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Comparative Analysis of Physiological and Biochemical Responses of Native and Introduced Plant Species to Water Stress in the Ranchi Region, Jharkhand

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ABSTRACT:

Water stress is one of the major non-biological factors that limit growth, yield, and the survival of plants, particularly in semi-arid areas like Ranchi, Jharkhand. The present study explores and contrasts the water stress in the selected native and exotic plant species through studying their physiological and biochemical reactions. The factors examined are relative water content (RWC), stomatal conductance, chlorophyll fluorescence, proline accumulation, antioxidant enzyme activities (superoxide dismutase, catalase, peroxidase), and lipid peroxidation (malondialdehyde content). The results indicate the occurrence of species-specific adaptive mechanisms that coincide with the native species showing greater resilience to water deficit through the combined application of osmotic adjustment, effective stomatal regulation, and complete antioxidant defense systems as opposed to the introduced ones. The implications of these results for plantings and restorations under climate variability are that the native flora has no less than an ecological role that is in drought-prone areas. The understanding of such responses is critical for development of sustainable landscape management practices and for predicting changes in vegetation in the Eastern Indian plateau region under the climate change scenarios matching with the projected ones.

Keywords: *Classical nucleation theory, electric field, free-energy barrier, critical radius, electrochemical nucleation, field-assisted crystallization.*

1. INTRODUCTION:

1.1 Background and Global Context:

Availability of water is one of the most essential limiting factors for plants and the whole ecosystem productivity and functioning around the world. With the global warming, alterations in the precipitation patterns, increased temperature extremes, and prolonged droughts are becoming a common phenomenon in many regions and their intensity is increasing too. These alterations not only threaten the survival of natural vegetation but also challenge the agricultural systems and managed landscapes, thus, the necessity of understanding plant responses to water limitation more deeply. In the Indian subcontinent, where agriculture is the mainstay of more than half of the population and forests are the main source of support for the ecosystem, water scarcity has become a major limiting factor for plant growth. The Eastern Plateau area, especially the state of Jharkhand, has a typical monsoonal climate with well-defined wet and dry seasons. The Ranchi area, located in Jharkhand's center, is subjected to seasonal droughts that occur every year and increasing variability of monsoon which places a lot of water stress on the plants that grow naturally as well as those that are planted.

The water shortage is one of the most difficult environmental stresses for plants. However, during such a stress condition, plants resort to a very complex mechanism of physiological and biochemical changes, which maintain the proper functioning of the cells, protect the very important components of the cells, and lessen the damages caused by oxidation. These processes are acting at a number of organizational levels. One of them is molecular and cellular and the other is whole plant morphology and phenology. The ability to turn on and bring together these protective measures is what defines a plant's drought tolerance and how it continues to live in water-stressed conditions.

1.2 Native Versus Introduced Species: Evolutionary Perspectives:

The difference between native and non-native plant species goes beyond their place of birth and includes the basic differences in their evolutionary adaptations and their ecological integration. Native plant species have gone through a long evolutionary process to adapt to the specific local climatic, soil, and living conditions, thus developing their own mechanisms to withstand the environmental stresses, one of which being the occasional lack of water. These adaptations can be in the form of morphological features e.g. deep root systems, small leaf area, or special tissue structures as well as in physiological mechanisms like efficient stomatal control, osmotic adjustment, and strong antioxidant systems.

Plant species that have been introduced into an area might still be beneficial for economic, ornamental, or ecological purposes but their drought tolerance will be quite different depending on their evolutionary history. Some introduced species show an amazing ability to adapt to new situations and can adjust to the local conditions while others still stay poorly acclimated to the existing stresses. In the Ranchi region, many different trees have been imported for various purposes like afforestation programs, urban greening, and plantations; however, the data regarding their performance under water stress compared to that of native species is still very scarce.

The ecological effects of the species introduction in water-stressed environments are very complex. The non-natives could take water from the local plants, change the ground water conditions by different transpiration activities, or they could be completely dried out without extra water given to them. So, it is really important to know and understand the drought resistance of native plants compared to the introduced ones for making the right choices in landscape management, restoration, and climate adaptation planning.

1.3 Water Stress: Mechanisms and Plant Responses

Water stress is a condition where the water lost by transpiration surpasses the water absorbed by the roots. This results in a decrease in the potential of the plant tissues and gradual drying of the cells. The primary effect of water stress is the start of a chain reaction of secondary responses which influence almost all plant physiological and metabolic processes. One of the first responses is stomata closure through which the plant tries to minimize water loss due to transpiration. However, this results in a simultaneous reduction of carbon dioxide intake and therefore of photosynthesis. With the increase of stress, the plants show a decrease in the size of their cells, a change in the balance of hormones, an increase in the concentration of osmotically active solutes, and production of reactive oxygen species (ROS) that may cause damage to the cellular structures.

The tolerance of plants to water stress involves the use of various adaptive strategies that are in different time scales. The immediate reactions are stomatal closure and the slowdown of the growth. The short-term adaptation is the osmoregulation through the gathering of the compatible solutes like proline, glycine betaine, and soluble sugars. These solutes not only help in maintaining the turgor pressure of the cells but also serve to protect the macromolecules. The long-term changes in the plants may consist of increased production of the antioxidant enzymes, protective proteins, and changes in the roots and leaves that make them more resistant.

1.4 Research Objectives and Significance

The study aimed at comparing the physiological and biochemical responses of the native and introduced species exactly in the Ranchi region in terms of water stress. Among other things, it was set to determine the changes in water relations, photosynthetic efficiency, osmotic adjustment capacity, antioxidant defense systems, and oxidative damage markers under different water stress levels accompanied by characterizing species-specific adaptive and tolerance traits, assessing the drought resilience of native vs. introduced species, and the establishment of plant selection guidelines for water-limited areas based on evidence.

The results of this study have been made to be very useful for different forest programs, urban landscape design, ecological restoration projects, and most especially in the climate change adaptation strategies for the region. In addition, this research has played a part in the scientific community's knowledge of plant drought responses and the ecological significance of native biodiversity in areas that are prone to stress.

2. Materials and Methods

2.1 Study Area Characterization

Ranchi, recognized as the capital city of the state Jharkhand, has approximate geographical coordinates of 23.3°N and 85.3°E that average its elevation to 650 m above sea level. The region experiences a subtropical climate and has three main seasons: summer, which is characterized by extreme heat from March to June, with a peak temperature of 42°C; monsoon, which extends from July to September and gives 80-85% of the annual rainfall of 1400 mm; and winter, which lasts from November to February and has nights of around 10°C.

The geological composition of the area is mainly characterized by the metamorphic rocks of the Chota Nagpur plateau that date back to the Precambrian era, whereas the soil types range from lateritic in the highlands to alluvial in the lowlands and riverbanks. The texture of the soil varies between sandy loam and clay loam being water-holding capacity ranging from moderate to poor. The primary natural vegetation cover was moist deciduous forests, but the wide spread cutting down of trees has led to a drastic decline in forest area. Water supply shows a clear seasonal pattern, with a great deal of moisture in the rains and the dry season from October to May having a sharp contrast with the soil moisture deficit.

The climatic and edaphic context that is present in the region imposes a serious water stress challenge to the vegetation, thus making the area a perfect one for carrying out comparative drought tolerance studies.

2.2 Plant Materials and Selection Criteria

The plant species concerned in this research were picked according to several factors: one of the main is their ecological and economic significance in the region. The other crucial factors were the availability of uniform plant material, the different functional groups, and the very clear differentiation of native or introduced species.

Among the selected native species was Mesua ferrea (Ironwood, Nagkesar), which is a family member of the slow-growing evergreen tree of Calophyllaceae plantation, naturally found in moist deciduous forests of the region. The tree has economic value for its timber and medicinal applications. Lagerstroemia parviflora (Dhar), a deciduous tree belonging to the Lythraceae family, is commonly encountered in the dry deciduous forests of Jharkhand and is considered valuable for timber and traditional uses. Ficus benghalensis (Banyan), a giant evergreen of the Moraceae family, has been a symbol of Indian landscapes with vast aerial root systems and cultural significance.

the introduced species are: Azadirachta indica (Neem), initially from Myanmar but extensively planted across India for centuries, now found in a lot of places like Jharkhand, where it is highly appreciated for its wood, shade, and healing properties. Eucalyptus tereticornis (Forest Red Gum), from Australia, has been extensively planted in India for reforestation and commercial purposes since the colonial period. Cassia siamea (Kassod tree), from Southeastern Asia, was brought in for decorative and shady purposes in the urban-rural landscape.

It is important to mention that the classification of Azadirachta indica as "introduced" is arguable due to its long history of cultivation in India, although it is not native to the Ranchi area specifically.

2.3 Experimental Design and Treatments

The experiment was carried out at the Department of Botany's research center in the dry season, when the natural water stress is at its highest. Uniformly-sized and vigorous one-year-old saplings were sourced from a nearby nursery and were kept for two weeks to adapt before the start of the treatment. The plants were put in 10-liter plastic pots that were filled with a standardized soil mixture made of local lateritic soil, sand, and compost in a 2:1:1 ratio. The soil mixture was subjected to tests for texture, pH, organic carbon content, and water-holding capacity to confirm its uniformity across the experimental units.

Three distinct water treatment regimes were set up: Control treatment where soil moisture was kept through regular irrigation, determined gravimetrically, at field capacity, and thus well-watered conditions. Moderate water stress treatment maintaining soil moisture at around 50% of field capacity to represent periodically drought situation. Severe water stress treatment where soil moisture was maintained causing a prolonged drought scenario at about 25% of field capacity.

The water treatments were given little by little over a period of five days in order to prevent any shock effects, and then they were continued for 21 days. Soil moisture was monitored every day with the help of a soil moisture probe and then adjusted by weighing pots and adding water in the calculated amounts. The experiment was carried out in a completely randomized manner with five replications for each species-treatment combination, which makes a total of 90 experimental units. The plants were kept in a shade house under semi-controlled ambient conditions where a 30% light reduction was applied to minimize additional heat stress while still allowing natural photoperiod and temperature fluctuations that are typical of field conditions.

2.4 Data Collection Procedures

2.4.1 Physiological Measurements

Relative Water Content (RWC) was evaluated according to standard methods. In the morning, fresh leaf samples were taken and weighed immediately so that fresh weight could be determined. Then, the samples were put in closed petri dishes with distilled water for four hours under dim light to reach full turgidity. After that, turgid weight was recorded by gently blotting the leaf surface to remove water. The samples were then dried in an oven at 70°C for 48 hours to determine the dry weight. RWC was calculated as: RWC(%) = [(FW - DW) / (TW - DW)] × 100, with FW referring to fresh weight, TW to turgid weight and DW to dry weight.

Stomatal Conductance was determined by a steady-state porometer on fully expanded mature leaves between 9:00 and 11:00 AM to reduce diurnal variation. Measurements of three per plant were taken on the abaxial leaf surface and averaged.

Chlorophyll Fluorescence was obtained using a pulse-amplitude modulation fluorometer after the dark adaptation of 20 minutes with leaf clips. The maximum quantum efficiency of photosystem II was calculated as Fv/Fm = (Fm - F0) / Fm, where Fm is maximum fluorescence and F0 is minimum fluorescence. This parameter reflects the status of the photosynthetic apparatus in terms of its efficiency in using light and its tolerance to light stress.

2.4.2 Biochemical Assays

The collection of fresh leaf tissue was done and soon after frozen in liquid nitrogen for the purpose of doing biochemical analyses. All the steps of enzyme extraction and assays were made at 4Â°C in order to decrease the rate of enzyme degradation.

The proline content in the plant material was measured following the ninhydrin method. The leaf tissue was first homogenized in sulfosalicylic acid, then the homogenate was filtered and the filtrate was treated with the acid ninhydrin reagent. After that, the solution was boiled in a water bath, the chromophore was separated by toluene, and its absorbance was measured at 520 nm. The proline concentration was determined by the standard curve.

Antioxidant Enzyme Extraction: The leaf tissue was first frozen in liquid nitrogen, then it was thoroughly ground and homogenized with the cold phosphate buffer comprising polyvinylpyrrolidone and EDTA. The mixture was then centrifuged at 15,000 g for 20 minutes at 4Â°C, and the supernatant used in the enzyme assays was collected.

The SOD activity was measured through the inhibition of the photochemical reduction of nitro blue tetrazolium dye. The enzyme amount responsible for the reaction rate's 50% inhibition was taken as one unit of SOD activity.

The CAT activity, then, was determined by the measurement of hydrogen peroxide decomposition at 240 nm. The extinction coefficient of hydrogen peroxide was used for the calculation of activity.

POD activity was assessed by spectrophotometrically monitoring the oxidation of guaiacol at 470 nm in the presence of hydrogen peroxide. The activity was reported as the change in absorbance per minute per milligram of protein.

The determination of lipid peroxidation was carried out through the quantification of malondialdehyde (MDA) by the Thio barbituric acid (TBA) method. The leaves were ground in trichloroacetic acid and then the resulting mixture was boiled with TBA. The absorbance at 532 nm was measured after 600 nm correction for non-specific turbidity. The MDA concentration was calculated using the extinction coefficient of MDA.

The protein content was measured by the Bradford method with bovine serum albumin as a standard, and the activities of the enzymes were expressed on a protein basis.

2.5 Statistical Analysis

The analysis of variance was performed on the data with a two-way factorial design where species and water treatment were the fixed factors. The normality of the residuals was assessed using the Shapiro-Wilk test, while the homogeneity of variance was determined through Levene's test. In those cases where the assumptions were not met, the data were transformed accordingly. Means of treatments considered significantly different were evaluated by using Tukey's Honest Significant Difference test at the $p < 0.05$ significance level.

To analyze the multidimensional dataset and to classify the species according to their physiological and biochemical response profiles, Principal Component Analysis was applied. Correlation analysis was utilized to discover relationships between different parameters measured. All statistical computations were made with the help of R statistical software.

3. Results

3.1 Physiological Responses

3.1.1 Relative Water Content

The RWC of various species, various water treatments, and their interaction were the main factors that led to the major fluctuations. Under the control conditions, both native and non-native plants maintained RWC over 85% and this meant that water was not a problem for them. In the case of moderate water shortage, the RWC of native plants was much higher than the RWC of non-native ones. Ficus benghalensis was the winner of RWC with the highest retention rate of 78.4%, then Lagerstroemia parviflora with 74.2%, and Mesua ferrea with 72.8% followed. In the meantime, among the invasive plants, Azadirachta indica was 68.5% RWC and had the largest, followed by Cassia siamea with 64.3%, and finally Eucalyptus tereticornis with the lowest one, 61.2% RWC.

With the severe water stress treatment, the differences between the species became even more pronounced. Ficus benghalensis exhibited its remarkable water retention capacity and maintained RWC at 68.7% thus only a 20% reduction from control conditions. Other native species reported RWC decline of about 25-28%. On the other hand, the introduced species were more drought-resistant Eucalyptus tereticornis going down to just 48.3% RWC which is indicative of severe cell dehydration. The high-water retention in native plants could be attributed to their effective water uptake, reduced water loss, or better cellular water-holding capability.

3.1.2 Stomatal Conductance

All species showed a progressive decline in stomatal conductance with an increase in water stress intensity, which was the reflection of stomatal closure as an effective water conservation method. Nevertheless, the native and the introduced species differed significantly in their patterns and the extent of stomatal regulation. The stomatal conductance under the control conditions was species-dependent and ranged between 285-340 millimoles per square meter per second, but the difference was not significant.

From the data, we see that the native species cut down their stomatal conductance by 45-52% under moderate stress, but the introduced ones only reduced it by 38-44%. The more stringent stomatal regulation of the native species suggests that the loss of transpirational water is more sensitive to be monitored. As a matter of fact, even though the stomatal closure in the native species was greater, they still had higher photosynthetic rates, which means that they had more effective carbon assimilation per unit of stomatal opening.

All the species showed considerable stomatal closure under severe stress conditions, but the native species still kept the minimal conductance that was enough for their metabolic needs, while the non-native species, especially Eucalyptus tereticornis, almost completely closed their stomata, which might hinder their ability to recover through photosynthesis.

3.1.3 Chlorophyll Fluorescence (Fv/Fm Ratio)

The highest quantum efficiency of photosystem II, which is indicated by the Fv/Fm ratio, is very sensitive to the integrity of the photosynthetic apparatus and photoinhibition, and, thus, serves as an indicator. Non-stressed, healthy leaves generally have Fv/Fm values of about 0.80-0.83. All species under the control condition kept their Fv/Fm ratios in this optimal range, signifying that no photoinhibition occurred.

In the case of water stress at moderate levels, there were very minor changes in Fv/Fm with the native plants going down to 0.75-0.77 and the introduced ones to 0.71-0.74. This indicated very little photoinhibition. However, the difference became more visible in the case of severe stress conditions. Native species still had Fv/Fm ratios of 0.68-0.72, thus indicating moderate but manageable photoinhibition effects. On the other hand, the introduced species recorded much bigger reductions with Eucalyptus tereticornis reaching 0.58 and Cassia siamea going down to 0.62, which were signs of significant damage to photosystem II reaction centers and impaired photosynthetic capacity.

The fact that native species kept the higher Fv/Fm ratios under stress indicates that their photosynthetic apparatus was better protected, maybe because of more efficient antioxidant defenses or photoprotective mechanisms.

3.2 Biochemical Responses

3.2.1 Proline Accumulation

Proline, a compatible osmolyte, gradually and progressively increased in all species with the increasing intensity of the water stress, thus confirming its role in osmotic adjustment. In the case of control conditions, the concentrations of proline were found to be low in all species, being in the range of 2.1 to 3.4 micromoles per gram of fresh weight.

Under moderate stress, there was a significant increase in proline accumulation, but the native species displayed much higher accumulation than the introduced species. The highest proline accumulation was found in Mesua ferrea at 24.8 micromoles per gram, followed by Ficus benghalensis at 22.3 and Lagerstroemia parviflora at 20.5 micromoles per gram. The introduced species, on the other hand, had a much smaller proline accumulation with Azadirachta indica at 16.2, Cassia siamea at 14.7, and Eucalyptus tereticornis at 13.9 micrograms per gram.

The native plant species under stress had the highest proline concentration of 38-45 micromoles per gram, which was considerably higher than the 24-31 micromoles per gram of the non-native species. The accumulation of proline by the natives allows them to fight against and keep their water condition and pressure under low soil water potential. In addition, proline is a free radicals' enemy and a protector of proteins and membranes in their stress conditions. The close relationship between proline accumulation and maintenance of relative water content implies that proline is an important functional role in the drought tolerance of native species and not just a stress symptom marker.

3.2.2 Antioxidant Enzyme Activities

Water stress causes the release of reactive oxygen species, such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals, which are all capable of inflicting damage to lipids, proteins, and nucleic acids. On the other hand, the activity of antioxidant enzymes represents a major defensive measure against oxidative stress.

Superoxide Dismutase (SOD) Activity: SOD is the enzyme responsible for the conversion of superoxide radicals to hydrogen peroxide and molecular oxygen, thus it is the first line of defense provided by the antioxidants. The activity of SOD in non-stressed conditions was quite low and uniform among the species. Water stress resulted in a pronounced elevation of SOD activity, being the native trees responsible for greater increase in production of the enzyme compared to the introduced trees. In cases of very high stress, the SOD activities of the natives were 3.2-3.8 times more than the control ones, while the introduced ones had 2.1-2.6 times more. Among all, Ficus benghalensis had the highest SOD activity with 142.5 units per mg protein under extreme stress.

Catalase (CAT) Activity: Catalase disintegrates hydrogen peroxide into water and oxygen, thus safeguarding the cells from the toxic effects of the peroxide. Like SOD, the activity of catalase was heightened with the intensity of stress, with the native species showing the most remarkable activation. Under extreme conditions, the native species displayed CAT activities of 95 to 118 units per mg of protein, while the introduced species had only 62 to 78 units. The synchronized rise of the SOD and CAT activities guarantees that both superoxide radicals and their dismutation product, hydrogen peroxide, are efficiently removed.

Peroxidase (POD) Activity: Using a variety of substrates, peroxidases reduce hydrogen peroxide which aids in the action of catalase. The native species under stress resulted in much higher peroxidase activity, with levels going up to 68 to 84 units per milligram of protein in extreme conditions while the introduced species had only 46 to 58 units. oxidative damage to native species was reduced and this was measured by lipid peroxidation tests that showed the same trend as the increase in antioxidant enzyme activities.

3.2.3 Lipid Peroxidation (MDA Content)

Malondialdehyde (MDA) the content regarded as a marker of oxidative damage to membrane cells, was monitored and the over control treatment MDA content was low in all species indicating that oxidative stress was not a factor at all. The less tropical species under water stress with increased lipid peroxidation but the degree of increase was very dissimilar.

The indigenous flora under moderate stress gave off comparatively less MDA of just 1.4 to 1.8 times more than control levels. In contrast, the introduced species had higher and more variable MDA increases that ranged from 2.1 to 2.7 times. The difference between the native and non-native species became more apparent under extreme stress. The former's MDA rate was from 12.4 to 16.8 nanomoles fresh weight which corresponds to 2.2 to 2.9 of the initial levels. The latter's level was 24.3 to 32.6 nanomoles per gram which represents 3.8 to 5.1 times the rise. Eucalyptus tereticornis was the most impacted plant with the highest MDA of 32.6 nanomoles per gram at the end of the trial.

The still lower lipid peroxidation rates in native species despite the very same or worse conditions may mean that the species are better at oxidatively preventing damage. This prevention may have its roots in the highly efficient antioxidant enzyme systems of these species and perhaps in the increased levels of phytochemicals that are not directly associated with enzymatic reactions.

3.3 Principal Component Analysis

Principal component analysis (PCA) performed on the merged physiological and biochemical dataset revealed a good separation of species based on their stress response profiles. The joint variance of the first two principal components was 73.4%. The first principal component (PC1), which accounted for 48.2% of the total variance, indicated a positive correlation with relative water content (RWC), Fv/Fm, proline content, and antioxidant enzyme activities, while a negative correlation with malondialdehyde (MDA) content was noted. The second principal component (PC2) accounted for 25.2% of the variance and was mainly associated with the stomatal conductance trend.

The native species were located at the positive end of PC1, which is typical of high stress tolerance indicators. On the other hand, the non-native species were in a separate cluster with lower PC1 values, which implied that they were more stressed. This multivariate analysis provides strong evidence for the idea that the native and the introduced species differ in terms of stress response strategies and tolerance levels, as they are not only different in the amount of stress they can withstand but also in the way they deal with it.

4. Discussion

4.1 Integrated Drought Adaptive Strategies

The drought tolerance of native plant species from the Ranchi area is much higher than that of the introduced species selected for the study, which is confirmed by the integrated physiological and biochemical adaptive strategies operating at different levels.

Water Relations and Conservation: During the stress periods, the native species kept their tissues with a lot of water, thus being the most efficient through the combination of mechanisms. Possibly, having deeper or more widespread root systems that can reach the moisture in deeper soil might help with water retention, but root parameters were not measured in the pot study to verify this factor. The more efficient stomatal regulation in the native species signals a crucial adaptive trait, which is the very close water conservation and carbon acquisition balance. The ability to greatly reduce stomatal conductance while still having moderate photosynthetic rates is a sign of high-water use efficiency, which is a trait that favors survival in drought-prone areas.

Osmotic Adjustment: The Native plants' adaptation to the stress condition through the accumulation of proline is one of the main contributors to the osmotic adjustment which consequently decreases the cellular osmotic potential and preserves a water potential gradient that draws water from the drier soil. Besides the osmotic action, proline plays a number of important roles including protein and membrane stabilization, scavenging of free radicals, and redox potential buffering. The affinities of other solutes such as sugars, glycine betaine, and polyols to osmotic adjustment are also suspected but they were not quantified in this study. Being able to perform effective osmotic adjustment has turned out to be an indispensable drought tolerance mechanism which appears to be more pronounced in the case of native species.

Antioxidant Defense Systems: One of the most important differences between native and introduced species was the antioxidant response. The native species' coordinated upregulation of the activities of SOD, catalase, and peroxidase, which were all about 2-3 times higher than those in the non-native species, ultimately led to their being very well protected against oxidative damage during water stress. Besides, the native species' lower lipid peroxidation rates confirm this reasoning since their additional antioxidant capacity is used up as active protection of the cells during the water stress period.

The antioxidant response is a defense system that can be induced and is based on the metabolic investment. The native species' greater ability to generate this response may suggest their possessing better stress sensitivity and signaling along with the genetic and metabolic provision to produce hierarchical antioxidant enzymes. This might mean an evolutionary selection in a habitat that has been subject to drought stress conditions recurrently.

Photoprotection during Photosynthesis: The native species' higher Fv/Fm ratios predominantly show that the photosynthetic system was protected from stress-induced damage to a larger extent. Stress conditions, in general, cause the burning of the photosystem II, which is particularly vulnerable to the whole process of light capturing and electron transport in photosynthesis. However, the local plants appear to have more effective photoprotection mechanisms, which could be, for example, the better thermal dissipation of excess light energy, the faster repair of damaged PSII components, or the more efficient adjustment between light capture and metabolic demand.

4.2 Evolutionary and Ecological Context

The native flora's drought tolerance appears to be the major factor, indicating their evolutionary adaptation to the Ranchi climatic conditions. During the evolution of the native flora, the plants had to withstand soil desiccation for almost two months every year and significant variations in the annual rainfall. The most tolerant, in terms of water taking up the least rather than going through dying, were the ones that survived genetic bottleneck and led to the local populations well adapted to the regional patterns of water stress.

On the contrary, non-indigenous plants were not subjected to the same harsh conditions and hence evolved differently. Some might possess the genetic-lot of phenotypic plasticity, which helps in local conditions partial acclimatization, but still, they would lack the entire range of native plants adaptive mechanisms. The inconsistent performance of the introduced species in the present research could be mainly attributed to their different evolutionary histories, with some species coming from dry and others from moist areas.

The local adaptation theory assumes that populations are the best-fit-for-the-condition where they come from. Our results show that this theory is valid for drought-resistant characteristics. Nonetheless, it must be remembered that even within alien species, there can be genetic variability with regard to drought resistance and that the appropriate selection of genotypes or cultivars can result in better performance.

4.3 Ecological and Practical Implications

The findings of this research are quite crucial for the ecological management, landscape planning, and climate change impacts in the Ranchi area and other places with similar conditions.

Reforestation and Afforestation Programs: The exceptional drought tolerance of the native species makes them the best option for reforestation in the degraded lands and the afforestation programs in the water scarcity areas. The local ones have a higher probability of being successfully transplanted and surviving with the non-intensive management inputs like no irrigation at all. The application of native species not only contributes to the conservation of biodiversity but also to the restoration of habitat for the native fauna and the continuation of the ecological processes that have evolved with the local flora.

Urban Greening and Landscape Design: When deciding whether to use native or exotic species for urban forestry and landscape, the decision includes different factors, such as aesthetic, growth rate, ecosystem services, and resource use. The research indicates that, in the aspect of water input for maintaining and aesthetically pleasing trees and shrubs during dry periods, the native species will require less leading to a reduction of irrigation necessities and expenses along with energy consumption. The scenario of water scarcity which is becoming a standard in urban areas has led to the selection of native species that can survive with limited or no water as a green city method that is environmentally friendly and sustainable.

Climate Change Adaptation: The climate projections for the region give a rise in temperature, rainfall that is more variable, and the occurrence of droughts with a frequency and intensity that is more than before. In the light of these scenarios, vegetation communities and managed landscapes would undergo a significant increase in water stress. The native species that have shown drought tolerance are the ones that can survive and work best in the future climates. The incorporation of native species in the landscape planning is nothing but a proactive adaptation strategy that will strengthen the capacity to cope with climate changes.

Agricultural and Agroforestry Systems: The study, however, pointed to tree species, still, the uniting of local adaptation and drought tolerance standards bears crop selection and agroforestry design. The introduction of drought-tolerant native tree species into agroforestry systems can lead to multiple benefits like providing shade, conserving soil, and producing extra goods, and all this can happen with very little input and the species being less of a competitor with crops for the scarce water resources.

4.4 Comparative Performance of Introduced Species

Among the newly introduced species, it is very important to say that Azadirachta indica (Neem) turned out to be a much better choice than Eucalyptus and Cassia. This could be the result of several reasons: India has been Neem's area of cultivation for a long time, therefore it has a certain level of being local adapted, Neem has its origin in semi-arid regions and has consequently developed natural or inherent drought tolerance mechanisms, and also large-acreage farming might have led to the best adapted genotypes being the only ones left as a result of the farmers' selection.

The species Eucalyptus tereticornis was the one with the lowest performance among the studied ones, as it exhibited very serious symptoms of water stress, no RWC at all, and more than a half of the tree was already dead from photoinhibition. This means that this Eucalyptus is not suitable for the water-scarce conditions of the area, despite the fact that it has been planted widely. Different results might come from other Eucalyptus species or sources, hence, the selection of species and sources in plantation forestry is very important.

4.5 Limitations and Methodological Considerations

The pot experiment, though permitting controlled conditions and exact treatment application, might not completely mirror field conditions where soil heterogeneity, rooting depth and biotic interactions are influencing plant responses. The pot limitations might restrict root growth thus affecting different species depending on their root architecture. The 21-day stress period is indicative of a short-term stress event, while drought in the field may last for several months. The long-term adaptation and recovery dynamics might be entirely different from the short-term responses.

The research did no more than a few species within each category. A wider range of species being selected would reveal a more detailed picture of the general patterns versus species-specific responses. Root characters, hormone levels, gene expression profiles, and metabolomics would be the parameters that could render drought tolerance the deepest understanding on the mechanistic side.

Among the environmental factors of the semi-controlled ambient conditions, temperature changes and vapor pressure deficit in particular, could have had an impact on plant responses concurrently with water treatments in unpredicted ways that were not fully controlled in the experimental design.

Conclusion

The comparative study thoroughly demonstrated the native flora of the Ranchi area are exceptional in terms of their physiological and biochemical traits which are necessary for survival in water-deficiency conditions. Native plants controlled their water status more successfully by maintaining higher relative water content, regulating stomata more efficiently with a proper balance between conserving water and performing photosynthesis, having more capacity for osmotic adjustment through increased accumulation of proline, maintaining powerful antioxidant defense systems thus protecting themselves efficiently from oxidative damage, and keeping their photosynthetic apparatus intact better under stress.

The integrated adaptive mechanisms mentioned above are not only the basis for the drought tolerance of native species but also increase it to a great extent when compared to the introduced ones, and thus this factor is very much critical for ecological management and climate adaptation planning. The findings of the study also support the idea that native species should always be the first option in reforestation programs, urban greening initiatives, landscape restoration projects, and future climate planting in areas with limited water supply.

the scientific knowledge of plant drought responses and the ecological principle of local adaptation, while granting practical assurance to the sustainable vegetation management in the face of increasing water stress caused by climate change. With the Ranchi region and similar areas encountering more severe challenges due to climate fluctuations and water scarcity, exploiting the drought resistance of native species is a nature-based solution that not only enhances the resilience of the ecosystem but also supports the well-being of the human population.

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