ha^{-1} in the pediment area. The contribution of *T. pendula* in the combined population varied ($p > .05$) was 77.0% on hilltop to 91.1% in the pediment area. Thus, the population of other species (all species—*T. pendula*) increased the most in the hilltop area. While considering girth class across the topographical positions, the combined population was highest (i.e., 566.7 trees ha^{-1}) in the 30–60 cm girth class. It was lowest for trees of >60 cm girth class. In girth classes, the contribution of *T. pendula* in the combined population ranged between 74.7% in <30 cm and 97.6% in 30–60 cm girth class. Topography × girth class interaction was significant ($p <$ .01). Total as well as *T. pendula* populations were highest in the 30–60 cm girth class in the pediment area, and the lowest values were in >60 cm girth class on the hillslope area (Table 2).

Girth Class Distribution

Girth at breast height (gbh) of *T. pendula* varied from 14 cm to 133 cm, with an average gbh of 45.3 cm. Out of 809 trees of *T. pendula* measured, the highest population was in the 30–60 cm girth class, and the lowest was in >60 cm girth class (Fig. 4a). Girth at breast height showed a sigmoidal growth pattern at the site (Fig. 4b). There were significant variations in gbh of *T. pendula* due to both topographical positions ($p < .05$) and girth classes ($p < .01$). Among the topographical positions, the average gbh (42.8 cm) of trees was lowest ($F_{2/56} = 417$, $p < .05$) in the hillslope area. Girth at breast height increased by 8.6% on the hilltop and by 9.4% in the pediment area. Among the girth classes, the average gbh was 27.7 cm, 42.3 cm, and 67.9 cm in <30 cm, 30–60 cm and >60 cm girth classes, respectively, showing significant ($F_{2/56} = 428.77$, $p < .01$) variation in tree girth (Fig. 4b). Topography × girth class interaction was not significant ($p > .05$), though lowest and highest gbh was for <30 cm on hillslope and for >60 cm girth class in the pediment area, respectively (Fig. 4).

Inosculation Incidences

Population of non-inosculated and inosculated trees of *T. pendula* varied significantly ($p < .01$) due to both topographical positions as well as tree girth classes (Table 3). While considering topography across the girth classes, population of these categories of *T. pendula* trees was highest ($p < .05$) in pediment area, which did not differ ($p > .05$) significantly from the population on the hillslope. However, populations of non-inosculated and inosculated trees reduced to 24.9% and 9.0% on the hilltop than those in the pediment area, showing a decreasing trend towards the hilltop area. When tree girth classes were considered, non-inosculated and inosculated population of *T. pendula* trees was the highest ($p < .01$) in 30–60 cm girth class. Least population of non-inosculated trees was for the tree of >60 cm girth, whereas the population of inosculated trees was lowest in <30 cm girth class. However, these populations did not differ ($p > .05$, DMRT) between the trees of girth class <30 cm and >60 cm. Topography and girth class interactions were significant ($p < .05$) for non-inosculated population, which was highest in the 30–60 cm girth class present in the pediment area (Table 3). The interaction was not significant ($p > .05$) for the inosculated population, indicating independent behavior of these variables for inosculation. The number of inosculated trees was the highest (52.5±8.2 nos. ha^{-1}) in the 30–60 cm girth class of the pediment area (Table 3).

Table 2.
Population of All Species (Total) and Terminalia pendula *Alone in Akbarpur Forest Block of Banda District, Uttar Pradesh. Values are Mean ± 1SE of Multiple Replications*

	Girth Class (cm)				Two-Way ANOVA	
Topographical Position	<30	30–60	>60	Mean	Factor	*F*
Combined population of all species (nos. ha^{-1})						
Pediment	72.5 ± 12.8	331.7 ± 36.1	65.8 ± 12.3	156.7 ± 24.6^{b}	Topography (T)	9.83**
Hillslope	130.0 ± 14.1	207.5 ± 17.0	16.7 ± 6.7	118.7 ± 25.0^{b}	Girth class (G)	16.06**
Hilltop	77.5 ± 17.0	27.5 ± 8.5	30.0 ± 20.0	45.0 ± 11.0^{a}	T × G	9.63**
Mean	93.3 ± 10.0^{a}	188.9 ± 34.8^{b}	37.5 ± 9.6^{a}	106.7 ± 16.7		
T. pendula population (nos. ha^{-1})						
Pediment	55.8 ± 11.1	323.3 ± 36.0	65.0 ± 12.5	148.0 ± 24.6^{b}	T	10.91**
Hillslope	107.5 ± 17.0	197.5 ± 14.9	13.3 ± 8.8	106.1 ± 24.3^{b}	G	17.85**
Hilltop	50.0 ± 12.2	27.5 ± 8.5	20.0 ± 7.0	32.0 ± 7.0^{a}	T × G	8.83**
Mean	71.1 ± 9.0^{a}	182.8 ± 34.3^{b}	32.8 ± 9.8^{a}	95.5 ± 16.6		
T. pendula population (% of combined population)						
Pediment	77.0 ± 9.8	97.5 ± 1.5	98.8 ± 2.8	91.1 ± 4.1^{a}	T	2.50ns
Hillslope	82.7 ± 5.6	95.2 ± 3.2	79.6 ± 33.3	85.3 ± 8.8^{a}	G	7.39**
Hilltop	64.4 ± 15.6	100.0 ± 0.0	66.7 ± 20.0	77.0 ± 8.1^{a}	T × G	3.89**
Mean	74.7 ± 6.6^{a}	97.6 ± 1.1^{b}	81.7 ± 9.1^{a}	84.5 ± 3.3		

ns, not significant ($p > .05$).
**Significant at $p < .01$.
^{a,b}Non-significant difference ($p > .05$).

However, the percent inosculated population did not differ due to both topographical positions ($p = .094$) and girth classes (Table 3). This ranged between almost 0 and32.0%, with an average value of 16.0%. When topography was considered, the percent inosculated trees were greater in the pediment as compared to the other positions. The lowest value was in the hilltop area. For girth classes, the percent inosculation was greater in the 30–60 cm girth size, closely followed by >60 cm girth class. Topography × girth class interaction was not significant ($p > .05$), though highest values were in >60 cm girth class in the pediment area.

Height of Inosculation Joint

Height of inosculation joint did not differ between slope areas, but varied ($p < .05$) significantly between the tree girth classes (Table 3). Inosculation height ranged between 0.37 m and 3.29 m. When topography was considered, inosculation height was greater in the hillslope area, whereas it was smaller in the hilltop area compared to other areas. For girth classes, inosculation height was significantly ($p < .05$) less in trees of <30 cm girth. The other two girth classes did not differ (DMRT, $p < .05$) in inosculation height. Topography × girth class interaction was not significant ($p > .05$), but inosculation height was greater in the 30–60 cm girth class in the hilltop area (Table 3).

Correlations and Regression between Different Variables

Total population of all species and inosculated, non-inosculated, and *T. pendula* population decreased ($r = -0.303$ to -0.387, $p < .05$) with the increase in altitude (pediment to hilltop). Inosculated trees showed positive correlations with non-inosculated ($r = 0.724$, $p < .01$) as well as the population ($r = 0.812$, $p < .01$) of *T. pendula* trees. Percent inosculated trees showed weak positive correlations with the population of inosculated trees ($r = 0.390$, $p < .01$) and tree girth size ($r = 0.283$, $p < .05$). Inosculation height exhibited positive correlations with the percent population of *T. pendula* ($r = 0.414$, $p < .05$) and girth class ($r = 0.318$, $p = .067$) with the and negative correlations ($r = 0.414$, $p < .05$) with the percent population of other species. However, we did not find correlations between population and topographical position/tree gbh. Regression analysis indicated a linear relationship between total population (TP) and inosculated population (IP) of *T. pendula*, i.e. Y (IP) = 3.8472+0.3217TP ($F_{1/58} = 111.87$, $R^2 = 0.659$, $p < .001$) and between percent tree inosculated (TI) and gbh of *T. pendula* like Y (TI) = 3.847+0.322gbh ($F_{1/53} = 4.618$, $R^2 = 0.080$, $p < .05$) showing positive effects of population/ gbh of *T. pendula* on inosculated population/ percent inosculated trees (Fig. 5).

Discussion and Conclusion and Recommendations

The study site was a diverse forest area due to the availability of 18 tree species with varying populations. However, most of the species were thinly populated, as shown by the IVI of 187.8 for *T. pendula,* with average population of 286.7 trees ha^{-1}. Significant decrease in the total as well *T. pendula* population from the pediment to the hilltop area was due to wide variability in soil resources (i.e., soil depth and soil water) in these topographical areas (Singh et al., 2013; Asanok and Marod, 2016). Though non-significant, the decrease in the percent contribution of *T. pendula* in the hillside and hilltop areas compared to that in the pediment area indicates an increase in the percent contribution of other species in the upper reaches. Furthermore, strong adaptability in this species to varying environmental conditions was also shown by a non-significant difference in percent *T. pendula* population between different topographical positions. However, the highest population and percent contribution of *T. pendula* trees in the 30–60 cm girth class and contribution of other species in the trees of <30 cm girth may change the composition of this forest in the future. Tripathi et al. (2022) observed a decrease in the area under *T. pendula* during 2019 compared to 1981

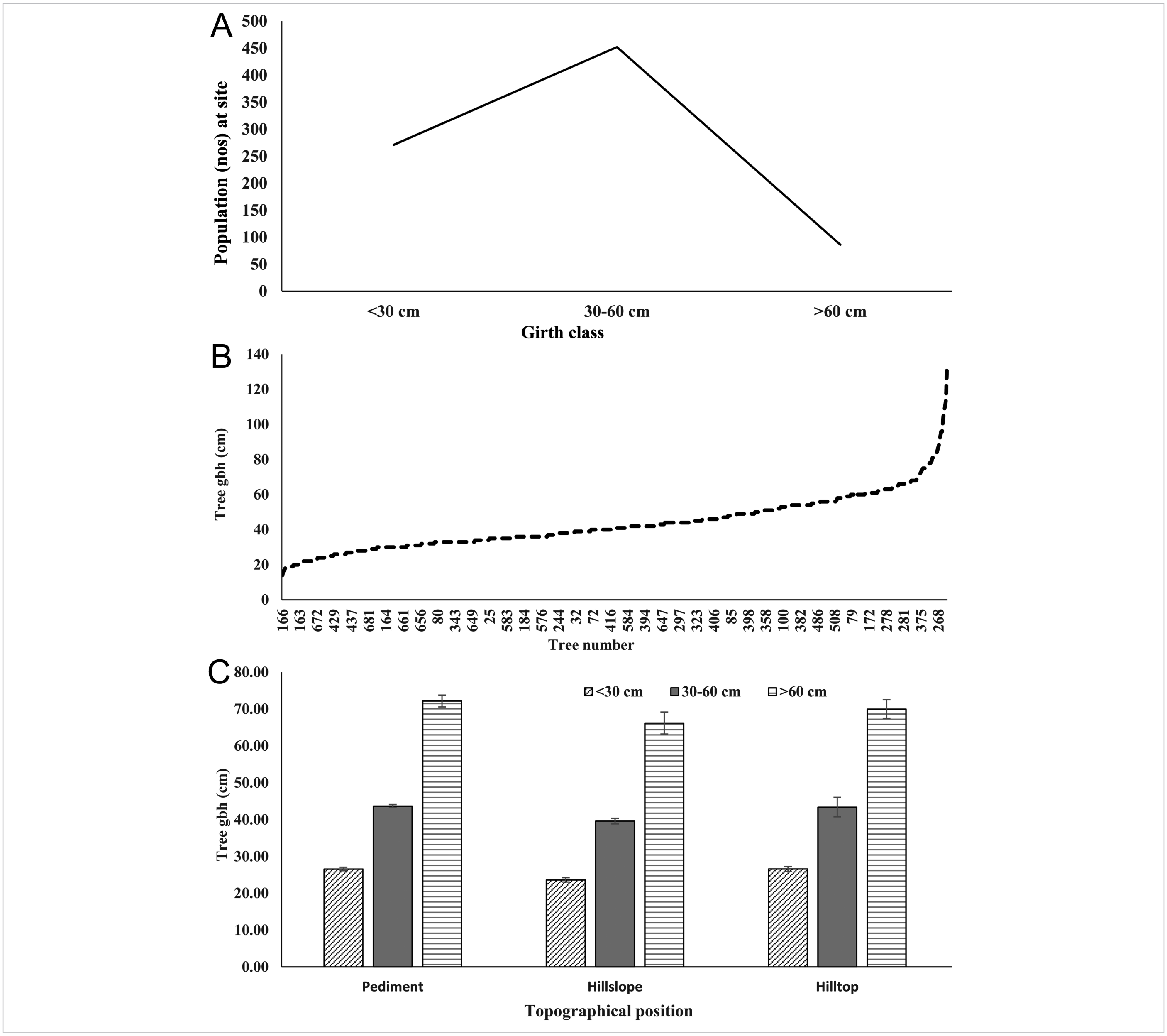

Figure 4.
Growth Pattern of Girth at Breast Height (A), Total Population in Different Girth Classes (B), and gbh of T. pendula Distributed in Different Girth Classes and Topographical Positions (C) in Akbarpur Forest Block in Banda District of Uttar Pradesh. Error Bars Are ±1 SE of Multiple Number of Trees.

due to tree felling, reduced regeneration (low germination capacity of the seeds), and a tendency to die back in the germinated seedlings under drought. Resource-induced growth in *T. pendula* trees was also supported by the highest (46.8 cm) average gbh trees in the pediment area and the lowest of 42.8 cm on the slope area. Agbeshie and Abugre (2021) also observed negative effects of low available soil organic carbon, total N, available P, exchangeable K, and NO_3-N in the upslope position on tree growth in tropical forests of Ghana. However, relatively higher gbh on the hilltop compared to the slope area was due to less population (more growing space) and hence less competition for soil resources on the hilltop area compared to those on the hillside area (Singh et al., 2007; Asanok and Marod, 2016; Pretzsch 2020). According to Singh et al. (2007), a reduction in stand density and the resultant increase in the amount of growing space available to the remaining trees usually stimulate tree growth and the mean diameter increment of the stand. Moreover, effects of wind speeds on height and gbh growth (which declined at higher wind speeds) cannot be ruled out in this region (Bonnesoeur et al., 2016; Telewski 2006). For instance, the canopy height of forests on hillsides exposed to occasional high wind speeds is shorter than those in calmer climates like that of the pediment area (Coomes et al., 2018; Wang et al., 2022). Such wind action might be an important factor facilitating frictions for inosculation observed in *T. pendula*.

The tendency of *T. pendula* tree species to grow close together or have a close canopy has extended the likelihood of inosculation in

Table 3.
Non-inosculated and inosculated population and inosculation height of Terminalia pendula *trees in Akbarpur forest block of Banda district, Uttar Pradesh. Values are mean ±1SE of multiple replications.*

	Girth Class (cm)				Two-Way ANOVA	
Topographical Position	<30	30–60	>60	Mean	Factors	*F*
Non-inosculated population (nos. ha^{-1})`						
Pediment	45.8 ± 9.9	270.8 ± 31.5	44.2 ± 8.0	120.3 ± 21.1^{b}	Topography (T)	8.84**
Hillslope	100.0 ± 20.4	152.5 ± 16.5	10.0 ± 7.5	87.5 ± 19.8^{b}	Girth class (G)	15.25**
Hilltop	47.5 ± 14.4	22.5 ± 4.8	20.0 ± 10.0	30.0 ± 6.9^{a}	T × G	9.25**
Mean	64.4 ± 8.8^{a}	148.6 ± 29.5^{b}	24.7 ± 6.5^{a}	79.2 ± 14.1		
Inosculated population (nos ha^{-1})						
Pediment	10.0 ± 4.6	52.5 ± 8.2	20.8 ± 5.3	27.8 ± 4.6^{b}	T	6.99**
Hillslope	7.5 ± 4.8	45.0 ± 6.4	3.3 ± 2.5	18.6 ± 6.3^{b}	G	10.12**
Hilltop	2.5 ± 1.5	5.0 ± 3.0	0.0 ± 0.0	2.5 ± 51.8^{a}	T × G	2.05ns
Mean	6.7 ± 3.0^{a}	34.2 ± 6.6^{b}	8.0 ± 3.9^{a}	16.3 ± 9.9		
Inosculated population (%)						
Pediment	17.9 ± 6.0	16.2 ± 2.8	32.0 ± 5.1	22.03 ± 2.8^{a}	T	1.51ns
Hillslope	7.0 ± 7.9	22.8 ± 3.9	24.8 ± 20.0	18.2 ± 9.5^{a}	G	0.57ns
Hilltop	5.0 ± 2.5	18.2 ± 10.0	0.0 ± 0.0	7.7 ± 6.1^{a}	T × G	0.67ns
Mean	10.0 ± 4.4^{a}	19.1 ± 2.7^{a}	18.9 ± 6.7^{a}	16.0 ± 2.7		
Inosculation height (m)						
Pediment	1.6 ± 0.15	2.1 ± 0.2	2.1 ± 0.3	1.9 ± 0.1^{a}	T	0.44ns
Hillslope	1.7 ± 1.06	2.0 ± 0.4	3.1 ± 0.0	2.3 ± 0.4^{a}	G	5.16*
Hilltop	0.4 ± 0.00	3.3 ± 0.0	0.0 ± 0.0	1.2 ± 1.5^{a}	T × G	2.10ns
Mean	1.2 ± 0.3^{a}	2.5 ± 0.2^{b}	1.7 ± 0.3^{b}	1.8 ± 0.1		

ns, not significant ($p > .05$).
**Significant at $p < .01$.
*Significant at $p < .05$.
[a,b]Non-significant difference ($p > .05$) for the respective variable.

the species. Increased population density resulted in the closeness of the canopy of individual trees, making the branches come in contact with each other more frequently favouring inosculation (Mylo et al., 2023; Shu & Ludwing 2023). Tarroux et al. (2014) observed a correlation between root grafting frequency and stand type (i.e., greater in naturally regenerated stands), and it appeared principally linked to tree proximity. However, gradual abrasion of the barks of the touching stems or branches under wind action exposes the layer of cambium cells inside the phloem, which promotes self-grafting and joint growth (Pillai & Pillai 2021; Wang et al., 2020). This inference was also supported by a positive correlation ($r=0.812$, $p < .01$) between the population of inosculated trees and the population of *T. pendula* trees. Bark thickness also plays an important role, as thinner bark in species like apple, pear, olive, and beech leads to inosculation at a high frequency (Julia 2017). The highest number of inosculated trees in the pediment area was also due to the dense canopy under high population density and the availability of a higher number of stems/branches in the vicinity of each other, which favored bark abrasions followed by fusion (callusing). A linear relationship ($Y=0.1609X+2.2565$) between inosculated and the total population of *T. pendula* also supports this inference (Fig. 4a). Thus, the decrease in the population of inosculated trees from the pediment (22.0%) to the hilltop (7.7%) area was certainly due to a decrease ($r=0.335$, $p < .01$) in population of *T. pendula* and increase in the openness of the tree canopy. A relatively greater percentage of inosculated *T. pendula* trees on the hillslope compared to the hilltop was due to greater tree density as well as mechanical stimulus caused by wind speed, which promoted bending stresses and contact between the branches of *T. pendula,* stimulating callusing and fusion of the abraded stems/branches (Kelly 2022). This was also supported by the relatively small girth size and greater height of the inosculation joint in *T. pendula* trees on the hillslope as compared to other areas.

Thus, the increase in percent inosculation and inosculation height with the increase in tree DBH, particularly in pediment and hillslope areas, suggests the importance of tree girth in promoting inosculation by increasing canopy size. This was also evidenced by positive correlation ($r=0.383$, $p < .05$) and linear relationship ($Y=0.3217X+3.8472$) between the percent of inosculated trees and tree girth (Fig. 4b). The extent of abrasion is generally influenced by bark thickness (which varies with species) that decreases with the increase in height of the trees. Wilms et al. (2021) also observed a significant effect of diameter at breast height and height on the bark thickness of Scots pine (*Pinus sylvestris* L.), in which diameter was positively and tree height was negatively correlated with bark thickness. Moreover, the highest population and percentage of inosculated *T. pendula* trees in the 30–60 cm girth class exhibited relatively greater suitability of this girth for inosculation. Shu and Ludwig (2023) interpreted genetic constitution, location of the site, tree age, health and size, rate of growth, and position along the bole

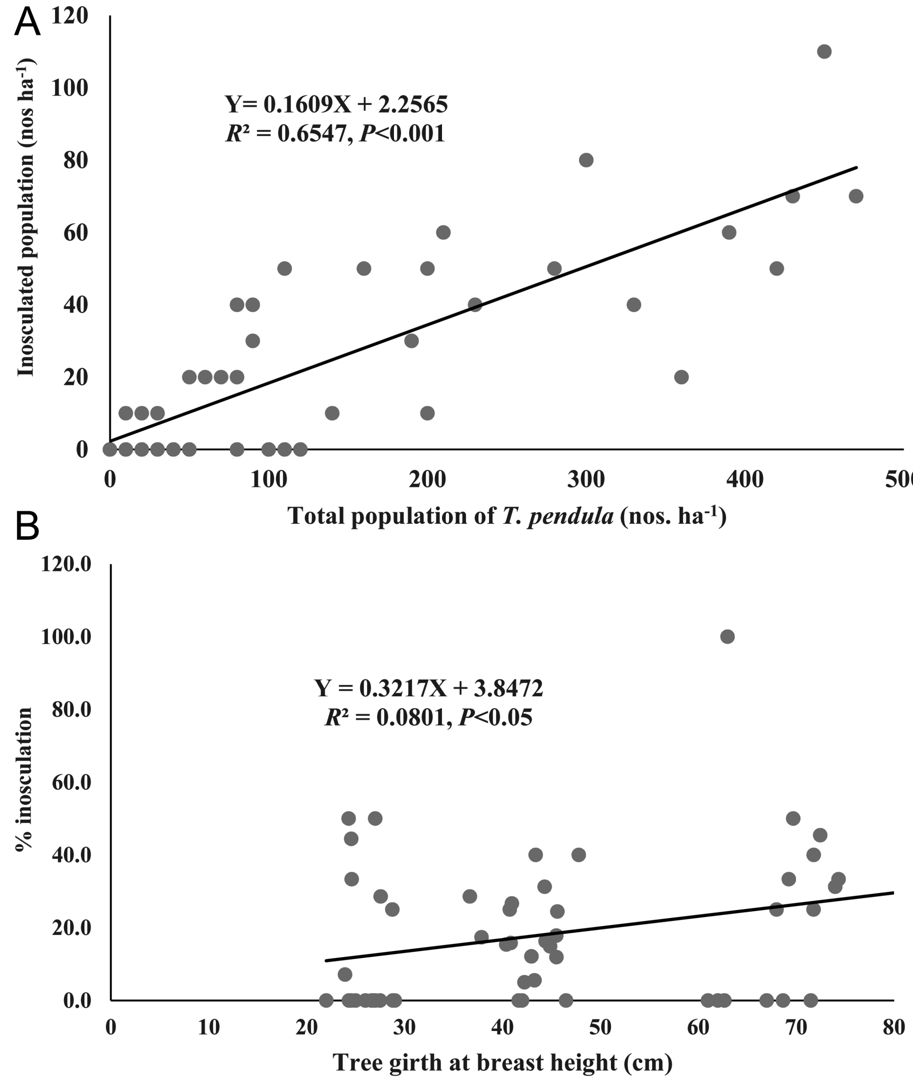

Figure 5.
Relationship Between Total Population and Inosculated Population (A) and Tree gbh and Percent Inosculation (B) in T. pendula in forests of Banda, Uttar Pradesh.

as the factors influencing the trunks, branches, or roots bending and joining to form a complex inosculated network. Such natural processes appeared more useful for artificial living architecture in hardwood tree species, which can adjust to variable environmental stresses like soil water, temperature, frost, and wind velocity and provide aesthetic pleasure (Wang et al., 2020). This indicates that tree density and girth size played a favorable role in inosculation in *T. pendula* species. Hence, this appears to be a suitable species with a thin bark layer and hardy characteristics, fulfilling these requirements and providing itself for exploitation in the inosculation technique to provide nature-based solutions for urban green infrastructure (Meena et al., 2018; Oommen 2021).

The forest block under study was occupied by 18 tree species belonging to 13 families. However, *T. pendula* was the dominant species with an 84.5% contribution to the total population and exhibited the inosculation phenomenon. The population of all species in combination and the total and inosculated population and girth of *T. pendula* were highest in the pediment area and decreased to their lowest values in the hilltop (except tree girth, which was lowest in the hillslope area). Densely growing, closed-canopy *T. pendula* trees provided a condition where branches in proximity abrade together, resulting in the fusion of the exposed cambium/xylem tissues. Though varied between topographical areas influenced by environmental conditions and soil resource availability, tree density and girth size both showed positive effects on inosculation frequency. Thus, naturally occurring self-grafting in *T. pendula* observed in the field may help bypass the lengthy process of cultivating inosculation and devising green infrastructure for the welfare of the urban population and mitigating the effects of climate change effects. Inosculation in this species may be promoted by densely growing *T. pendula* trees of suitable girth and height. However, the physiological connectivity and mechanical insight of the stems of this species require further research.

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