



# Impact of Salinisation on the Neighbour-based Spatial Diversity of Tree Species in the Sundarbans Mangrove of Bangladesh

Md Mizanur Rahman<sup>1\*</sup>

<sup>1</sup>Secondary and Higher Secondary Education Division, Ministry of Education, Dhaka 1207, Bangladesh

\*Correspondence: [rahmanboku@gmail.com](mailto:rahmanboku@gmail.com)

Received: 03/01/2026

Accepted: 13/03/2026

Available online: 16/03/2026



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**Abstract:** Climatic stressors, notably increased salinity, influence the vegetation dynamics of the Sundarbans, the largest single block of tidal halophytic mangrove forest in the world. However, their role in the spatial stand structure of trees remains poorly understood. The overall objective of the study was to assess the role of salinity on the spatial diversity of tree species by using some neighbourhood-based variables. Thirty permanent sample plots were classified as low, medium, and high saline areas based on water salinity level for collecting primary data. With the increase of salinisation, the trees started clumping from the random aggregation and dispersion by suffering the loss of species richness and natural regeneration. The highest species was found in the low saline area adjacent to human settlements despite the presence of merciless anthropogenic disturbances like illegal logging. This area also consisted of a handful of size (dbh and height) classes, which in turn described a decent mixture of young, adult, and old-growth trees. Contrarily, the high saline area was inhabited by only adult dwarf trees. Neighbourhood-based variables and methods were proven to be simple, easy, less technical, time-saving, and non-expensive, which can articulate the spatial dimensions of a complex ecosystem. Immediate mitigation actions are warranted to maintain the status quo and to protect from further degradation. The species-centric spatial dimensions should be examined further to measure the impact of stressors on the spatial pattern of each species.

**Keywords:** Climate change: Neighbourhood analysis: Aggregation: Dispersion: Regularity: Clumping: Size differentiation.

## INTRODUCTION

The Sundarbans (Bangladesh, 60% and India, 40%) are the World's largest tidal mangrove and delta system (Chowdhury et al. 2024; Rogers and Goodbred 2014). It is a Ramsar Wetland Site and World Heritage Site (Bhargava Gajre et al., 2024; Roy et al. 2018; Sarker et al. 2016) that supports luxuriant biodiversity (Gopal and Chauhan 2006; Islam 2019; Sarker et al., 2019) and multiple ecosystem services (Bera et al. 2022; Chakraborty et al. 2009; Ghosh et al., 2016; Dasgupta et al., 2020; Titumir and Shah Paran 2022). In a botanical survey, Prain (1903) enumerated 334 plant species in this mangrove. This mangrove is a habitat of aquatic animals including dolphins (Aziz and Paul 2015); birds (Chowdhury 2020); amphibians, including crocodiles (Gopal and Chauhan 2006; Smith et al. 2010); reptiles (Saha and Sarkar 2022); mammals including the Bengal Tiger (Mukul et al. 2019; Rahman 2023); crustaceans (Borrell et al. 2019); algae (Aziz and Paul

2015); phytoplankton (Aziz et al. 2012); zooplankton (Basu et al. 2022); and benthic invertebrates (Begum 2017).

Hydrological changes modulate the ecosystems of this mangrove, which is interlinked to the Bay of Bengal, and river discharges (Sarker et al., 2021; Ahmed et al., 2023; Rahman 2023a). The Sundarbans mangrove encounters anthropo-climatic stressors like sea level rise (Hazra et al. 2002; Loucks et al. 201; Jabir et al. 2021; Mondal et al. 2021; Payo et al. 2016, Samanta et al. 2021, Rahman 2023c), frequent cyclones (Mondal et al. 2022; Mandal and Hosaka 2020; Halder et al. 2021; Dutta et al. 2015, Rahman 2023d); increased salinity (Nandy et al. 2007; Dasgupta et al. 2010, 2012, 2014, 2018) and changes in seasonal pattern (Ghosh et al. 2017; Giri et al. 2007). On the other hand, massive anthropogenic disturbances like encroachment (Islam et al. 2018; Iftekhar and Hoque 2005; Ortolano et al. 2016), illegal logging (Giri et al. 2007; Aziz and Paul 2015; Emch & Peterson 2006; Reddy et al. 2016); poaching (Aziz et al. 2017; Saif and MacMillan 2016; Hossain et al. 2018),

piracy (Saif and MacMillan 2016; Cons 2021) orchestrated wildfire, and poisoning of the wetland (Chowdhury et al. 2007; Weiss<sup>o</sup> 2003; Das 2013; Rahman 2022) are worsening the scenario. The recently introduced co-management added extra pressures on the ecosystem (Rahman 2021, a; Rahman 2008; Rahman 2022a; Rahman and Islam 2018). Among these stressors, increased salinisation is considered a silent disaster and the most prominent factor affecting biodiversity, notably plant communities in this mangrove of Bangladesh (Rahman 2020). Consequently, this study will focus on the impact of incremental salinity on the tree community.

The Sundarbans is a transitional territory between the freshwater rivers originating from the Ganges and the Bay of Bengal (Rogers and Goodbred 2014; Subramanian et al. 2023; Jayanthi et al. 2023; Hossain et al. 2023). The *Farakka* barrage in the Indian Territory (since 1975) on the upper stream has substantially reduced freshwater discharge from the main distributary river to the Sundarbans (Uddin et al. 2024; Paszkowski et al. 2021; Bain et al. 2019). Frequent tropical cyclones cause saline water intrusion into the Sundarbans over and over again (Chowdhury et al. 2023; Rahman 2020). Consequently, the previous freshwater sources are transmuting into saline water bodies. The salinity is exaggerated by tiger prawn culture in the coastal areas of Bangladesh (Bhowmick et al. 2016; Chowdhury and Maiti 2016; Szabo et al. 2016). The encroachers exploit the government-owned canals for tiger prawn culture. The blockades in these canals immobilise the free flow of water, which increases salinity gradually (Rahman 2020). Brackish culture requires long stagnation of saline water, which causes the concentration of salinity around the plant root zone (Rahman 2020).

The pioneer, indicator, and dominant species of Sundarbans are suffering from increased salinity due to 'top dying' disease, and biological invasion (Biswas et al. 2007; Rahman and Vacik 2016). Currently, the fresh swamp forests are no longer in their historical range (Rahman 2020). On the other hand, a few plant species became locally extinct and stand on the brink of extinction. The salt-loving plant species are enjoying the hegemony over the pioneer species. Resultantly, ecoregional changes occur very rapidly by affecting the dominance, distribution, composition, structure, and growth of the plant species (Chapman 1976; Rahman and Vacik 2015). Excessive salinity degrades water and soil characteristics, which reshapes the physiological behaviour (Nandy (Datta) et al. 2007), biochemical traits (Dasgupta et al. 2010), and genetic polymorphism (Dasgupta et al. 2018) of the plant species. On that account, adaptability, natural regeneration, and growth of the plants are altered (Dasgupta et al. 2012). Salinity tolerance level among the plant species oscillates broadly (Rahman 2023d).

Climate change exerts an influence on the temporal and spatial distribution of the species. (Mukherjee & Siddique 2024; Pearson & Dawson 2003). There is some literature regarding the temporal effect of salinity on plant diversity, notably species richness and composition of the Indian part

of the Sundarbans, but it is rare in Bangladesh's part. The Sundarbans are unique in terms of species richness, community composition, and stand structure (Azad et al. 2022; Chanda et al. 2016; Mukhopadhyay et al. 2018). Together with species diversity, the stand structure of Sundarbans is very important for carbon storage in the mangrove ecosystem (Rani et al. 2016; Azad et al. 2020). New studies are required to understand the effect of climatic stressors on various dimensions of the stand structure of this mangrove. The spatial stand structure pinpoints the spatial distribution, dimensions, arrangement, and mingling of the different tree species (Aguirre et al. 2003, Rahman et al. 2008a). It not only determines species diversity, species composition, and horizontal and vertical variation but also stressors' effects within the forests (Helms 1998; Aguirre et al. 2003; Rahman et al. 2008). Simultaneously, it helps to understand how the species are arranged in a space (Rahman et al. 2007a, b). The studies regarding the effect of salinity on the above-mentioned characteristics of spatial stand structure, notably dimensions, arrangement, and mingling of different tree species of the Sundarbans, might be absent. Hence, this study strives to bridge the gap.

Lund pair correlations in measuring spatial arrangements require tree coordinates (Aguirre et al. 2003; Pommerening 2002; Pretzsch 2001; Stoyan and Stoyan 1992) together with a large database, which may not always be a practical case (Aguirre et al. 2003; Rahman et al. 2008). Clark and Evans (1954) and Pielou (1969) proposed distant dependent indices to have a glimpse of the spatial arrangements of trees (Zenner and Hibbs 2000). Gadaw (1998) and Staupendahl (2001) came up with single tree-based variables, which are also known as neighbourhood-based variables, and 'measure of surround'. They are used in a quick assessment of the spatial stand structure of a large forest (Pommerening 2002, Graz 2006) and to assess the regularity of neighbouring trees' positions, sizes, and interspersions with reference trees. In a country like Bangladesh, researchers always struggle with funds, large databases, and technical sophistication. It is wise to find affordable, easier, cost-effective, time-saving, and comprehensive assessment techniques. The study also aims to assess the applicability of these neighbourhood-based variables in the Sundarbans of Bangladesh, to assess the role of salinity on mangrove's spatial stand structure.

## MATERIALS AND METHODS

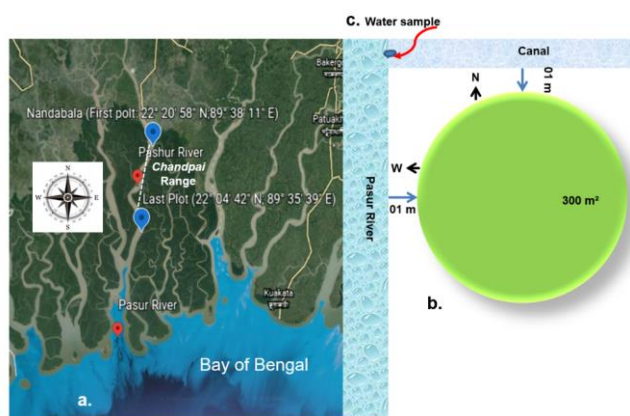
### Study area

Among the 04 administrative ranges of the *Sundarbans* in Bangladesh, the *Chandpai* range was selected for this study. It is located on the left side of the *Pashur* River, which flows in the North-South direction from the central point of this mangrove. This eastern bank is famous for its luxuriant plant diversity. Geographically, the study site was positioned at latitudes 22°04'42" N and 22°20'58" N, and longitudes 89°35'39" E and 89°38'11"E (Fig. 1). It also encompassed an ecologically critical area, a wildlife

sanctuary, a dolphin sanctuary, a crocodile breeding centre, and two tourist spots.

**Sampling**

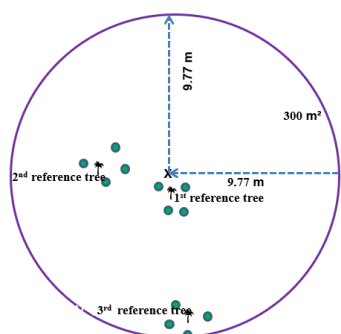
Data was collected from 30 circular, permanently established plots based on salinity levels (low, medium, and high). The plots were established at the intersection of the Pashur River and an equal number (30) of canals. The plots were circular (radius=9.77 m) covering a 300 m<sup>2</sup> area for each. Every plot was surrounded by the Pashur River in the west and a canal in the north. The edge of each plot maintained a minimum of 01 m distance from the high tide water level (Fig. 1). The centre of each surrounding canal's mouth was settled on for saline water collection (Fig.1). The sampling started from the Nandabala canal, the nearest one to the mainland (Joymonirghol), and gradually moved in the south direction. The distances among plots were asymmetrical due to the dependency on the interceptions of canals and the river.



**Figure 1.** 2. a. A Google map showing the study area, b. sampling technique of the vegetation plot, c. water sample point

**Data collection**

A total of 03 reference trees, notably *Sundari* (*Heritiera fomes*), were designated from the centre, middle point, and edge of each vegetation plot (Fig. 2).



**Figure 2.** Selection technique of reference trees and their neighbours from a vegetation sample plot

The most abundant tree species was chosen where *Sundari* was absent. For the neighbourhood variables, the dbh and height of each reference tree and its four neighbouring trees were measured. The angle (smaller or bigger than 90°) between the reference tree and each neighbour was estimated through open eyes. In this context, the reference tree with its four neighbours was termed a ‘group of five (G5)’.

One-litre bottles were used to collect the saline water samples. They were stored in Boston round, made of flint glass, and equipped with a poly seal to prevent leakage and evaporation. Each bottle was rinsed several times with the sample water and then filled to the neck. After filling, all were kept at room temperature. A digital handheld salinity meter was used to measure dissolved salt in the water. The reading was arrayed in parts per million (ppm) and later transfigured into parts per trillion (ppt).

It is a life-threatening issue to collect data physically from this mangrove, a death trap where Bengal Tigers, Marsh Crocodiles, venomous snakes, poachers, pirates, robbers, and wildlife traders reside together. Considering the security issues and lack of funds, the current study’s cornerstone was only water salinity level, paying no attention to other physiochemical parameters of water and soils.

**Data analysis**

For characterising spatial stand structure, four indices: contagion, mingling, height, and diameter differentiation for each plot were measured. The contagion ( $W_i$ ) delineates the degree of regularity of the spatial distribution of the neighbours to a reference tree (Gadow 1998, Staupendahl 2001). The G-5 ( $W_i$ ) provides five possible values (0, 0.25, 0.50, 0.75, and 1).  $W_i$  classifies the angles ( $\alpha_j$ ) between each reference tree and its four neighbours.

$$W_i = \frac{1}{4} \sum_{j=1}^4 W_{ij} \quad W_i \in [0,1]$$

$$W_{ij} = \{1, \text{if } \alpha_j < \alpha_0; 0 \text{ otherwise}\}$$

$W_i = 0$  indicates complete regularity, whereas  $W_i = 1$  an irregular or clumped distribution. Gadow (1998) classified the average contagion value as ‘regular’, ‘random’, and ‘clumped’ distributions. Albert (1999) outlined the mean contagion value greater than 0.6 as ‘clumped’, those with values between 0 and 0.5 as ‘regular’, and between 0.5 and 0.6 as ‘random’ tree distributions.

The mingling ( $M_i$ ) evaluates the species diversity in the vicinity of a reference tree by counting the proportion of the nearest neighbours ( $j=1 \dots n$ ) that do not belong to the same species as the  $i^{th}$  reference tree (Fuldner, 1995).

$$M_i = \frac{1}{4} \sum_{j=1}^4 v_j$$

with

$\begin{cases} 1, \text{neighbour } j \text{ belongs to the same species as reference tree } i \\ 0, \text{otherwise} \end{cases}$   
and  $0 \leq M_i \leq 1$ .

Likewise,  $M_i$  provides five possible values (0, 0.25, 0.50, 0.75, and 1). The arithmetic mean for a particular species of reference tree ( $M_{Sp}$ ) provides a measure of the degree of interspersion of the species in an area. The values close to or equal to 1 indicate a high degree of mingling, i.e., trees of the reference species do not occur in a clumped manner. Inversely, values near or equal to 0 express a low degree of mingling and a high aggregation.

Hui et al. (1998) quantified the size dominance ( $S_i$ ) of the ‘measure of surrounding’ based on diameter (D) and height (H).

$$S_i = \frac{1}{4} \sum_{j=1}^4 S_{ij} \quad S_i \in [0,1]$$

$$S_{ij} = \begin{cases} 1, \text{if tree } j \text{ is thicker or higher than the reference tree } i \\ 0, \text{otherwise} \end{cases}$$

Similarly, considering four neighbours, five possible values (0, 0.25, 0.50, 0.75, and 1) are obtained for S. The average value of S=0 indicates that all neighbours are smaller in size than the reference tree, where the value 1 indicates that all neighbours are taller or have a larger diameter than the reference trees.

Size differentiation index ( $S_{ij}$ ) gives the size difference of neighbouring trees on a continuous scale describing the spatial distribution of tree sizes (Fuldner 1995, Pommerening 1997, 2002). For the  $i^{th}$  reference tree and its  $n = 4$  nearest neighbour  $j$  ( $j = 1 \dots n$ ), the size differentiation ( $S_{ij}$ ) is defined as:

$$S_{ij} = 1 - \frac{\text{Min}(\text{size}_i, \text{size}_j)}{\text{Max}(\text{size}_i, \text{size}_j)} \quad S_i \in [0,1]$$

The value of  $S_{ij}$  increases with increasing average size difference between reference and neighbouring trees.  $S_{ij} = 0$  means that neighbouring trees have an equal size. Pommerening (1997, 2002) interpreted the range value of  $S_{ij}$  in the following way (Table 1). In this study, the size differentiation was defined by diameter differentiation ( $D_{ij}$ ) and height differentiation ( $H_{ij}$ ).

**Table 1.** Size differentiation levels

Range value	Differentiation level
0-0.3	Low
0.3-0.5	Average
0.5-0.7	Big
0.7-1	Very big

SPSS was used for the one-way analysis of variance.

## RESULTS AND DISCUSSIONS

### Effect on the regularity and aggregation of tree species

The water salinity varied significantly in the study area (Table 2). The mean value of water salinity in the high, medium, and low saline areas was 8.93, 11.06, and 13.64 ppt, respectively. The lowest mean contagion value (0.57) was found in the low saline area, indicating a ‘random’ dispersion of trees (Table 2 and Fig. 3). With the increase in salinity, the tendency of clumping of the tree species surged. The high saline area exhibited the highest irregularity of the spatial distribution, while the medium saline area showed a decent clumped dispersion.

**Table 2.** Mean values of neighbour-based indices

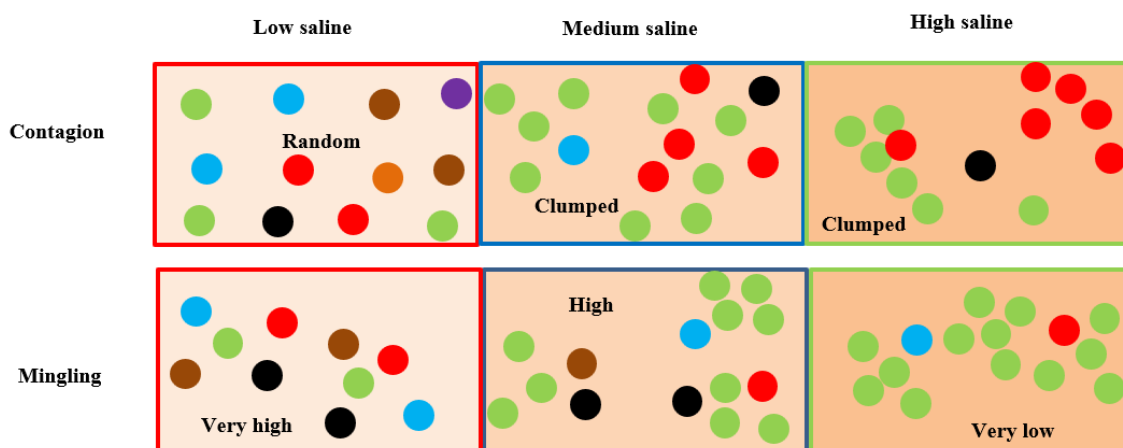
Indices	Low Saline	Medium Saline	High Saline	Test static F	P-Value
Water Salinity (ppt)	8.93±0.49	11.06±0.68	13.64±1.1	86.2	0.00
Contagion	0.57±0.19	0.66±0.17	72±0.14	2.3	0.15
Mingling	0.82±0.19	0.74±0.16	0.07±0.11	71.4	0.00
Height dominance	0.46±0.17	45±0.16	0.41±0.14	0.21	0.81
Diameter dominance	0.49±0.17	0.48±0.16	0.44±0.14	0.308	0.74
Height differentiation	0.63±0.13	0.49±0.20	0.22±0.11	18.9	0.00
Diameter differentiation	0.57±0.11	0.42±0.23	0.21±0.11	11.7	0.00

The abundance of tree species is a detrimental factor for the species dispersion. Rare species prefer random dispersion to avoid intraspecific competition at a local scale (Fangliang et al.1997). It was found that a few historical associate species like *Ora* (*Sonneratia caseolaris*), *Passur* (*Xylocarpus mekongensis*), *Dhundul* (*Xylocarpus granatum*) were sporadically accompanying the *Sundari* (*Heritiera fomes*), the pioneer tree species in the low saline area, while rarely in the medium saline area. For survival, these associate species may tend to be dispersed randomly or uniformly to avoid mortality due to intra- or interspecies

competitions. The spatial pattern is often associated with local density-dependent effects, including mortality caused by the competition among neighbouring species (Fibich et al. 2016; Fangliang et al.1997; Leps & Kindlmann 1987; Stoll & Bergius 2005). The clumped dispersion in the medium and high saline areas indicates greater colonisation of tree species resulting from the rarity of the associate species. Rahman (2020) revealed that salt-loving species gradually replaced the pioneer and dominant tree species of Sundarbans. On the other hand, it also exhibits that natural regeneration is highly affected in the medium and high-

saline areas. The spatial pattern shifts from clumping to random distribution when the tree species moves from juvenile to adult (Fangliang et al. 1997). It can be concluded that high-saline areas represent only mature tree species due to a lack of natural regeneration. Rahman et al. (2009) revealed that natural regeneration was highly associated

with stressors. Perry et al. (2008) reported that clumped aggregation occurs in forests due to regeneration in gaps. Biotic factors, environmental heterogeneity, and dispersal limitation and their combined influence on the spatial pattern (Comita et al. 2007; Fibich et al. 2016; Wiegand et al. 2014).



**Figure 3.** A sketch map showing the spatial dispersion and aggregation of different tree species based on the results

Table 2 shows that the highest average mingling value (0.82) was recorded in the low saline area; in contrast, the high saline area witnessed a sharp decline in that value (0.07). The medium area maintained a consistent mean value (0.74) with the low saline area. The degree of interspersed of the species in an area indicates the degree of species richness. The highest species was found in the low saline area despite the presence of merciless anthropogenic disturbances like illegal logging due to its location near human settlements. Clear felling was also observed in the medium saline area, but the intensity was not as extreme as in the low saline area. The high saline area has almost lost species richness, affecting functional diversity. Ahmed et al. (2023) revealed that salinity critically changed diversity in the *Sundarbans* across salinity eco-zones. The clumped spatial pattern of plant communities is influenced by species richness (Bastias et al. 2020).

The relative abundance of tree species had a robust negative relationship with the salinity level (Rahman 2020). The historical pioneer, dominant, and indicator tree species can survive in a wide range of salt tolerance capacities, but they are not truly salt lovers. They respond physiologically and show abnormal behaviours when the salinity level exceeds 15 psu (Chaudhuri and Choudhury 1994). The infestation rate of ‘top dying’ disease is more prominent in the more saline areas. Seed germination and growth, and other physiological characteristics are highly affected by salinity (Mitra et al. 2004; Santiago et al. 2000; Parida et al. 2003, 2004). Mangrove apple (*Sonneratia apetala*), Grey mangrove, or white mangrove (*Avicennia marina*) show incremental hegemony over the *Sundari* and its associate species due to their highest adapting capacity and salt

tolerance level (Rahman 2020; Reef et al. 2010). They can tolerate high levels of acidity, temperature, and frost (Morrissey et al. 2010). Therefore, it is revealed that these salt-tolerant species colonised in the high saline area, resulting in clumped aggregation and the lowest mingling and species richness. However, it is not conclusive that only salinity regulates the species diversity in a complex ecosystem. Besides, other predictable and non-predictable climatic stressors, along with micro-climate, may affect the species diversity singly or collectively. Despite the absence of data on other anthropogenic and non-anthropogenic perturbations, the results indicate that salinity is the most influential factor that regulates the degree of regularity and aggregation of tree species in this mangrove ecosystem.

### Effect on size dominance and size differentiation

Though the height dominance did not vary significantly in the study area, the highest mean values were observed in the low saline area (0.46), followed by medium (0.45) and high saline area (0.41). It indicates that 46%, 45%, and 41% of neighbours were larger than the reference trees in the low, medium, and high saline areas. Almost the same results were reported for the diameter dominance (Table 2). The size dominance cannot explain how much taller and larger the neighbours were, which is the drawback of this index. To overcome this shortcoming, size differentiation was enumerated. Significantly, the highest height differentiation value (0.63) was found in the low saline area, followed by the medium (0.49). This value (0.22) sharply fell in the high saline area. The diameter differentiation maintained a symmetrical fashion together with height differentiation (Table 2). Based on the

interpretation (Table 1) made by Pommerening (1997, 2002), it is evident that the low, medium, and high saline areas exhibited big, average, and low size differentiation, respectively. The big size differentiation proved that the low saline area consisted of a handful of size (dbh and height) classes, which in turn described a decent mixture of young, adult, and old-growth trees. Likewise, the medium saline area represented an average differentiation, indicating a mixture of young and adult trees. Similarly, the high saline area was comprised of trees with almost similar height and diameter. In the field observation, it was observed that only the adult trees represented the high-saline area. Like the contagion index, the size differentiation value showed that the pioneer species and its associates lost natural regeneration in the high saline area.

Very few salt-loving successional species are growing and turning into pure stands there. Big size differentiation is attributed to multi-species and multi-layered forests, while low differentiation to even-aged, single-layered, and pure stands (Temesgen et al. 2014; Schmidt et al., 2011). Ahmed et al. (2023) revealed that salinity critically affected the diameter and height of trees in the *Sundarbans*. It was also reported that the size of the tree species showed significantly higher values in the less-salinity areas than in the high-salinity areas (Ahmed et al. (2023). They also revealed negative growth dominance in the high saline area, while positive growth dominance in the low saline area. It was also found that the high saline area was inhabited by dwarf trees, which indicates the convergence to the mangrove scrub. Rahman (2020) revealed that the high saline area, which has been turned into a mangrove scrub, is characterized by dwarf and bushy trees of similar shape. Hence, it can be argued that the findings of this study are well supported by ample literature. The simple, easy, less technical, time-saving, and non-expensive neighbourhood-based variables and methods can articulate the spatial dimensions of a complex ecosystem. Despite some limitations, it can be repeated that salinity plays a vital role in shaping the spatial diversity of tree species in the *Sundarbans* mangrove.

### CONCLUSION

The study aimed to examine the influential role of salinity on the spatial diversity of the *Sundarbans* mangrove in Bangladesh by taking a few neighbour-based variables. The results will draw immense attention from policymakers, academicians, and researchers to maintain at least the status quo of the current status and will intervene to protect it from further degradation. Bangladesh can do a little to mitigate global stressors, but can minimise local pressures that are fueling the salinisation. The *Sundarbans* cannot afford brackish shrimp culture in the coastal areas anymore. The fresh shrimp culture by preserving rainwater can be an alternative. Protecting the government-owned canals and clearing the blockades raised by the encroachers is an urgent issue that can minimise sedimentation and salinity levels by increasing water volume. Alternative income-generating activities should be adopted for the

people who depend on the natural resources of the *Sundarbans* to minimise anthropogenic pressures and luxuriant biodiversity in this mangrove. This study tried to focus on the spatial stand structure as a whole, ignoring the species-centric spatial dimensions. Taking this limitation into account, further studies will be required to measure the impact of stressors on the spatial pattern of each species. The combined impact of other predictable and unpredictable anthropogenic and non-anthropogenic perturbations on the survivability of plant species should be studied.

### Conflict of Interest

The author, with this, declares that there is no conflict of interests and conflicting issues in this research paper.

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