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Evaluation of Tree Species for Biodrainage and its Impact on Soil Health-A Review

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Abstract

This review focussed on recent scientific insights to explain the ability of different tree species to lower water tables, thereby improving the soil health and environment. Biodrainage has emerged as an innovative and sustainable biological approach to mitigate waterlogging and soil salinity, which were two major impediments to agricultural productivity. It was proven beyond doubt as a practical and eco-friendly alternative to conventional drainage methods in poorly drained areas. Fast-growing, deep-rooted, and high-transpiring species such as *Eucalyptus*, *Casuarina*, and *Acacia* have demonstrated significant efficacy in managing excess soil moisture in affected landscapes. Adopting these species facilitated natural drainage and contributed positively to soil properties and microbial activity. Furthermore, it gained momentum as a low-cost, self-sustaining, and renewable solution that integrated well with agroforestry systems and sustainable land use practices. It could help reclaim saline soils, and supported resilient farming systems besides improving resource-use efficiency, stabilizing crop productivity under stress conditions thus generating additional economic returns through tree-based outputs. In the context of global sustainability frameworks, this green concept aligned with key Sustainable Development Goals, including SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). However, its effectiveness depended on appropriate tree species selection, site-specific soil and ground water conditions, and long-term management practices. Therefore, systematic evaluation of tree species was essential to optimize biodrainage performance and ensured sustainable land and water resource management.

Keywords: Agroforestry, biodrainage, salinity, soil health, transpiration, waterlogging

1. Introduction

Waterlogging and salinity are major soil degradation issues that hinder sustainable agriculture, especially in irrigated and canal-command areas of arid and semi-arid regions of India. Together, they affect over 13 m ha of land, resulting in poor crop productivity, loss of arable land, and declining soil health (Masilamani et al., 2020). Waterlogging occurs when the water table rises close to or above the root zone, leading to expulsion of oxygen, root decay, and the mushrooming of anaerobic soil microbes (Maitra and Zaman, 2017). Concurrently, salinity develops due to the upward movement of dissolved salts from the rising groundwater, which accumulate in the root zone. This accumulation creates osmotic stress, limits water absorption, and disrupts nutrient uptake by plants, thereby impairing their growth and yield potential (Singh and Lal, 2018). The combined effect of waterlogging and salinity significantly reduces soil fertility and poses a serious threat to long-term agricultural sustainability. Conventional surface and subsurface drainage systems, though technically viable, are often unaffordable and pose environmental concerns due to the generation and disposal of saline effluents (Dash et al., 2005). Traditional engineering-based drainage systems, such as surface and subsurface tile drainage, have long been employed to combat waterlogging and salinity. However, these methods are capital-intensive, requiring significant technical expertise, and often generate large volumes of saline effluents that pose serious environmental disposal challenges (Dash et al., 2005). Moreover, resource poor small and marginal farmers frequently lack the resources and infrastructure needed to install and maintain such systems, making them impractical for widespread rural adoption (Singh and Lal, 2018). Additionally, they provide no added value in terms of biomass production, ecological services, or long-term soil rejuvenation. With increasing climate variability, land degradation, and pressure on natural resources, there is a growing need for sustainable, cost-effective, and environmentally friendly alternatives to conventional drainage systems. In this context, biodrainage has emerged as a viable and efficient biological approach to address waterlogging and salinity. It involves the strategic use of deep-rooted, fast-growing tree species with high transpiration capacity to extract excess soil moisture and lower the water table through evapotranspiration, particularly in areas with shallow groundwater tables (Maitra and Zaman, 2017; Masilamani et al., 2020; Venkatraman and Ashwath, 2016). Biodrainage is identified as a promising green technology for improving tree crop growth and soil health. Unlike mechanical drainage methods, biodrainage offers multiple ecological and economic benefits. It enhances soil organic matter through litter deposition, improves soil structure, and stimulates beneficial microbial activity (Prabha et al., 2024). In addition, it contributes to carbon sequestration, thereby aiding in climate change mitigation. The tree species used in biodrainage systems can also provide valuable products such as timber, fuelwood, and fodder, thereby generating additional income for farmers (Heuperman et al., 2002; Anonymous, 2003; Sarkar et al., 2018; Jain, 2021). The integration of biodrainage with agroforestry systems and land reclamation programs further strengthens its potential for restoring degraded ecosystems. Such integration not only improves soil moisture regimes but also enhances biodiversity, ecological stability, and overall system productivity (Sarvade et al., 2017; Ramanjaneyulu et al., 2025). Therefore, evaluating different tree species for their biodrainage potential and understanding their long-term impact on soil health indicators was essential for promoting sustainable land management and improving agricultural resilience. Thus, this review focussed on recent scientific insights to explain the ability of different tree species to lower water tables, thereby improving the soil health and environment.

2. Biodrainage

Waterlogging and salinity are the major soil degradation issues that significantly hinder sustainable agricultural production, particularly in irrigated and canal-command areas of arid and semi-arid regions of India. Collectively, these constraints affect more than 13.0 m ha of land, leading to reduced crop productivity, loss of cultivable land, and progressive deterioration of soil health (Masilamani et al., 2020). Waterlogging occurs when the groundwater table rises close to or above the root zone, resulting in poor soil aeration, anoxia, root decay, and proliferation of anaerobic soil microorganisms (Maitra and Zaman, 2017). It finally affects adversely the plant physiological processes leading to reduced crop growth and productivity. The second problem i.e. salinity develops due to the upward movement of salts from the shallow groundwater table through capillary rise, leading to their accumulation in the root zone. This accumulation impairs osmotic balance and ion uptake, thereby restricting water and nutrient absorption by plants (Singh and Lal, 2014). Poor aeration under waterlogged conditions, coupled with salinity, suppresses seed germination and plant growth, promotes proliferation of hydrophytic weeds that compete with crops for nutrients and other resources. It finally leads to conversion of productive agricultural land into unproductive marshy areas.

Conventional drainage systems, including surface and subsurface (tile) drainage, have traditionally been employed to mitigate waterlogging and salinity. Though these engineering based solutions are technically effective, their adoption remains limited due to high installation and maintenance costs, as well as the requirement for specialized technical expertise (Dash et al., 2005; Kamra et al., 2019). Furthermore, such systems often generate substantial volumes of saline effluents, which pose serious environmental challenges in terms of safe disposal and downstream pollution (Dash et al., 2005). For small and marginal farmers, who constitute a large proportion of agricultural community in India, these systems are often economically unviable and practically unattainable (Singh and Lal, 2014). Additionally, conventional drainage approaches primarily address hydrological issues but leave limited or no ancillary benefits.In the context of increasing climate variability, land degradation, and the need for resource-efficient technologies, there is a growing demand for sustainable, low-cost, and environmentally compatible drainage solutions.

Biodrainage has emerged as a promising alternative that utilizes biological processes to manage excess soil water (Sarkar et al., 2018; Dagar, 2014). This approach involves the strategic plantation of deep-rooted, fast-growing tree species with high transpiration capacity to lower the water table through enhanced evapotranspiration (Maitra and Zaman, 2017; Masilamani et al., 2020). In other words, it is the process of removing excess soil water through the natural evapotranspiration of deep-rooted, high water-consuming vegetation, especially trees (Jujin et al., 2023). Unlike engineered drainage systems, which physically remove water through pipes or channels, biodrainage relies on the plant's biological ability to extract water from the soil and release it into the atmosphere. The mechanism involves the absorption of groundwater by roots, its upward movement through the plant's vascular system, and its final release as water vapor through transpiration from the foliage (Figure 1). Tree plantations remove substantial amount of salts and minerals through transpiration process and utilize them in biomass production(Venkatraman and Ashwath, 2016). Tree species with large leaf area, deep and extensive root systems, and rapid growth rates are preferred.

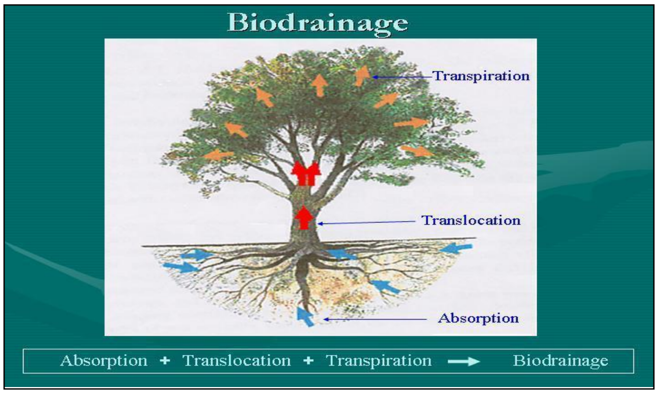

Figure 1: Process of biodrainage (Source: Ram et al., 2008)

Biodrainage helps lower the water table and reduce soil saturation in a natural and continuous manner, thus wetting the atmosphere. Beyond hydrological regulation, biodrainage systems offer multifarious ecological and agronomic benefits. These include carbon sequestration, enrichment of soil organic matter, improved soil structure, and stimulation of microbial and enzymatic activities, which collectively contribute to enhanced soil health (Heuperman et al., 2002; Jain, 2021; Anonymous, 2003). It also plays a critical role in the reclamation of waterlogged and salt-affected soils by lowering the groundwater table and reducing salt accumulation in the root zone. This leads to improved soil aeration, enhanced infiltration rates, and better root development, ultimately restoring soil productivity. Furthermore, this novel eco-friendly concept can also be implemented under both rainfed and irrigated conditions, but their effectiveness largely depends on the selection of suitable plant species, optimal planting density and geometry, as well as site-specific soil and hydrological conditions, climatic adaptability, and appropriate long-term management practices (Sarkar et al., 2018; Singh and Lal, 2018). Nevertheless, the integration of biodrainage with agroforestry systems creates diversified production systems that support biodiversity and provide additional economic returns through timber as well as non-timber forest products (NTFP) (Sarvade et al., 2017). Similarly, it's integration into land reclamation and sustainable land-use strategies has been recognized as an effective means of rehabilitating degraded ecosystems and promoting climate-resilient agriculture (Jena et al., 2011; Bala et al., 2014; Sarvade et al., 2017). Lastly, the accumulation of leaf litter and root biomass enhances nutrient cycling and promotes biological activity in the soil, thereby improving its fertility and resilience over time.

3. Comparison With Conventional Drainage Methods

Conventional drainage systems, such as surface and subsurface drains or vertical drainage via pumping wells, involve significant investment in construction, operation, and maintenance. These systems are effective but generate large volumes of effluent that must be managed or safely discharged, posing potential environmental risks (Dash et al., 2005). Biodrainage, on the other hand, is a cost-effective, renewable and eco-friendly green option as it requires minimal infrastructure, low maintenance needs, and provides co-benefits such as fuelwood, fodder, timber, and carbon sequestration. However, it's impact is gradual and highly dependent on tree species, edapho-climatic conditions, and groundwater depth (Jain, 2021). Moreover, unlike engineered drains, biodrainage does not remove salts from the system; hence, in highly saline environments, it may need to be complemented with leaching or conventional drainage (Singh and Lal, 2014).

4. Importance In Arid, Semi-Arid, And Canal-Command Areas

In arid and semi-arid regions, excessive irrigation, poor natural drainage, and canal seepage frequently lead to rising water tables and salinization of soils. In canal commands, continuous irrigation and seepage from unlined canals contribute to waterlogging. Planting suitable biodrainage species along canals, bunds, and field boundaries can help intercept seepage, stabilize water tables, and rehabilitate saline soils without disturbing the surrounding environment. According to Ram et al. (2011), a cumulative groundwater drawdown of 0.84–0.86 m was observed over three years (April, 2006–2008) in Haryana under *Eucalyptus tereticornis* (clone C-7) cultivated in association with wheat. Their deep root systems (>2.0-3.0 m) and high-water consumption make them ideal for controlling shallow water tables in canal-irrigated areas, offering a sustainable alternative to conventional mechanical drainage systems.

5. Criteria For Selecting Tree Species For Biodrainage

Selecting the right tree species is essential for the success of biodrainage systems. The species must possess certain physiological and ecological traits that enable effective water removal and support soil recovery, as furnished below:

5.1. High transpiration rate

Tree species used in biodrainage must have a high capacity to uptake and release water through transpiration. This ensures a steady removal of excess groundwater, which helps lower the water table over time. Trees with larger leaf areas and higher stomatal activity are generally more effective in this regard. For instance, *Eucalyptus* species can transpire over 25–40 l of water plant^{-1}day^{-1} under optimal conditions, making it one of the most efficient biodrainage species (Kumar et al., 2012).

5.2. Deep rooting system

A strong and deep root system allows the tree to access water from lower soil layers, especially from zones close to or within the water table. This feature is vital for removing water from highly saturated subsoil and for ensuring the long-term effectiveness of biodrainage. *Milletia pinnata* is characterized by an extensive lateral root network reaching depths of up to 9 m, supported by a robust taproot that can extend to about 10 m deep (Immanuel et al., 2019). Ram et al. (2011) reported that the roots of *Eucalyptus tereticornis* extended up to 3.30 m deep from the top of a 0.50 m ridge, equivalent to about 2.80 m below the field surface.

5.3. Tolerance to salinity and waterlogging

The chosen species should be able to survive in difficult soil conditions, such as high salinity and water-saturated environments, without loss of its productivity and health. Marriboina et al. (2021) reported that under well-drained saline conditions, *Milletia pinnata* seedlings tolerated salinity levels of ~20 dS m^{-1} (approximately 200 mM NaCl) for up to 15 days without displaying visible stress symptoms. In contrast, under waterlogged saline conditions, survival was limited to salinity levels of ~15 dS m^{-1} (≈ 150 mM NaCl), indicating its moderate-to-high salt tolerance varies with water regime.

5.4. Compatibility with crops (allelopathy and shading)

When biodrainage trees are integrated into cropping systems, they should not negatively impact the growth of nearby crops. Species that produce minimal shade and do not release harmful biochemical substances (allelopathy) into the soil are preferable. This helps maintain healthy crop growth in agroforestry systems. Nearly 88.7% higher yield was obtained from ricebean (5.85 t ha^{-1}) under *Dalbergia sissoo* alleys, than under *Acacia auriculiformis* (3.10 t ha^{-1}), wherein the latter exhibited allelopathic effects contributing to reduced productivity. Similarly, the highest average fresh fruit yield of lady's finger obtained was 5.34 t ha^{-1} from the alleys of *Dalbergia sissoo, against* 5.31 t ha^{-1} under *Eucalyptus citriodora* and only 3.51 t ha^{-1} under *Acacia auriculiformis at* West Bengal. Allelopathy-based incompatibility could be the root cause for drastic decline in yield (Khara et al., 2001).

5.5. Fast growth and biomass yield

Fast-growing trees are ideal as they establish quickly and begin draining water in a shorter time. Additionally, trees that provide high biomass, such as fuelwood, fodder, or timber, offer economic benefits alongside their ecological role. This makes biodrainage systems more appealing and sustainable for farmers and land managers. Tree species exhibited varying levels of salinity tolerance under field conditions at Puthi, Hisar district of Haryana as reported by Kumar et al. (2012), where the study area experiences year-round waterlogging. The evaluation was conducted in three-year-old plantations. Species such as *Eucalyptus tereticornis*, *Tamarix articulata*, *Terminalia arjuna*, *Dalbergia sissoo*, and *Acacia ampliceps* showed good adaptability across low (<5 dS m^{-1}), moderate (10–20 dS m^{-1}), and high (>30 dS m^{-1}) salinity levels. Biomass production decreased with increasing salinity; however, the highest biomass was recorded in *Tamarix articulata* (115.5, 85.7, and 57.4 kg $tree^{-1}$ at low, moderate, and high salinity, respectively), followed by *Eucalyptus tereticornis* (106.4, 78.4, and 67.6 kg $tree^{-1}$) and *Terminalia arjuna*. In contrast, the lowest biomass production was observed in *Prosopis alba* (44.6, 30.6, and 34.4 kg $tree^{-1}$) and *Emblica officinalis* (36.5, 25.4, and 17.5 kg $tree^{-1}$), particularly under higher salinity stress. These findings indicate that *Tamarix articulata* and *Eucalyptus tereticornis* are among the most salt-tolerant and high biomass-producing species, whereas *Emblica officinalis* represents one of the least productive under saline conditions.

Oil palm (*Elaeis guineensis*) has a relatively highwater requirement of about 200–300 litres day^{-1} and an evapotranspiration demand of 120–150 mm $month^{-1}$. However, its shallow, fibrous root system limits deep water extraction and reduces its ability to effectively lower the groundwater table. Moreover, it shows only moderate tolerance to waterlogging and low salinity tolerance, often experiencing stress under prolonged saturated conditions. Thus, it is not a good candidate for biodrainage.

6. Evaluation of Tree Species For Biodrainage

Several tree species have been evaluated for their effectiveness in biodrainage under varying soil and climatic conditions based on their observed characteristics and field performance.

6.1. Eucalyptus spp.

Eucalyptus species are widely recognized for their exceptional water-use efficiency. Their deep root system and high transpiration rates make them particularly effective in areas with shallow water tables. These trees grow quickly, adapt well to a variety of soil types, and are tolerant to both salinity and intermittent waterlogging. Their upright growth habit and narrow canopy also reduce shade, making them suitable for agroforestry systems. Additionally, *Eucalyptus* provides substantial biomass in the form of timber and fuelwood, adding economic value. Under intermittently irrigated saline dryland conditions, *Eucalyptus* species like *argophloia, melliodora, moluccana, sideroxylon,* and *tereticornis* can be grown using irrigation water with an EC of 4–8 dS m^{-1} whereas *E. occidentalis* and *E. camaldulensis* are reported to tolerate even higher salinity levels (up to 16–20 dS m^{-1}), indicating their suitability under extreme saline irrigation conditions (Masilamani et al., 2020).

6.2. Milletia pinnata

Millettia pinnata offers moderate but steady transpiration. It being a leguminous tree, fixes atmospheric nitrogen (50 to 150 kg N ha^{-1} $year^{-1}$) through its root nodules, thus enhances soil nutrient status (Ramanjaneyulu et al., 2025). Its seeds also yield oil, offering commercial potential. While it has a broader canopy than *Eucalyptus*, proper spacing can help maintain compatibility with agricultural crops.

6.3. Acacia nilotica, Albizia lebbeck, Dalbergia sissoo

These native species are well-suited for biodrainage in many Indian agro-ecological zones. They exhibit moderate transpiration and reasonable tolerance to salinity and waterlogging. *Acacia nilotica* is a nitrogen-fixing tree with good adaptability but may exhibit some allelopathic effects. *Albizia lebbeck* has fast growth and high fodder value, but tends to produce denser shade. *Dalbergia sissoo* is valued for its timber and performs well under variable moisture conditions. These species also contribute to improved soil structure and organic matter content through leaf litter, making them beneficial for long-term soil health.

6.4. Other potential species

Several other tree species also show promising results in biodrainage systems (Table 1 and Figure 2).

6.4.1. Casuarina equisetifolia

Well-suited for coastal areas, it tolerates salinity and has high transpiration capacity.

6.4.2. Populus deltoides

Performs well in temperate regions with moderate water use and fast growth.

6.4.3. Prosopis cineraria

Known for its extremely deep roots and drought resistance, it is ideal for arid zones.

6.4.4. Terminalia arjuna

Offers moderate performance in waterlogged conditions and has additional ecological value along riverbanks.

These species, though diverse in their characteristics, can be integrated strategically based on regional soil, water, and climatic conditions.

7. Lysimeter Studies

Lysimeter experiments are a key method to assess the biodrainage potential of tree species under controlled waterlogged conditions (Figure 3). A study conducted at the Tropical Forest Research Institute (TFRI), Jabalpur, tested seven tropical tree species in non-weighing lysimetric

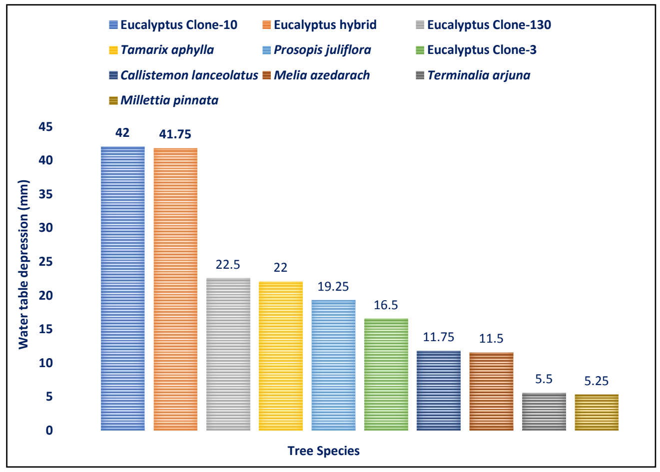

Figure 2: Comparative assessment of drop in water table (mean of four days, i.e., 1st, 2nd, 3rd, and 4th September, 2007). (Source: Angrish et al., 2009)

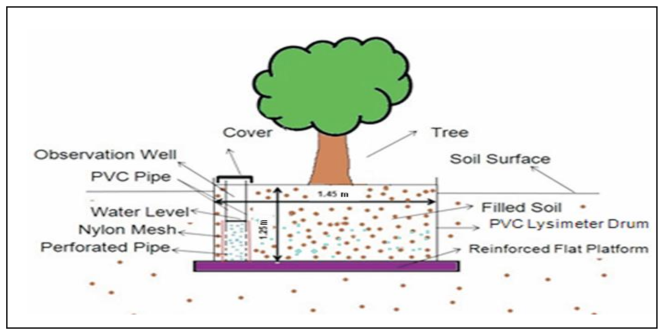

Figure 3: A schematic diagram of the lysimeter setup (Source: Madaan et al., 2018)

tanks under different water saturation levels (0–0.25 m, 0.25–0.50 m, and 0.50–0.75 m). Among these, Eucalyptus hybrid exhibited the highest transpiration rate (0.97 mmol H_2O m^{-2} s^{-1}) with water consumption ranging from 44.75 to 38.92 l day^{-1}, followed by *Millettia pinnata*, which recorded a transpiration rate of 0.71 mmol H_2O m^{-2} s^{-1} and water use between 41.17 and 35.83 l day^{-1} under varying waterlogged

Table 1: Average daily water consumption (l day^{-1}) by tree species under different water levels, biodrainage potential and transpiration rate

Tree species	0–0.25 m	0.25–0.50 m	0.50–0.75 m	Biodrainage potential	Transpiration rate (mmol H_2O m^{-2} s^{-1})
Eucalyptus hybrid	44.75	42.58	38.92	Highest	0.97
Milletiapinnata	41.17	39.83	35.83	High	0.71
Dalbergia sissoo	32.42	31.08	28.5	Moderate–High	-
Acacia nilotica	31.92	29.17	28	Moderate–High	0.41
Albizia procera	37.25	35.5	32.58	Moderate	-
Albizia lebbek	37.92	35.25	33.75	Low–Moderate	-
Terminalia arjuna	34.25	31.83	31.25	Low	-

Source: (Jain, 2021)

conditions, thereby indicating their superior biodrainage potential (Jain, 2021).

According to Singh and Lal (2018), *Eucalyptus tereticornis* plantations reduced the water table by up to 0.84–0.86 meters in three years in Haryana, India. Further, large-scale plantations of *Eucalyptus camaldulensis* reduced groundwater levels by up to 14 m over six years, depending on soil type, plantation density, and depth to water table in the Indira Gandhi Nahar Project (IGNP) area of Rajasthan. Similar results were observed by Heuperman et al. (2002), who reported significant groundwater decline due to *Eucalyptus* plantations in semi-arid regions of Australia. In areas with water tables upto 2–5 m depth, declines of 0.5–1.2 m annum^{-1} were recorded depending on stand density and root penetration (Heuperman et al., 2002). In the lysimeter studies at TFRI, Eucalyptus hybrid recorded the highest transpiration rate (0.97 mmol H_2O m^{-2}s^{-1}), followed by *Millettia pinnata* (0.71 mmol H_2O m^{-2}s^{-1}). These values were substantially higher than those of *Acacia nilotica* (0.41 mmol H_2O m^{-2}s^{-1}), showing that Eucalyptus and Millettia were significantly more efficient in water use under waterlogged conditions (Jain, 2021). Australian studies also support high annual transpiration in *Eucalyptus* spp., with values ranging from 1200–2300 mm year^{-1} depending on stand density and soil type (Anonymous, 2003). *Eucalyptus hybrid* consistently exhibited superior WUE due to its fast-growing ability, rapid canopy development and high leaf area index. In lysimeter-based comparisons, *Eucalyptus* consumed 30–50% more water than native species like *Dalbergia sissoo* and *Albizia lebbeck* under similar waterlogged conditions (Jain, 2021).

8. Growth Parameters Under Waterlogged Conditions

Tree growth (height and girth) is a reliable indicator of adaptation and biodrainage effectiveness under water stress. Tree species must not only transpire water but also survive and grow under stress conditions. In a study at TFRI, Eucalyptus hybrid recorded a height of 9.1 m and girth of 34.2 cm within three years under lysimeter-controlled waterlogging. *Millettia pinnata* followed closely with 8.1 m in height and 32.9 cm in girth. In contrast, *Terminalia arjuna* and *Acacia nilotica* showed lower growth (5.2–6.3 m height), indicating reduced adaptability to continuous water saturation (Jain, 2021).

Species like *Eucalyptus* also showed strong resistance to varied water table levels, exhibiting lower reductions in growth at higher waterlogging depths compared to other species. This resilience, along with sustained transpiration, supports their selection for reclaiming waterlogged lands. Moreover, field assessments by Angrish et al. (2009) revealed similar trends in Punjab and Haryana, where Eucalyptus and Casuarina outperformed Albizia and Prosopis in terms of height, survival, and canopy spread in waterlogged sites.

9. Impact of Biodrainage on Soil Health

Biodrainage not only helps in managing waterlogging and salinity but also plays a vital role in restoring and enhancing soil health. Tree plantations used in biodrainage influence several physical, chemical, and biological properties of the soil, improving its overall quality and sustainability for agriculture.

9.1. Soil texture and structure

Tree roots improve soil structure by breaking compacted layers and enhancing aggregate stability. Organic matter from leaf litter and root turnover contributes to better soil aggregation, especially in clayey and degraded soils (Masilamani et al., 2020).

9.2. Water infiltration and retention

Root channels created by deep-rooted trees increase water infiltration capacity, while shade provided by tree canopies reduces surface evaporation and enhances soil moisture retention. These effects are more pronounced under species like Eucalyptus and Casuarina (Anonymous, 2003).

9.3. Bulk density and porosity

Several studies, including those by the TFRI, Jabalpur have shown a gradual reduction in bulk density and a rise in porosity under tree plantations. This is attributed to continuous root activity and accumulation of organic residues in the rhizosphere (Masilamani et al., 2020; Anonymous, 2003). A study in the Cauvery Delta region of Tamil Nadu, India assessed soil under plantations of Eucalyptus, Casuarina, Melia, and Teak, demonstrating that bulk density generally decreased over time under tree plantations. For instance, bulk density at 0–15 cm depth under Eucalyptus (over 6 years old) was around 1.26 g cc^{-1}, significantly lower than other tree plantations. This reduction is attributed to increased organic matter and enhanced soil structure around mature trees (Prabha et al., 2024).

9.4. Soil pH and electrical conductivity (EC)

Long-term biodrainage plantations have demonstrated significant reductions in pH and EC in alkali and saline soils. For instance, *Eucalyptus tereticornis* plantations have shown a decrease in soil EC from 6.7 to 3.4 dS m^{-1} over three years, and a slight neutralization in pH from alkaline levels toward near neutrality due to the removal of excess sodium ions and improved soil aeration (Singh and Lal, 2014). The minimum soil pH of 5.96 was recorded in >15 years of *T. grandis* plantation at 0–15 cm depth and the maximum of 7.40 was recorded in 2 to 4 years of Melia at 30–45 cm depth (Prabha et al., 2024).

9.5. Organic matter and nutrient dynamics

Litterfall and root biomass contribute to higher soil organic carbon, while leguminous species such as *Milletia pinnata* and *Acacia nilotica* enrich nitrogen levels through biological fixation. These processes improve soil nutrient cycling and fertility (Anonymous, 2003; Singh and Lal, 2014). The maximum OC (0.69%) at 0–15 cm depth, nitrogen (307.57 kg ha^{-1}) and potassium (339.57 kg ha^{-1}) availability was observed in >5 years of Casuarina clonal plantation (CH-5), while the available phosphorus content was high in >6 years old *E.*

camaldulensis (26.31 kg ha^{-1}) (Prabha et al., 2024).

9.6. Soil microbial activity

Microbial biomass and respiration are enhanced under biodrainage systems due to organic matter input and improved soil aeration. This increase in microbial activity supports nutrient mineralization and soil resilience (Anonymous, 2003). Based on the three-years experimental data in *Millettia pinnata* block, increase in soil microbial biomass carbon (SMBC) from 1029.39 µg g^{-1} to 1306.41 µg g^{-1} and soil microbial biomass nitrogen (SMBN) from 117.62 µg g^{-1} to 146.33 µg g^{-1} was observed (Meshram et al., 2020).

9.7. Enzyme activities

Activities of soil enzymes such as dehydrogenase, phosphatase, and urease are known to increase under tree plantations. These enzymes are key indicators of soil biological health and help support efficient nutrient transformation (Singh and Lal, 2014). Based on the three-year experimental data, the incorporation of *Millettia pinnata* leaf litter significantly improved Dehydrogenase enzyme activity (DHA) from 397.99 µg TPF g^{-1} soil 24 hr^{-1} to 446.53 µg TPF g^{-1} soil 24 hr^{-1}, acid phosphatase activity from 80.01 µg p-NP g^{-1} soil hr^{-1} to 100.09 µg p-NP g^{-1} soil hr^{-1} and alkaline phosphatase activity from 232.98 µg p-NP g^{-1} soil hr^{-1} to 283.90 µg p-NP g^{-1} soil hr^{-1} (Meshram et al., 2020).

10. Limitations And Challenges

Despite magnificent benefits, biodrainage has many constraints as furnished below.

10.1. Land requirement

Biodrainage requires space for planting deep-rooted, high-transpiring trees, which can be challenging for small and marginal farmers who cannot afford to set aside productive land (Anonymous, 2003).

10.2. Salt accumulation in the root zone

While biodrainage removes excess water, salts are not actively taken up by trees. Instead, they may accumulate in the root zone or subsoil, especially in arid areas with high evaporation. Without proper leaching or drainage, this can degrade long-term soil quality (Singh and Lal, 2014).

10.3. Long-term sustainability issues

The effectiveness of biodrainage may decrease over time as tree growth stabilizes, root systems age, and water uptake reduces. In areas with poor rainfall, sustainability is a concern without supplemental water management strategies (Heuperman et al., 2002).

10.4. Farmers' adoption barriers

Lack of awareness, technical knowledge, and immediate economic returns discourages adoption. Additionally, concerns about competition with crops and restrictions on tree harvesting in some regions pose institutional and legal challenges (Masilamani et al., 2020).

11. Future Scope and Recommendations

The success of biodrainage depends on selecting species adapted to the region's soil type, salinity, waterlogging depth, and climate. Research institutions should develop region agro-ecological zone specific biodrainage packages. In areas with high salinity risk, biodrainage should complement, not replace, engineering drainage systems to ensure both water removal and salt leaching. Public lands, canal bunds, and roadsides provide ideal locations for biodrainage plantations without affecting cropping areas. These spaces can also serve as community woodlots for fuel and fodder. Government programs should promote biodrainage through incentives, capacity building, and inclusion in watershed and land reclamation schemes. Clear guidelines and legal provisions for tree harvesting would encourage farmer participation.

12. Conclusion

Species like Eucalyptus hybrid, *Millettia pinnata*, and *Dalbergia sissoo* have demonstrated high efficiency in lowering water tables and improving soil physical and biological properties. Proper species selection, integration with Agroforestry systems, and site-based planning were essential for long-term success. When aligned with policy support and awareness, biodrainage offered a dual-benefit solution of restoring ecological balance while supporting farmers through fuel, fodder, and timber yields. This approach also supported key Sustainable Development Goals (SDGs) by promoting sustainable land and water management.

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