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Soil and Water Quality as Determinants for Mangrove Survival in Bimmanga, Tagudin, Ilocos Sur

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ABSTRACT

Mangrove ecosystems are essential in terms of protecting the coast, biodiversity and mitigating climate change. Most of the restoration projects however do not succeed because of lack of knowledge on the local environmental conditions. The paper evaluated the quality of soil and water of the Bimmanga estuary at Tagudin, Ilocos Sur, to determine its ability to sustain the survival of mangroves and reforestation plans in the future. Through descriptive-exploratory design, samples were taken in three stations and studied to determine main physical and chemical parameters, such as soil moisture, texture, tidal effect, pH, salinity, temperature, dissolved oxygen, nitrate, phosphate, and nutrient level. The ecological tolerances of four mangrove species namely Avicennia marina, Bruguiera gymnorrhiza, Sonneratia alba, and Rhizophora mucronata were compared with the results in order to identify species suitability. Results revealed spatial differences in environmental conditions and that environmental conditions were suboptimal in some regions and might have caused poor mangrove establishment. Among the species evaluated, Avicennia marina, Brugueria gymnorrhiza and Sonneratia alba, which are reported to have wider ecological adaptation, were found to be more appropriate species in the site. Findings were used to develop science based policy brief, which was confirmed by the local government stakeholders to inform the restoration planning process. The research has a contribution to the Sustainable Development Goals 13 (Climate Action), 14 (Life Below Water) and 15 (Life on Land) since it highlights that evidence-based mangrove management is required. In totality, the study demonstrates the extreme importance of baseline ecological studies in the success of mangrove restoration initiatives and provides a model of a replaceable type in other coastal ecosystems in the Philippines.

INTRODUCTION

Mangroves are isolated but endangered ecosystems that offer ecological, economic, and social values in the world. They serve as natural defenses against storm surges, floods, and erosion, and are also home to a variety of marine and land-based species and are significant atmospheric carbon sinks (Food and Agriculture Organization of the United Nations, 2023; Sofue *et al*., 2025). Nevertheless, mangroves have experienced severe degradation because of the growing human activities, such as deforestation, development of aquaculture, urbanization, and climate change effects, as over 20 percent of the overall mangroves have been destroyed worldwide over the past 40 years (FAO, 2023). The same tendencies are evident in the Philippines, though this country, though having one of the largest mangrove reserves, suffered a steep fall as the area declined to only 117,700 hectares of mangroves in 1995 (Buitre *et al*., 2019).

The restoration measures have been actively taken, but most of them do not work, as a result of poor site-specific evaluation of ecological situations. Mangroves have specific environmental needs, especially about soil characteristics such as the texture, salinity, and organic composition, and water quality indicators such as nutrient content, tidal submergence and pollution (Alongi, 2018; Choudhary *et al*., 2024; De Silva & Amarasinghe, 2021). Any project that ignores the following critical factors may end up with high mortality rates of the seedlings and wastage of resources as witnessed in the failed planting project in Bimmanga Estuary, Tagudin, Ilocos Sur in 2007. Although the area has had an ecological potential, the failure highlighted the need to have baseline environmental data to inform the restoration planning and implementation.

Since the Philippines is prone to natural disasters and mangroves are vital in protecting the territory, any conservation measures implemented should be based on local scientific analyses. This paper thus examines the soil and water quality of Bimmanga Estuary to ascertain whether it is viable in the restoration of the mangroves or not. The research also informs national and provincial conservation priorities by creating evidence-based recommendations and addressing Sustainable Development Goals (SD G's) 13, 14, and 15, focusing on climate action, marine ecosystem protection, and sustainable land management. The results will enhance further reforestation programs and provide the ability to protect the ecological sustainability and community welfare in the long term.

LITERATURE REVIEW

Ecological Importance of Mangrove Ecosystems

Mangroves are unique coastal forests that thrive at the interface of land and sea in tropical and subtropical

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regions (Welling, 2023). These ecosystems consist of trees and shrubs adapted to fluctuating oxygen levels, salinity, and tidal influences (Chowdhury *et al.*, 2024; Friess *et al.*, 2019; Huntley, 2023). Because of their ecological richness, mangroves are often referred to as the "rainforests of the sea" (Law *et al.*, 2019). They provide a wide range of ecosystem services such as supporting aquaculture and agriculture (Das *et al.*, 2022), supplying timber and medicinal resources (Mitra, 2019; Vinoth *et al.*, 2019), protecting coastal communities from floods, storms, and tsunamis (Beck *et al.*, 2022; Kamil *et al.*, 2021), and serving as habitats for both terrestrial and aquatic species (Ma *et al.*, 2020).

Mangroves are also vital for climate regulation, as they sequester large amounts of atmospheric carbon—often more effectively than many terrestrial ecosystems (Tillardat *et al.*, 2018; Zhu & Yan, 2022). Globally, mangroves are estimated to store up to 21,896.56 Mt CO_2e, with the majority stored in soils (Bunting *et al.*, 2022; Sumarmi *et al.*, 2021). However, when degraded, mangroves release stored carbon, contributing to climate change (Jennerjahn, 2020). Moreover, mangroves function as natural water filters by regulating salinity, trapping pollutants, and improving the condition of adjacent ecosystems such as coral reefs and seagrass beds (Jordan & Frohle, 2022; Liu *et al.*, 2021).

Beyond ecological services, mangroves provide direct socio-economic benefits. They supply food, fodder, timber, and livelihoods to millions, particularly in developing nations (Arora & Arora, 2023; Eger *et al.*, 2023). Mangroves also enhance ecotourism, which supports local economies while fostering conservation awareness (Basyuni *et al.*, 2018; Friess, 2017). In the Philippines, mangroves play a key role in disaster risk reduction. For instance, during Typhoon Rai in 2021, intact mangrove stands in Palawan helped reduce property damage and supported fisheries recovery (Beck & Lange, 2017; Fabro, 2022).

Soil and Water Quality in Mangrove Growth

The growth, distribution, and species richness of mangroves are closely tied to soil properties. Mangrove soils are typically saline, waterlogged, and rich in organic matter, requiring species-specific adaptations (Alongi, 2018). Soil texture, particularly clay and loam, enhances aeration and nutrient retention (Twilley *et al.*, 2019). Likewise, soil organic carbon (SOC) supports microbial activity and nutrient cycling (Hamilton & Casey, 2016). Optimal nutrient levels, particularly nitrogen and phosphorus, sustain productivity, whereas imbalances can hinder growth or trigger eutrophication (Appoo *et al.*, 2024; Verano *et al.*, 2023).

Water quality is equally critical. Tidal exchange regulates salinity, nutrient cycling, and sediment deposition factors vital to mangrove survival (Choudhary *et al.*, 2024). Key water parameters include salinity, pH, dissolved oxygen (DO), nutrients, and temperature (Mariappan *et al.*, 2015). Drastic salinity shifts reduce canopy height and biodiversity (Perri *et al.*, 2023), while low DO levels cause hypoxic stress that impairs root respiration (Dubuc *et al.*, 2019). Seasonal changes in water temperature and nutrient influx from land runoff also affect mangrove health (Aljahdali *et al.*, 2021; Sulochanan *et al.*, 2022). These findings highlight the importance of soil and water quality in mangrove restoration and conservation.

Environmental Factors Affecting Mangrove Survival

Mangrove survival is influenced by both natural and anthropogenic factors. Natural variables include salinity, tidal fluctuations, temperature, and soil characteristics, which determine species distribution and resilience (Dapar *et al.*, 2023; Kodikara *et al.*, 2017). Excessive salinity reduces biodiversity and canopy growth (Perri *et al.*, 2023). Climate change, particularly rising temperatures and sea-level rise, further exacerbates mangrove dieback, as seen in Northern Australia (Ward *et al.*, 2016).

Human activities, such as overharvesting, deforestation, aquaculture expansion, pollution, and urbanization, accelerate mangrove degradation (Freedman, 2024; Velez-Mendoza *et al.*, 2023). However, cultural practices can play a protective role. For instance, in Benin, mangroves are preserved through traditional spiritual practices that align with modern conservation (Valo & Strek, 2024).

Scientific Approaches in Assessing Soil and Water Quality

Recent studies employ advanced methods to assess soil and water quality in mangrove ecosystems. Techniques such as fuzzy comprehensive evaluation, geostatistical modeling, and multivariate statistics are used to measure parameters like pH, salinity, organic matter, and heavy metals (Nguyen *et al.*, 2024; Zhang *et al.*, 2024). In Malaysia, geostatistical analysis revealed site-specific variations in soil quality between regenerating and mature forests, suggesting the need for tailored restoration strategies (Assessing Soil Quality..., 2018).

A systematic review of mangrove soil research emphasized that soil health does not always directly correlate with ecosystem services, underscoring the importance of developing indices tailored to mangrove conditions (Mello *et al.*, 2024). These approaches provide scientific benchmarks that guide conservation practices and restoration planning.

Policy and Management Strategies for Mangrove Conservation

Despite their ecological and economic value, mangroves are declining globally due to deforestation, aquaculture expansion, and climate change (Goldberg *et al.*, 2020). Conservation strategies now emphasize sustainable use and protection. Integrating traditional knowledge with scientific practices through community-based conservation has proven effective (National Law and Policy..., 2023). Financial mechanisms, such as payments for ecosystem services, carbon credits, and debt-for-nature swaps, also promote restoration efforts (World

Bank *et al.*, 2023).

Nonetheless, challenges persist. Weak enforcement, conflicting land-use priorities, and limited incorporation of scientific evidence in policymaking hinder progress (Elsa, 2024). Experts recommend multi-stakeholder approaches that integrate legal, economic, and community-based strategies to ensure long-term sustainability (Patrick, 2024).

MATERIALS AND METHODS

Materials

Three sampling stations were placed along the Bimmanga Estuary in Tagudin, Ilocos Sur with a transect based technique with 100 meter intervals between sampling stations. The collection of both soil and water samples was done using sterilized plastic containers, which were well labeled and coded to ensure that the samples could be traced back. Grab sampling was the sampling method as the soil was collected using either shovels or augers and the water collected was taken by hand at defined depths and time. All the trials obtained at least 3 kg of soil and 3 L of water per station.

To measure the quality of soil and water a variety of equipment and reagents were used in laboratory analysis. A pH meter was used to measure the soil pH and an electrical conductivity meter was used to measure salinity. The content of moisture, texture, organic matter and the content of the essential nutrients like nitrogen, phosphorus, and potassium were evaluated using soil test kits. In the case of water parameters, dissolved oxygen was measured by a dissolved oxygen meter and potassium and sodium concentrations in the nutrient were tested by the use of spectrophotometer or colorimeter. The test kits were water test kits to measure the nitrate and phosphate concentration and the thermometers were used to measure the water temperature. Moreover, chemical reagents were used to detect nutrients; namely, cadmium reduction and ascorbic acid. The processes were used to identify the overall condition of soil and water and were used as the basis of determining the suitability of mangroves in the estuary.

Research Design

The descriptive-exploratory design was used. The descriptive component quantified the characteristics of soil and water systematically, and the exploratory component examined some of the background factors, which determine the survival of mangroves. This type of design fitted understudied settings with a small amount of baseline data (McCombes, 2023; Heffernan, 2025).

Sampling Procedures

Soil and water samples were collected simultaneously from three stations along the estuary lower stream (Station 1), middle stream (Station 2), and upper stream (Station 3) at 15-day intervals on March 23, April 7, and April 22, 2025, following Cortez (2015). Sampling was conducted between 6:00 and 8:00 a.m. using the grab method described by Elvira *et al.* (2020) and Groten *et al.* (2023). Soil was obtained at a depth of 50 cm, while at least 3 L of water was collected per trial, with both samples placed in sterilized, labeled containers and transported for analysis. Soil parameters included moisture, texture, pH, organic matter, nitrogen, phosphorus, potassium, salinity, and tidal influence, while water parameters comprised pH, salinity, temperature, dissolved oxygen, nitrate, phosphate, potassium, sodium, and tidal influence.

Laboratory Analysis

All the samples were delivered within 24 hours to the Integrated Agricultural Laboratories Division-Regional Soils Laboratory, Sta. Barbara, Pangasinan, the Philippines. Chemical and physical analyses were performed using standard laboratory procedures and field-based parameters (tidal effect, salinity, nitrogen, dissolved oxygen and temperature) were noted by the researcher.

Suitability Assessment

Following González-Zamora *et al.* (2024) and Martinez and Buot (2018), soil and water parameters were compared against the optimal ranges required for mangrove species in the Second District of Ilocos Sur. Reference values for species-specific tolerances were adopted from different books, journals and articles. This assessment identified which mangrove species could survive under existing environmental conditions.

Policy Brief Development

A policy brief was drafted based on empirical findings from the soil and water assessments and the suitability evaluation. Its preparation followed international guidelines for policy brief development (University of Waterloo, n.d.; CEFTA, 2018; The Prevention Centre, 2023), ensuring clarity, scientific rigor, and practical application. The policy brief was validated by three experts from the Local Government Unit (LGU) of Tagudin representatives from the Agriculture Office, Tourism Office, and MENRO to align recommendations with local programs and stakeholder needs.

Data Gathering Procedure

To minimize variability, three replications per site were collected at 15-day intervals. A minimum of 500 g of soil and 1 L of water per replicate was submitted for laboratory analysis, as required by the testing facility. Documentation of sampling procedures ensured transparency and reproducibility. Parameters not analyzed in the laboratory (tidal influence, salinity, dissolved oxygen, temperature) were directly measured by the researcher using field instruments. Results were then compared with species-specific tolerances to identify suitable mangrove species.

Statistical Treatment

Collected data were analyzed using mean values to represent average conditions of soil and water parameters across the three trials. Descriptive statistics were employed to interpret suitability levels of the observed values against environmental thresholds of mangrove species in the study area.

RESULTS AND DISCUSSION

Table 1 shows the physical parameters of soil in Bimmanga Estuary in terms of soil moisture, soil texture (particle size) and tidal influence.

Table 1: Soil Quality of Bimmanga Estuary along Physical Parameters

Soil Physical Parameters	Station 1 Lower Stream	Station 2 Middle Stream	Station 3 Upper Steam	Weighted Mean
Soil Moisture (%)	8.29	8.68	9.15	8.71
Soil Texture (Particle Size)	Clay	Clay	Clay Loam	------
Tidal Influence	No tidal influence	No tidal influence	No tidal influence	------

Table 1 shows the physical properties of soil in three stations, Lower Stream (Station 1), Middle Stream (Station 2), and Upper Stream (Station 3) and calculated mean (M) to give a summary. The moisture content of the soil in the various stations varies between 8.29 percent and 9.15 percent with Station 3 having the highest content of moisture. The mean of soil moisture in the study area was 8.71%. These values show that there are comparatively low moisture content that can affect the establishment and growth of vegetation especially to species that thrive on water like mangroves. Alongi (2007) argues that the distribution and productivity of mangroves is highly dependent on soil moisture in areas where tidal inputs are unimportant.

The low soil moisture may affect the establishment of the seedlings and the physiological activity of the mangrove species which demand regular availability of water. According to Krauss *et al.* (2008), soil moisture influences root respiration and nutrient uptake particularly in stressful situations. Since the site is relatively dry, mangrove species that can endure moderate lack of water like Avicennia marina or Sonneratia alba could be more appropriate to test the planting at first. In addition, low moisture can also signify low microbe activity and slow rate of detrimental matter, both critical in nutrient relocation and soil fecundity (Uphoff, 2006).

With regard to the soil texture, Stations 1 and 2 are clay soils whilst Station 3 had a variation with clay loam that includes sand, silt and clay particles. Clay soils rapidly retrieve water but have low permeability, thus potentially hindering penetration of roots and aeration (Weil and Brady, 2016). Clay loam on the other hand has superior travel and aeration as well as capitalize on sufficient moisture thus being more conducive to the growth of plant roots. The average classification of the study places is that the site has clay as the most prevalent texture which implies that there may be difficulties to the species that need well-drained soils.

Salinity buffering and redox potential may also be influenced by the largely occurring clay. The soils with high degrees of compactness are frequently anaerobic, and thus, oxygen becomes limited to roots; hence, mangrove roots respiration and seedling development are also limited (Alongi, 2012). Nevertheless, these soils may also be used to lend some structural support and reduce the erosion in the riverine or estuarine setting. Walter *et al.* (2008) argue that long-term survival of mangrove plantations is more likely when the selection of the species is made in line with the soil conditions and the soil is stable and not easily perturbed like sites with clay or clay loam.

All the identified stations were found to be characterized by the absence of tidal effect, which means that the localities are inland or upwardly located where tidal movements do not reach them. This is a crucial aspect that has a great impact on the ecological features of a given area especially when conducting a study on wetland or mangrove restoration. According to Kathiresan and Bingham (2001), tidal fluctuation is important in the mangrove ecosystem as it is vital in nutrient cycling, seed dispersal, and controlling of salinity in soil. It is possible that the lack of tidal effects in the area of the study will restrict the range of species of mangroves that can be naturally present, and support the mangrove adapted to more stagnant hydrological regimes.

It could also lead to a decrease in natural deposition of fine sediments and hinder flushing of toxins and salt in the soil which could lead to poor soil aeration and stagnant conditions (Twilley & Rivera-Monroy, 2005). Hence, this kind of habitat can be upgraded with additional hydrological treatments, e.g. artificial canals or managed water circulation systems to mimic tidal exchange, and make the site favorable to an increasing variety of mangrove species.

The differences in the suitability of mangroves are also in terms of variations in the soil texture (between sandy loam and clay loam), moisture, and tidal effects among the three sampling stations. Clay loam sites (e.g. Station 3) have superior retention and anchorage of moisture, thus preferring species to need stable substrates such as Rhizophora mucronata. Conversely, the sandy soils can result in a greater drainage and lower nutrition absorption rates, which is appropriate to the more resilient species such as Avicennia marina (Alongi, 2018; Suello *et al.*, 2022). Tidal power improves the process of aeration and sediment deposition (Choudhary *et al.*, 2024), and it means that those locations where the tidal impact is strong are potential places to restore mangroves unless the appropriate species are provided.

The general trend of the physical properties of the soils in the three stations implies that the environment is moderately moist, fine-textured, and has low hydrological diversity. The findings can be used as a reference point to assess the appropriateness of the area in terms of particular land use or ecological intervention, like planting mangroves, or rehabilitating habitat. The soil amendments (e.g. the inclusion of organic matter or mulching) and, potentially, hydrological enhancement should be prioritized in the future site planning that is aimed at facilitating the planting and survival of mangroves. The low moisture and absence of tidal flushing may also be minimized by the incorporation of bioengineering methods, which include planting nurse species or creating micro-dykes (Primavera *et al.*, 2012).

Table 2: Soil Quality of Bimmanga Estuary along Chemical Parameters

Soil Physical Parameters	**Station 1 Lower Stream**	**Station 2 Middle Stream**	**Station 3 Upper Steam**	**Weighted Mean**
pH levels	7.99	8.19	8.05	8.08
Salinity (mS/m)	2.36	2.35	2.24	2.32
Organic Matter (%)	2.68	3.10	2.41	2.73
Nitrogen (mg/L)	10.00	10.00	10.00	10.00
Phosphorus (ppm)	3.34	6.99	11.29	7.21
Potassium (cmol/kg)	2.20	1.62	1.64	1.82

Table 2 presents the chemical parameters of soil in terms of pH levels, salinity, Nutrients content (OM, N, P, K) across three stations in the Bimmanga Estuary: Lower Stream (Station 1), Middle Stream (Station 2), and Upper Stream (Station 3), with computed means for each parameter.

The level of pH of the soil is between 7.99 and 8.19 with a mean of 8.08 which shows it is slightly alkaline. The pH of soil has a strong influence on nutrient availability, such as phosphorus and micronutrients including iron and zinc which are less available in alkaline soils (Fageria & Baligar, 2008; Weil & Brady, 2016).

However, physiological adaptations that allow these mangroves to absorb nutrients in diverse pH conditions have been observed to allow many mangrove species to endure such mildly alkaline conditions, including Avicennia marina and Sonneratia alba (Tomlinson, 2016; Hossain and Nuruddin, 2016). Also, pH causes changes in the microbial activity and decomposition rates, which ultimately causes changes in soil fertility (Uphoff, 2006).

The salinity at all three stations is homogeneously low with a variety ranging between 2.24 and 2.36 mS/m with an average value of 2.32 mS/m. These salinity levels are far lower than the salinity tolerance levels of most mangrove species. As a case in point, Avicennia marina is capable of surviving in a salinity that is greater than 400 mS/m (Ball, 1988), with Rhizophora stylosa and Sonneratia caseolaris also reported to thrive in moderate to high salinity (Parida & Jha, 2010). Therefore, the salinity level in the research area is not a constraint and can, in fact, be beneficial to those species that are adapted to live in freshwater or a slightly salty habitat, such as Brugueria gymnorrhiza. In addition, low salinity boosts the microbial activity, nutrient cycle in the soils, which are favorable to the establishment of mangroves (Alongi, 2002; Choudhary *et al.*, 2024).

The range of organic matter (OM) content is between 2.41 and 3.10 with an average of 2.73, which means that the soil of the area is fertile. Weil and Brady (2016) argue that soils containing over 2 percent organic matter tend to sustain the healthy growth of plants because of the high moisture retention and nutrient availability of the soil and the better soil structure. Organic matter also plays an important role in the wetlands ecosystem because it sustains microbial communities and adds to the food chains built on detritus (Alongi, 2012). Nevertheless, the fact that the OM is a bit lower in Station 3 could indicate that organic enrichment has to be made in that region, especially in case some mangrove species with nutrient requirements could be introduced. Fertility and biomass of microbes can be improved by adding compost, green manure, or litter (Primavera *et al.*, 2012).

Nitrogen levels are also high in all the stations with 10.00mg/L, which is in the optimum range of 5-15mg/L that most plant species require (Havlin *et al.*, 2005). Nitrogen plays the vital roles of vegetative growth, protein synthesis, and photosynthesis. Nitrogen in mangroves is also known to support seedling early growth and root and shoot biomass (Reef *et al.*, 2010). The evenly distributed nitrogen levels indicate that the region is capable of supporting species that have a medium to high nitrogen demand, although nitrogen dynamics should be monitored through time especially in other parts that are not exposed to tidal effects to prevent the accumulation or loss of nutrients.

There is a greater variation in phosphorus content with the range being between 3.34 and 11.29 ppm, mean being 7.21 ppm. Phosphorus plays an important role in the development of the root, transfer of energy and reproductive growth in plants (Burt, 2004). The average phosphorus content reflects a moderate level of fertility but the large range of values across the stations, especially the low one at Station 1, indicates that the amount of phosphorus might be uneven. Phosphorus in alkaline soils is likely to precipitate and thus its intake is restricted (Uphoff, 2006). To overcome this, fertilization with phosphorus or application of phosphate-solubilizing microorganisms could be a useful idea particularly in phosphorus-deficit regions.

The potassium level is between 1.62 and 2.20 cmol/kg with the mean K level as 1.82 cmol/kg. This is on the adequate range of the majority of plant species (Webster, 2007). Potassium maintains many physiological functions, such as activating enzyme functions, water regulation, and disease resistance. It is also essential in the stomatal activity and improves plant tolerance to environmental stress (Wang *et al*., 2013). The relatively constant levels of potassium indicate that the soil in the estuary is capable of promoting healthy development of seedlings of the mangrove. Nevertheless, it has been found that site-specific variation in the retention of potassium can be due to the soil texture and cation exchange capacity that are subject to change locally even in other similar ecosystems. Altogether, the chemical properties of the soil in the estuary of the Bimmanga River suggest that the environment is moderately fertile, non-salty, and slightly alkaline. Although the amounts of nitrogen and organic matter are desirable, differences in the phosphorus and potassium between the stations indicate that the stations require specific soil management practices. Other species that like nutrient-enriched areas, e.g. Rhizophora mucronata and Brugueria gymnorrhiza, might have to be supplemented in low areas of OM or phosphorus. In the meantime, Avicennia marina, a robust and stress-resistant species can be considered better suited to locations that are less fertile or have unequivocal nutrient content (De Silva & Amarasinghe, 2021; Appoo *et al*., 2024). Generally, the soil productivity has potentials of restoring the mangroves however, it requires site specific treatment like organic mulching, mycorrhizal inoculation and slow release of fertilizers in order to guarantee long term success.

Table 3: Water Quality of Bimmanga Estuary along Physical Parameters

Soil Physical Parameters	**Station 1 Lower Stream**	**Station 2 Middle Stream**	**Station 3 Upper Steam**	**Weighted Mean**
Tidal Influence	No tidal influence	No tidal influence	No tidal influence	-------
Water Temperature (^{0}C)	29.50	30.63	30.53	30.22

Table 3 summarizes the physical characteristics of water across three stations: Lower Stream (Station 1), Middle Stream (Station 2), and Upper Stream (Station 3), focusing on tidal influence and water temperature, both of which are critical for determining the ecological suitability of aquatic and riparian habitats.

Each of the stations was reported to be of no tidal effect, which suggests that the sampled points are inland or on elevated location to be affected by ordinary tidal encroachment. Tidal flushing does not occur anymore, limiting the nutrient inflow and sediment deposition, which are important in the nutrient cycling, regulation of salinity and dispersal of propagules within the mangrove ecosystem (Kathiresan & Bingham, 2001).

Mangroves species that rely on tidal variations, e.g. Rhizophora stylosa or Bruguiera gymnorrhiza, in such conditions could find it difficult to flourish without external efforts or soil remedies. Nevertheless, more freshwater- or low-energy-tolerant species can still occur on this stable hydrology, such as Avicennia marina and Sonneratia caseolaris, which also live in systems of less mobility, non-tidal estaurine (Perri *et al*., 2023).

The temperature of the water ranged between 29.50degC at Station 1 and 30.63degC at Station 2 with an average of 30.22degC, which is well within the optimal temperature range of biological activity in the tropical waters. UNESCO (2006) asserts that tropical freshwater ecosystems are most effective at a thermal range of 25degC to 32degC that facilitates enzymatic industries, photosynthesis, and other metabolic activities in aquatic plants and microbial societies. As Alongi (2007) remarks, warm water temperatures are specifically conducive to the growth of mangrove seedlings and their biomass in the sense that other stressors of the seedlings like salinity, turbidity, or nutrient deficit will not be limiting. The thermal conditions imply that the study area has potential to be used in re-foresting of mangroves or enrichment planting especially of freshwater-tolerant or euryhaline species.

Also, it is worth mentioning that, due to the thermal stability in the absence of tidal exchange, the oxygenation and sediment turnover of the aqua regia may be low and, as such, it may have an impact on the root respiration and the development of the young seedlings. As pointed out by Akram *et al*. (2023), the decreased water motion can slow down the penetration of light and elevate the chances of sediment anoxia, which has adverse impacts on the below-ground structures of mangroves and submerged communities of plants. Water clarity and dissolved oxygen levels although not a part of the main table are essential to a healthy root zone. Additionally, the lack of tidal influence eliminates one of the vectors of nutrient delivery and necessitates that strategies of nutrient supplementation or enrichment planting will be successful in ecological restoration (Choudhary *et al*., 2024).

Overall, the freshwater conditions at the three stations are non-tidal and thermally stable, and this observation allows a few and ecologically significant restoration options. Such conditions might not be conducive to all mangrove species, although they do promote the establishment of some of the taxa which are better adapted to lower salinity conditions and stable freshwater conditions. Where there is strategic selection of species and management of the habitat, the site has the potential of being a possible restoration area to conserve biodiversity and sequester carbon.

Table 4 presents the chemical parameters in terms of dissolved oxygen, pH levels, salinity, Nutrients content (K, Na), Nitrate (NO_3) and Phosphate (PO_4). It presents the chemical parameters of water in the Bimmanga Estuary, highlighting key aspects of water quality across

Table 4: Water Quality of Bimmanga Estuary along Chemical Parameters

Soil Physical Parameters	Station 1 Lower Stream	Station 2 Middle Stream	Station 3 Upper Steam	Weighted Mean
Dissolved Oxygen (mg/L)	1.10	1.50	1.33	1.31
pH levels	7.56	7.61	7.67	7.61
Salinity (us/cm)	3304.67	3325.33	3522.67	3384.22
Nutrient Content Potassium (ppm) Sodium (ppm)	25.79	23.78	22.96	24.18
	407.73	372.08	349.46	376.42
Nitrate	5.00	5.00	5.00	5.00
Phosphate	1.00	1.00	1.00	1.00

the three stations: Lower Stream, Middle Stream, and Upper Stream.

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The temperature of the water ranged between 29.50degC at Station 1 and 30.63degC at Station 2 with an average of 30.22degC, which is well within the optimal temperature range of biological activity in the tropical waters. UNESCO (2006) asserts that tropical freshwater ecosystems are most effective at a thermal range of 25degC to 32degC that facilitates enzymatic industries, photosynthesis, and other metabolic activities in aquatic plants and microbial societies. As Longi (2007) remarks, warm water temperatures are specifically conducive to the growth of mangrove seedlings and their biomass in the sense that other stressors of the seedlings like salinity, turbidity, or nutrient deficit will not be limiting. The thermal conditions imply that the study area has potential to be used in re-foresting of mangroves or enrichment planting especially of freshwater-tolerant or euryhaline species.

Also, it is worth mentioning that, due to the thermal stability in the absence of tidal exchange, the oxygenation and sediment turnover of the aqua regia may be low and, as such, it may have an impact on the root respiration and the development of the young seedlings. As pointed out by Akram *et al.* (2023), the decreased water motion can slow down the penetration of light and elevate the chances of sediment anoxia, which has adverse impacts on the below-ground structures of mangroves and submerged communities of plants. Water clarity and dissolved oxygen levels although not a part of the main table are essential to a healthy root zone. Additionally, the lack of tidal influence eliminates one of the vectors of nutrient delivery and necessitates that strategies of nutrient supplementation or enrichment planting will be successful in ecological restoration (Choudhary *et al.*, 2024).

Overall, the freshwater conditions at the three stations are non-tidal and thermally stable, and this observation allows a few and ecologically significant restoration options. Such conditions might not be conducive to all mangrove species, although they do promote the establishment of some of the taxa which are better adapted to lower salinity conditions and stable freshwater conditions. Where there is strategic selection of species and management of the habitat, the site has the potential of being a possible restoration area to conserve biodiversity and sequester carbon.

Table 5: Suitability of the Soil's Physical and Chemical Parameters for specific mangrove species.

Parameter	Observed Range	Ideal Range for Mangroves	Interpretation
Soil Moisture (%)	8.29–9.15 (Mean: 8.82)	>20% (tidal zone); 8–15% acceptable inland	Not Suitable
Soil Texture	Clay to Clay Loam	Clay, Silty Clay, Clay Loam	Suitable
Tidal Influence	No Tidal Influence	Intertidal preferred, but some tolerate none	Not Suitable
pH	7.99–8.19 (Mean: 8.08)	6.50 – 8.50	Suitable
Salinity (mS/m,dS/m)	2.24–2.36 mS/m (≈ 0.22–0.24 dS/m)	5–30dS/m (brackish to saline)	Not Suitable
Organic Matter (%)	2.41–3.10 (Mean: 2.73)	>2%	Suitable
Nitrogen (mg/L)	10.00 (constant)	5–15 mg/L	Suitable
Phosphorus (ppm)	3.34–11.29 (Mean: 7.21)	3–10 ppm	Suitable

Table 5 presents the physical and chemical parameters of the soil in the Bimmanga Estuary, along with their respective ideal ranges for mangrove growth and their interpreted suitability. These parameters are critical in evaluating whether the soil environment can support sustainable mangrove restoration.

Soil moisture in the area ranged from 8.29% to 9.15%, with a mean of 8.82%. While this falls within the acceptable range for inland mangroves (8–15%), it is significantly below the >20% optimal requirement for intertidal mangroves. Low soil moisture limits nutrient mobility and root respiration, particularly in clay-rich soils where water availability determines root extension and gas exchange (Krauss *et al.*, 2008; Alongi, 2012). The observed values imply a non-optimal condition, likely to reduce mangrove seedling survival unless supplemented by periodic flooding or irrigation.

Soil texture ranged from clay to clay loam, which is considered suitable for mangrove establishment. Such textures are ideal for their high nutrient retention, moisture-holding capacity, and strong support for extensive root systems (FAO, 2001; Tomlinson, 2016). Fine-textured soils can also facilitate anoxic conditions necessary for mangrove-specific microbial processes, including nitrogen fixation and sulfate reduction (Alongi, 2007).

Tidal influence was absent in all sampled locations, marking it as not suitable based on standard mangrove ecological needs. Tidal action facilitates sediment deposition, nutrient cycling, and seed dispersal, key factors in mangrove regeneration (Kathiresan & Bingham, 2001). However, species like Avicennia marina and Heritiera fomes have shown resilience in low or non-tidal conditions, making them potential candidates for restoration in these areas (Primavera & Esteban, 2008; Ma *et al.*, 2020).

The pH levels, ranging from 7.99 to 8.19 (mean: 8.08), were within the optimal range of 6.50 to 8.50, making the site suitable in this regard. Neutral to slightly alkaline pH conditions enhance nutrient solubility and microbial activity, thus supporting root development and organic matter decomposition (Dewangan *et al.*, 2023). It also indicates minimal acid sulfate soil influence, which is favorable for long-term ecosystem health.

Salinity, measured between 2.24 to 2.36 mS/m (equivalent to 0.22 to 0.24 dS/m), is significantly below the ideal range of 5 to 30 dS/m required by most halophytic mangroves. Such low salinity conditions are not suitable for typical coastal mangrove species, although inland-adapted species like Bruguiera sexangula and Sonneratia caseolaris may still tolerate these environments (Ball, 1988; Kodikara *et al.*, 2017). Additionally, low salinity could promote competition from freshwater species, affecting mangrove dominance.

Organic matter levels ranged from 2.41% to 3.10%, with a mean of 2.73%, exceeding the >2% minimum for mangrove soils. This is suitable and beneficial for microbial biomass and nutrient cycling (Alongi, 2007). High organic matter improves soil aeration and enhances the soil's water-holding and nutrient retention capacity, especially in submerged or anaerobic conditions (FAO, 2001; Santos *et al.*, 2020).

Nitrogen was constant at 10.00 mg/L, which is within the ideal range of 5–15 mg/L. This makes it suitable for promoting leaf growth, chlorophyll production, and shoot development in mangroves (Kathiresan & Bingham, 2001). Adequate nitrogen levels also support the establishment phase of seedlings by increasing resilience to salinity and oxidative stress (Devlin & Brodie, 2023).

Phosphorus ranged from 3.34 to 11.29 ppm (mean: 7.21 ppm), which mostly aligns with the ideal range of 3–10 ppm. It is essential for root formation and energy metabolism, and its availability often limits growth in mangrove environments (Alongi, 2007; FAO, 2001). However, concentrations exceeding 10 ppm, as observed in some samples, may indicate localized anthropogenic inputs such as agricultural runoff, requiring monitoring to avoid potential eutrophication (Santos *et al.*, 2020).

The soil conditions present mixed suitability for mangrove growth. The favorable pH, texture, nutrient levels, and organic matter provide a supportive base for selected mangrove species. However, the absence of tidal influence, low soil moisture, and extremely low salinity significantly limit the establishment of most intertidal mangrove species.

Species such as Avicennia marina, Sonneratia alba, and Heritiera fomes may still thrive under these constraints due to their tolerance for low salinity and non-tidal conditions (Ma *et al.*, 2020; De Silva & Amarasinghe, 2021). Conversely, species like Rhizophora mucronata and Bruguiera gymnorrhiza may struggle without modifications to soil moisture or hydrological inputs. These findings underscore the necessity for species-site matching, hydrological restoration (e.g., controlled tidal flooding), and ecosystem-based planning to ensure long-term rehabilitation success (Primavera & Esteban, 2008; Alongi, 2012).

Table 6: Suitability of the Water's Physical and Chemical Parameters for specific mangrove species.

Parameter	Observed Range	Ideal Range for Mangroves	Interpretation
Tidal Influence	No Tidal influence	Preferred for dispersal and nutrient exchange, but not mandatory	Not Suitable
Water Temperature (°C)	29.50–30.63°C (Mean: 30.22)	26–32°C	Suitable
Dissolved Oxygen (mg/L)	1.10–1.50 mg/L (Mean: 1.31)	>2.00 mg/L (optimal); some tolerate <1.5 mg/L	Not Suitable
pH levels	7.56 – 7.67 (Mean: 7.61)	6.50 – 8.50 (neutral to slightly alkaline)	Suitable

Salinity (ppt)	~2 ppt/~3300–3500 µS/cm)	>2%	Suitable
(Mean: 3384.22)	5 – 35 ppt	5–15 mg/L	Suitable
(varies by species)	Not Suitable	3–10 ppm	Suitable
Potassium (ppm)	22.96 –25.79 ppm(Mean: 24.18)	20 – 30 ppm	Suitable
Sodium (ppm)	349.46–407.73ppm(Mean:376.42)	<800 ppm (generally tolerated)	Suitable
Nitrate (mg/L)	5.00 mg/L	0.5–10 mg/L (moderate is best)	Suitable
Phosphate (mg/L)	1.00 mg/L	1-3 mg/L	Suitable

Table 6 presents the water's physical and chemical parameters, including the observed and ideal ranges for mangrove growth, and their corresponding suitability for mangrove survival.

The mangroves thrive in tropical and subtropical coastal environments where specific physicochemical parameters fall within certain ideal ranges to support seedling establishment, growth, and long-term survival. Tidal influence plays a crucial role in mangrove ecosystems by facilitating nutrient exchange, seed dispersal, and sediment deposition.

The low tidal activity in the Bimmanga Estuary is said not to be compatible with most mangrove species, but the species that could endure low or no tidal force include Heritiera fomes and Xylocarpus granatum when the other environmental conditions are favourable (Primavera & Esteban, 2008).

Temperature of water was measured at 29.50-30.63degC that is within the optimal temperature of 26-32degC. It is appropriate in the growth of mangroves because it facilitates enzymatic activity, photosynthesis process, and respiration (Alongi, 2009; Gilman *et al.*, 2008). Nevertheless, it might lead to heat stress with time over 32degC, particularly in seedlings, which contributes to the need of shaded spots and canopy cover as microclimate controllers (Lovelock *et al.*, 2017).

The level of Dissolved Oxygen (DO) in the estuary was 1.31 mg/L that is not appropriate because it does not meet the optimal of more than 2.00 mg/L. Low DO might result into anaerobic condition, which suppresses the microbial activities that contribute to the nutrient cycling. However, some species of mangroves such as Avicennia marina and Rhizophora mucronata are able to withstand hypoxic water through the use of aerial roots (pneumatophores and prop roots) (Kathiresan & Bingham, 2001; Alongi, 2009). Even with the ongoing low DO levels, it could still cause limitation on the species diversity and the health of the microbes in the estuary (Reef *et al.*, 2010).

pH of 7.56 to 7.67, suitable to the growth of mangroves. This is the pH of neutrality to slightly alkaline, which favors the solubility of nutrients, the activity of microorganisms, and the growth of roots (Tomlinson, 2016; FAO, 2007). Due to extreme pH, acidic or highly alkaline, nutrient lock-out or toxic ion build-up may occur.

The salinity in the Bimmanga Estuary was about 2 ppt which is below the desired range of 5-35 ppt. This renders the region unsuitable to a great number of mangrove species, which rely on brackish to salty environment physiologically and competitively (Ball, 1988; Perri *et al.*, 2023). Nevertheless, Heritiera fomes and Bruguiera gymnorhiza might cope with such low salinity and Avicennia marina might not cope with its salinity being a halophyte.

Potassium has a range of 22.96-25.79 ppm which is in the optimum range (20-30 ppm) thus suitable. Potassium is involved in osmoregulation, and also in the activation of enzymes which prove to be of great importance especially in saline or desalinizing conditions (Parida and Jha, 2010; Scholander *et al.*, 1968).

Sodium was between 349.46-407. 73 ppm and is within the appropriate range as it is below the upper limit of 800 ppm. Sodium also helps in osmotic balance, however, in excess, it leads to ion toxicity. Avicennia marina, a type of mangrove, has salt glands which release excess sodium and is thus highly adapted to this range of salinity (Feller *et al.*, 2003).

Nitrate of 5.00mg/L is well within the optimal range of 0.50-10mg/L so it is appropriate. Nitrogen is also essential in the development of the leaf and the shoot, and this amount prevents the shortage as well as the danger of eutrophication (Alongi, 2009; Reef *et al.*, 2010).

At 1.00 mg/L, phosphate is within the 1-3mg/L ideal range and therefore acceptable. This promotes the growth of roots, energy metabolism, and seedling energy. Normal phosphate ensure the algal growing is inhibited and promotes a healthy estuarine environment (Dapar *et al.*, 2023; Perri *et al.*, 2023).

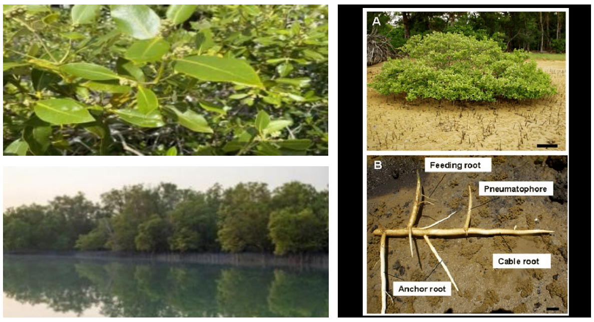
On the whole, tidal influence, dissolved oxygen and salinity were also determined to be inappropriate and this could limit the diversity and growth of the mangrove species. Nonetheless, Avicennia marina, Sonneratia alba and Rhizophora mucronata reveal the existence of adaptive resilience in some of these areas. These results highlight the significance of the match of species-specific tolerance with the environmental factors when mangroves should be restored (De Silva & Amarasinghe, 2021; Lovelock, *et al.*, 2017).

Table 7: Identified Mangrove Species based on the ideal ranges of Soil and Water Parameters. Avicennia marina (grey mangrove)

Avicennia marina (grey mangrove)	
Soil Parameter	**Ideal Range**
Soil Moisture (%)	>20% (especially in tidal zones)
Soil Texture	Clay to Clay Loam
Tidal Influence	Preferred but not essential
pH level	6.50 – 8.50

Salinity (mS/m)	20 – 300 mS/m (~2–30 dS/m)
Organic Matter (%)	>2%
Nitrogen (mg/L)	5 – 15 mg/L
Phosphorus (ppm)	3 – 10 ppm
Potassium (cmol/kg)	.50-1.50 (cmol/kg)
Water Parameter	Ideal Range
Tidal Influence	Preferred but facultative
Water Temperature (°C)	26 – 32°C
Dissolved Oxygen (mg/L)	>2.00 mg/L, but tolerates <1.50 mg/L
Water pH	6.50 – 8.50
Salinity (ppt)	5 – 45 ppt
Potassium (ppm)	20 – 30 ppm
Sodium (ppm)	<800 ppm (can tolerate higher)
Nitrate (mg/L)	0.50 – 10 mg/L
Phosphate (mg/L)	1-3 mg/L

Morphology



The individual ecological performance and expansion of Avicennia marina, a very versatile and salt-tolerant mangrove, are associated with certain physico-chemical characteristics of the soil and water. Regarding soil parameters, this species likes to be in an environment with a high level of soil moisture that usually goes along with the tidal zone such as above 20 percent. Wet soils enable the action of pneumatophor, aiding in exchange of the gases under anaerobic and waterlogged environments (Kathiresan & Bingham, 2001; Alongi, 2009).

Grey mangrove has a height of between 2 to 10 meters, although some may be up to 25 meters. It has a large trunk, fissured grey bark finely. The leaves are leathery, narrow-obovate to obovate-lanceolate, which are mostly oval-shaped and pointed and are opposed to each other on the stems and are about 8 cm long and 5 cm wide.

They are shiny green on the upper side and pale grey with some slight hairiness on the underside, which have also special glands which produce superfluous salt. The flowers are small, dense and either yellow or orange. Its fruits are hairy and almond-sized, pale green, and compressed ovoid in shape, which is about 2 cm long and 3 cm wide and carries one seed surrounded by a pericarp. The different characteristics of the grey mangrove are that it possesses spongy and pencil-shaped root structures which are used to breathe in the intertidal zone and these are pneumatophores and are vertical in nature and they grow outward on the root of the trunk. These roots have lenticels or air pores that help in exchanging the gases with the atmosphere (Grey Mangrove - Ocean Education & Conservation, n.d.).

Avicennia marina is also a species, which prefers a clay to clay loam soils capable of efficiently retaining water and nutrients, which are very important in anchoring the roots and supporting the growth of the seedlings (FAO, 2007; Tomlinson, 2016). Although tidal influence is welcome, the species is very flexible and can live in low or non-tidal regions and especially in the areas where the soil is saturated or the water table is high (Ball, 1988; Duke *et al.*, 1998). It can particularly be used to restore various estuarine environments owing to its capacity to colonize a vast array of hydrological environments (Primavera & Esteban, 2008).

The pH of the soil where the species prospers is 6.50 and 8.50, which is the right pH where nutrients are most soluble, and microorganisms are most active (FAO, 2007; Reef *et al.*, 2010). Avicennia marina is one of the most salt tolerant mangroves with a salinity range of 2 to more than 30 dS/m (~20-300 mS/m) and even hypersaline habitats as a result of salt secreting glands (Scholander, 1968; Ball, 1988). The fact that there is more than 2% organic matter is good since it promotes microbial processes that are important in nutrient cycling and in enhancing the overall soil fertility (Kathiresan & Bingham, 2001; Alongi, 2009). As far as nutrient requirements are concerned, Avicennia marina thrives in the soils containing a range of 5-15 mg/L of nitrogen level, which stimulates vegetative growth, and phosphorus concentrations of 3 to 10 ppm, which are required to promote root growth and transfer of energy (Feller *et al.*, 2003; Reef *et al.*, 2010). A potassium concentration of 0.50-1.50 cmol/kg also improves the osmotic balance and environmental stress resistance (Parida & Jha, 2010).

Regarding water parameters, Avicennia marina is adapted to water temperatures between 26degC and 32degC which is the optimal temperature of enzymes and seedling growth (Gilman *et al.*, 2008; Alongi, 2009). Its aerial root system makes it able to survive low levels of dissolved oxygen that are below 2.00 mg/L, but oxygenated water is also beneficial (Kathiresan and Bingham, 2001; Alongi, 2008). The water has a proper pH of between 6.50 and 8.50, which promotes the uptake of nutrients and physiological functions (FAO, 2007; Tomlinson, 2016).

The plants thrive in salinities of 5-45 ppt and extreme saline levels are tolerated by the species via salt filtration and excretion systems (Ball, 1988; Duke *et al.*, 1998). With respect to mineral nutrients the best values of water potassium should be 20-30 ppm, sodium level must preferably be below 800 ppm and nitrate levels must be within the range of 0.50-10 mg/L that will prevent nutrient deficiency or eutrophication (Scholander, 1968; Feller *et al.*, 2003; Reef *et al.*, 2010).

A phosphate concentration of 1.00 mg/L is considered an ideal phosphate level in the growth of mangroves (Verano *et al.*, 2023). This is favorable to the growth of roots and seedling development (Lovelock *et al.*, 2017), and thus is applicable to the targeted species such as Rhizophora mucronata, Avicennia marina, and Sonneratia alba. Therefore, phosphate content increases the probability of successful restoration of the mangrove in the estuary.

Also, the facultative nature of the species to tidal effect enables species to grow in highly tidal and less tidal ecocenoses. Such flexibility additionally enables Avicennia marina to be used in restoration studies in situations where tidal relationships are disturbed because of geomorphological changes or development of infrastructure (Primavera & Esteban, 2008; De Silva & Amarasinghe, 2021).

Monitored soil and water parameters fall within the recommended range of Avicennia marina and it is very versatile. It is able to endure broad pH ranges, medium-high salinity, and conditions with deficiencies (Ma *et al.*, 2020; Taillardat *et al.*, 2018). This is what makes it a good choice to be widely planted in various estuarine locations particularly as an early species in impoverished regions. It is important because it can stabilize the sediment and enhance the microhabitat conditions, which is essential to the long-term success of mangroves restoration (Suello *et al.*, 2022).

Table 8: Identified Mangrove Species based on the ideal ranges of Soil and Water Parameters. Bruguiera gymnorrhiza (large-leaf mangrove or orange mangrove).

Bruguiera gymnorrhiza (large-leaf mangrove or orange mangrove)	
Soil Parameter	**Ideal Range**
Soil Moisture (%)	>25%
Soil Texture	Clay to silty clay
Tidal Influence	Low to moderate
pH level	6.00 – 8.00
Salinity (mS/m)	10 – 200 mS/m (~1–20 dS/m)
Organic Matter (%)	>2%
Nitrogen (mg/L)	5 – 10 mg/L
Phosphorus (ppm)	3 – 8 ppm
Potassium (cmol/kg)	.50-1.50 (cmol/kg)
Water Parameter	Ideal Range
Tidal Influence	Intermittent or diurnal flooding
Water Temperature (°C)	25 – 32°C
Dissolved Oxygen (mg/L)	>1.50 mg/L
Water pH	6.50 – 8.00
Salinity (ppt)	5 – 25 ppt
Potassium (ppm)	20 – 30 ppm
Sodium (ppm)	<600 ppm
Nitrate (mg/L)	0.50 – 10 mg/L
Phosphate (mg/L)	1-3 mg/L

Morphology

Bruguiera gymnorrhiza, commonly known as the large-leaf or orange mangrove, is a prominent mangrove species occur in high inter tidal and river areas. It is a medium to tall mangrove species, which has a height of about 7 to 20 meters although it can be up to 35 meters. It has thick bark on the trunk, which is 2 cm or more in thickness, pale brown or grey, which is rough in texture and occasionally vertical fissures with big lenticels to facilitate gas exchange.

Leaves are dark green and elliptic, oblong, opposite, leathery, without mucronate extremities, and grooved on the underside and have a length of 8-22 cm and a breadth of 5-8 cm. The petioles are 2-4 cm and the stipulates are green with a range of 4-8 cm. The axils of the leaves produce solitary nodding, flower-like structures, the buds of which are 3-3.5 cm long, with 12-14 conspicuous lobes of the calyx being either red or yellow.

The flowers are creamy to orange-brown, bilobed, hairy, and they have a bristle and stamen with flowering being seasonal. The species is viviparous and has cylindrical, ribbed propagules (hypocotyls) that are 15-25 cm long and approximately 2 cm wide, and which detach and embed in the mud in order to organize new seedlings. The defining feature of its root system is above-ground knee roots which give the root system aeration and support and anchor shallowly at 1-2 meters deep whilst ensuring that the sediment is stabilised in soft waterlogged soils (Allen & Duke, 2006).

A series of soil and water physico-chemical parameters are very dominant in its development. This species has a preference to be found in waterlogged environments or intermittently flooded areas that are characterized by a high percentage of soil moisture (above 25 percent) that allows its lenticel-based gas exchange and viviparous seedling growth (Alongi, 2009; Tomlinson, 2016). Such moisture contents are important towards the growth of its huge propagules that need soft, saturated mud in order to be established successfully (Duke *et al*., 1998).

Clay soils and silty clay soils are the best soils because they have high nutrient and moisture retention capacity that is critical in anchoring roots and survival of seedling (Kathiresan & Bingham, 2001; FAO, 2007). The soils are also beneficial to stabilize the knee roots arising out of the trunk and branches, which are the characteristics of the adaptability to exchange gases and to aid them physically (Allen & Duke, 2006).

The pH range of 6.00 to 8.00 is ideal, which enhances the activity of the enzymes, the solubility of nutrients, and decomposition by the microbes, which are significant in the healthy mangrove ecosystems (Reef *et al*., 2010). Despite the relative salinity tolerance of Brugueria gymnorrhiza to 10-200 mS/m (1-20 dS/m), the salinity of the habitat is suitable at 10-20 mS/m (1-20 dS/m); therefore, it is brackish tolerance, but not hypersalty (Ball, 1988).

Organic matter content over 2 percent is also advantageous to the species since it increases the fertility of the soil and the seedling vitality (Alongi, 2009). Nitrogen content of 5-10 mg/L is crucial in leaf chlorophyll synthesis and canopy development whereas phosphorus levels 3-8 ppm play an important role in root elongation and the cell energy processes especially in the initial establishment (Feller *et al*., 2003; Reef *et al*., 2010). Potassium concentration of 0.50-1.50 cmol/kg aids osmoregulation and drought tolerance, but potassium deficiency in coastal soils is hardly restrictive (Kathiresan, 2018).

Brugia gymnorrhiza can also grow in water temperatures between 25-32deg C, and this is in line with tropical estuarine climates (Alongi, 2009; Gilman *et al*., 2008). It is able to survive in waters with dissolved oxygen of 1.50 mg/L albeit improved survival of seedlings where there is enhanced aeration (Kathiresan & Bingham, 2001). The water pH is preferred to be 6.50-8.00 that has a favourable ionic balance and nutrient level. Although it is not always constant, tidal effect contributes in controlling of these water conditions. Infrequent or diurnal tidal flooding improves oxygenation, salinity accumulation and nutrient-bearing sediments, which helps to maintain the growth of mangroves in estuaries (Duke *et al*., 1998; Primavera & Esteban, 2008).

Brugueria gymnorrhiza can survive salinity levels ranging between 5-25 ppt but it is subject to stress when subjected to long-term hypersaline environments (Scholander, 1968). Water potassium of 20-30ppm helps to maintain the stomatal activity and tolerance to stress. The optimum level of sodium is less than 600 ppm, and excessive levels may cause ionic imbalance and inhibition of growth (Reef *et al*., 2010). The nitrate concentrations between 0.50 and 10mg/L are a sufficient source of nitrogen in protein synthesis, and particularly relevant in systems that have low flow rates. The concentration of phosphates in 1-3 mg/L favor metabolic activity and are necessary to propagate in reproductive stages and propagule development.

Although Bruguiera gymnorrhiza are generally occurring in low tidal influence or moderate tidal influence (e.g., upstream estuaries or creek margins) they can survive occasional or irregular tidal inundation (Duke *et al*., 1998). Tidal impact has positive effects, yet not absolute necessities, in nutrient exchange and as such, Brugueria gymnorrhiza can be found in areas with less frequent flood cycles. Nonetheless, it is a species with moderate salinity, slightly acidic soils and sufficient nutrients, which are not fully found in Bimmanga Estuary, especially in Station 1. As Bruguieri gymnorrhiza is less resistant to salinity surges and nutrient-limited environments (Kathiresan, 2018), it must be selectively introduced to the places where freshwater flow is more intensive or where the soil can be supplemented. Otherwise, seedling mortality can be high as it has happened in the previous unsuccessful replanting attempts (Mariano *et al*., 2022).

Table 9: Identified Mangrove Species based on the ideal ranges of Soil and Water Parameters. Sonneratia alba (mangrove apple or white-flowered mangrove).

Sonneratia alba (mangrove apple or white-flowered mangrove)	
Soil Parameter	**Ideal Range**
Soil Moisture (%)	>25%
Soil Texture	Loamy to silty clay
Tidal Influence	High (diurnal or semidiurnal)
pH level	6.50 – 8.50
Salinity (mS/m)	20 – 250 mS/m (~2–25 dS/m)
Organic Matter (%)	>2%
Nitrogen (mg/L)	5 – 12 mg/L
Phosphorus (ppm)	3 – 10 ppm
Potassium (cmol/kg)	.50-1.50 (cmol/kg)
Water Parameter	Ideal Range
Tidal Influence	High to very high
Water Temperature (°C)	26 – 32°C
Dissolved Oxygen (mg/L)	>2.00 mg/L
Water pH	6.50 – 8.50
Salinity (ppt)	5 – 35 ppt
Potassium (ppm)	20 – 40 ppm
Sodium (ppm)	<1000 ppm
Nitrate (mg/L)	0.50 – 10 mg/L
Phosphate (mg/L)	1-3 mg/L

Established in the high intertidal and riverine areas. It is a medium to tall mangrove species, which has a height of about 7 to 20 meters although it can be up to 35 meters. It has thick bark on the trunk, which is 2 cm or more in thickness, pale brown or grey, which is rough in texture and occasionally vertical fissures with big lenticels to facilitate gas exchange.

Morphology

Leaves are dark green and elliptic, oblong, opposite, leathery, without mucronate extremities, and grooved on the underside and have a length of 8-22 cm and a breadth of 5-8 cm. The petioles are 2-4 cm and the stipulates are green with a range of 4-8 cm. The axils of the leaves produce solitary nodding, flower-like structures, the buds of which are 3-3.5 cm long, with 12-14 conspicuous lobes of the calyx being either red or yellow.

The flowers are creamy to orange-brown, bilobed, hairy, and they have a bristle and stamen with flowering being seasonal. The species is viviparous and has cylindrical, ribbed propagules (hypocotyls) that are 15-25 cm long and approximately 2 cm wide, and which detach and embed in the mud in order to organize new seedlings. The defining feature of its root system is above-ground knee roots which give the root system aeration and support and anchor shallowly at 1-2 meters deep whilst ensuring that the sediment is stabilised in soft waterlogged soils (Allen & Duke, 2006).

A series of soil and water physico-chemical parameters are very dominant in its development. This species has a preference to be found in waterlogged environments or intermittently flooded areas that are characterized by a high percentage of soil moisture (above 25 percent) that allows its lenticel-based gas exchange and viviparous seedling growth (Alongi, 2009; Tomlinson, 2016). Such moisture contents are important towards the growth of its huge propagules that need soft, saturated mud in order to be established successfully (Duke *et al.*, 1998).

Clay soils and silty clay soils are the best soils because they have high nutrient and moisture retention capacity that is critical in anchoring roots and survival of seedling (Kathiresan & Bingham, 2001; FAO, 2007). The soils are also beneficial to stabilize the knee roots arising out of the trunk and branches, which are the characteristics of the adaptability to exchange gases and to aid them physically (Allen & Duke, 2006).

The pH range of 6.00 to 8.00 is ideal, which enhances the activity of the enzymes, the solubility of nutrients, and decomposition by the microbes, which are significant in the healthy mangrove ecosystems (Reef *et al.*, 2010). Despite the relative salinity tolerance of Brugueria gymnorrhiza to 10-200 mS/m (1-20 dS/m), the salinity of the habitat is suitable at 10-20 mS/m (1-20 dS/m); therefore, it is brackish tolerance, but not hypersalty (Ball, 1988).

Organic matter content over 2 percent is also advantageous to the species since it increases the fertility of the soil and the seedling vitality (Alongi, 2009). Nitrogen content of 5-10 mg/L is crucial in leaf chlorophyll synthesis and canopy development whereas phosphorus levels 3-8 ppm play an important role in root elongation and the cell energy processes especially in the initial establishment (Feller *et al.*, 2003; Reef *et al.*, 2010). Potassium concentration of 0.50-1.50 cmol/kg aids osmoregulation and drought tolerance, but potassium deficiency in coastal soils is hardly restrictive (Kathiresan, 2018).

Brugueria gymnorrhiza can also grow in water temperatures between 25-32deg C, and this is in line with tropical estuarine climates (Alongi, 2009; Gilman *et al.*, 2008). It is able to survive in waters with dissolved oxygen of 1.50 mg/L albeit improved survival of seedlings where there is enhanced aeration (Kathiresan & Bingham, 2001). The water pH is preferred to be 6.50-8.00 that has a favourable ionic balance and nutrient level. Although it is not always constant, tidal effect contributes in controlling of these water conditions. Infrequent or diurnal tidal flooding improves oxygenation, salinity accumulation and nutrient-bearing sediments, which helps to maintain the growth of mangroves in estuaries (Duke *et al.*, 1998; Primavera & Esteban, 2008).

Brugueria gymnorrhiza can survive salinity levels ranging between 5-25 ppt but it is subject to stress when subjected to long-term hypersaline environments (Scholander, 1968). Water potassium of 20-30ppm helps to maintain the stomatal activity and tolerance to stress. The optimum level of sodium is less than 600 ppm, and excessive levels may cause ionic imbalance and inhibition of growth (Reef *et al.*, 2010). The nitrate concentrations between 0.50 and 10mg/L are a sufficient source of nitrogen in protein synthesis, and particularly relevant in systems that have low flow rates. The concentration of phosphates in 1-3 mg/L favor metabolic activity and are necessary to propagate in reproductive stages and propagule development.

Although Bruguiera gymnorrhiza are generally occurring in low tidal influence or moderate tidal influence (e.g., upstream estuaries or creek margins) they can survive occasional or irregular tidal inundation (Duke *et al.*, 1998). Tidal impact has positive effects, yet not absolute necessities, in nutrient exchange and as such, Brugueria gymnorrhiza can be found in areas with less frequent flood cycles. Nonetheless, it is a species with moderate salinity, slightly acidic soils and sufficient nutrients, which are not fully found in Bimmanga Estuary, especially in

Station 1. As Bruguieri gymnorrhiza is less resistant to salinity surges and nutrient-limited environments (Kathiresan, 2018), it must be selectively introduced to the places where freshwater flow is more intensive or where the soil can be supplemented. Otherwise, seedling mortality can be high as it has happened in the previous unsuccessful replanting attempts (Mariano *et al.*, 2022).

Table 10: Comparative Analysis of Soil and Water Parameters Suitable for Specific Mangrove Species.

Soil Parameter	**Avicennia marina**	**Bruguiera gymnorrhiza**	**Sonneratia alba**
Soil Moisture (%)	>20%	>25%	>25%
Soil Texture	Clay to clay loam	Clay to silty clay	Loamy to silty clay
Tidal Influence	Preferred, not required	Low to moderate	High (diurnal)
Soil pH	6.50–8.50	6.00–8.00	6.50–8.50
Salinity (mS/m)	20–300	10–200	20–250
Organic Matter (%)	>2%	>2%	>2%
Nitrogen (mg/L)	5–15	5–10	5–12
Phosphorus (ppm)	3–10	3–8	3–10
Potassium (cmol/kg)	0.50-1.50	0.50-1.50	0.50-1.50
Water Parameter			
Tidal Influence	**Preferred**	**Intermittent/diurnal**	**High to very high**
Water Temp (°C)	26–32	25–32	26–32
Dissolved Oxygen (mg/L)	>1.50	>1.50	>2.00
Water pH	6.50–8.50	6.50–8.00	6.50–8.50
Salinity (ppt)	5–45	5–25	5–35
Potassium (ppm)	20–30	20–30	20–40
Sodium (ppm)	<800	<600	<1000
Nitrate (mg/L)	0.50–10	0.50–10	0.50–10
Phosphate (mg/L)	1-3	1-3	1-3

Table 10 presents a comparison of the ideal soil and water parameters necessary for the growth and survival of identified mangrove species.

The soil and water parameters of Avicennia marina, Bruguera gymnorrhiza, and Sonneratia alba denote the specific ecological preferences of the plants with certain common needs. All three species are able to grow in soils that have high amounts of organic matter (>2%), have sufficient levels of nitrogen (5-15 mg/L), phosphorus (3-10 ppm), and potassium (0.50-1.50 cmol/kg).

But Avicennia marina has the most tolerant character as it can survive in clay to clay loam soils with a salinity ranging up to 300 ms m and with a wide water salinity (5-45 ppt), thus it is very adaptable. Brucei gymnorrhiza on the contrary favors more stable environments with a preference to clay over silty clay soils, decreased salinity (10-200 mS/m in soil; 5-25 ppt in water), and low to moderate tidal effects. Sonneratia alba on its part is adapted to shifting coastal areas, which grow well in loamy to silty clay soils where diurnal tidal flooding and water exchange are high and dissolved oxygen (>2mg/L) is slightly higher.

In general, though each of the three mangroves has similar needs of nutrients, moderate pH, and warm water temperatures (25-32degC), the differences in soil texture, salinity tolerance, and tidal reliance indicate their niche specializations Avicennia marina being the most adaptive and ubiquitous, Bruguera gymnorrhiza being more localized to sheltered and low-salinity environments, and Sonneratia alba being highly adaptive to open and well-flushed intertidal settings.

Developed and Validated Policy Brief

The policy brief points out that poor soil and water conditions, lack of tidal flow, and poor species selection were the key factors in the failure of the previous mangrove rehabilitation in the Bimmanga Estuary. These findings confirm the necessity to replace the current, generic planting procedures with the site-specific procedures, which are based on data. The most viable of the five alternatives taken into consideration is Comprehensive, Evidence-Based, Site-Specific Mangrove Restoration because it directly tackles the underlying causes of failure in the past, which include restoring tidal connectivity to add to the soil fertility through eco-remediation efforts, and continuous environmental monitoring as an adaptive control mechanism.

It is also crucial to take into consideration species-site matching in which Avicennia marina, Bruguiera gymnorrhiza and Sonneratia alba are given the priority and unsuitable species like Rhizophora mucronata should be avoided. Although this method consumes more resources, organization, and technical knowledge, its scientific basis and sustainability are associated with the greatest possibilities of ecological recovery in the long term, effective management of resources, and the overall benefit of the population.

The death of Rhizophora mucronata in the estuary can be attributed to the incompatibility of the ecological needs with the real situation on the site. This species is able to grow in middle and lower intertidal environments that are exposed to oxygen, salts, and nutrients through daily tidal flooding (Kathiresan & Bingham, 2001; Primavera *et al*., 2012). Nevertheless, Station 2 and 3 were more saline, electrically conductive and low in organic matter, which are above the tolerance range of the species and probably resulted in salt stress, nutrient deficiency and poor root growth (FAO, 2007; Alongi, 2009; Reef *et al*., 2010). Rhizophora mucronata usually likes slightly acidic and neutral soils, Clay substrates with fine texture, salinity ranging 5-35 ppt (Ball, 1988; Tomlinson, 2016), and enough nitrogen and phosphorus to grow (Feller *et al*., 2003; Reef *et al*., 2010). When such parameters are not attained e.g. in areas where there is poor inundation or where there is lack of nutrients, seedlings are exposed to osmotic stress, anoxia and consequential death. It was also determined that Station 1 offered more favorable conditions, which explains its rather higher suitability, in comparison with Stations 2 and 3.

On the whole, the demise of planted Rhizopora mucronata evidences the role of ecological incompatibilities in detriment of rehabilitation efforts and justifies the relevance of site-specific evaluation, adaptive management, and evidence-based practices in the rehabilitation of mangroves (Mariano *et al*., 2022; De Silva and Amarasinghe, 2021; Kathiresan, 2018; Appoo *et al*., 2024; Hossain and Nuruddin, 2016 Restoration should be based on science and the participation of the governance, academe and local communities; therefore, Option 5 will provide a long-term sustainable and socially endorsed route that can guarantee the success of mangrove rehabilitation in the Bimmanga Estuary.

Table 11: Validity of the Developed Policy Brief

Indicators		**Validator's Rating**			**Total**	**Average**
		1	2	3		
I.	General	4	5	5	14	4.7
II.	Heading and Subheading	5	5	5	15	5
III.	Abstract (Executive Statement)	4.4	5	5	14.4	4.8
IV.	Description of the Issue	5	5	5	15	5
V.	Policy Options	4.8	5	5	14.8	4.9
VI.	Recommendations	4.6	5	5	14.6	4.9
	General Average	4.6	5	5	14.6	4.9
Over-all Validity Index						4.9
Descriptive Equivalent				Highly Valid		

The validation of the policy brief results is presented in Table 11. The created policy brief received an overall validity index of 4.9, which can be described as descriptively equal to Highly Valid. This implies that the policy brief content, structure, and presentation are of excellent quality and acceptable, relevant and useful by the validators.

Among all the indicators, the best rating was achieved in the Heading and Subheading (5.0) and Description of the Issue (5.0), which implies that the policy brief is well organized as ideas are presented with clear headings and the issue is presented in a full and structured manner. These points are essential because they help the readers to comprehend the direction and topicality of the conversation.

Very high ratings were also on the Abstract/ Executive Statement (4.8), Policy Options (4.9) and Recommendations (4.9) indicating that the brief was a clear summary of the matter, they provided practical policy alternatives and made good and evidenced-based recommendations. These ratings are slightly below the ideal score, but this does not mean that there is not an excellent level of clarity and substance.

In the meantime, the General Section (4.7) is the lowest of all the indicators; yet it still represents a very good presentation. This minor, possibly, inconsistency can imply that some components of the policy brief could be improved slightly in terms of its general introduction, format, or overall structure, yet there is no significant decline in the overall strength of the policy brief.

Conclusively, the policy brief is rated as having a score of 4.9 as highly valid. The findings indicate that the paper is properly formatted, attentively written and conveys the problem, alternatives and suggestions. Even the minor amendments to the general aspects and abstract can be made further to ensure an even better validity and clarity, yet in general, the policy brief is well-proven and can be spread or put into effect.

CONCLUSION

The Bimmanga Estuary has a soil which is mainly of clay and clay loam of medium level of moisture, moderate pH, slightly alkaline and low salinity. It has adequate amounts of organic matter, nitrogen, phosphorus and potassium which means that it is reasonably suitable to support the growth of plants. The water is warm and stable, and the salinity is low, its pH is slightly alkaline, and the nutrient contents are acceptable. The lack of tidal effect however restricts the natural sediment flow and cycling of nutrients. Generally, the soil and water conditions are moderately favorable to the growth of the mangrove. Nevertheless, the free absence of tidal effect and low salinity would probably decrease the existence of the common saltwater-dependent species. According to the measured parameters, three mangrove species are most suitable in the estuary which include Avicennia marina, Brugueria gymnorrhiza, and Sonneratia alba because they can survive in freshwater, low salinity as well as non-tidal conditions. It suggests a proven policy brief to the Bimmanga Estuary that encourages mangrove restoration site-specific and science-based. Based on the assessment of the soil and water quality, it suggests species-site matching, habitat improvements (enhancement of soil moisture and balance of the salinity and tidal exchange), and periodic ecological monitoring. This policy brief was strengthened by the stakeholder involvement where the rating was Highly Valid (4.9) providing a sustainable roadmap to the mangrove rehabilitation and consistent with the climate action, biodiversity conservation and long-term coastal protection.

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