

Ecological and Climatic Insights from Seasonal Ponds of Nedyenga, Kerala, India: Vegetation Diversity and Environmental Variability

SARGA ABHIJITH^{1*}, JEESHNA MEETHALEY VALAPPIL¹, SREELAKSHMI THACHAN¹,
GREESHMA KADAMBOOR SURENDRAN² and ASHA EMBRANDIRI³

¹Department of Botany, Sree Narayana College, Kannur University, Kerala, India.

²Department of Botany, Govt. Brennen College, Kannur University, Kerala, India.

³WeSUSTAIN Project Management Services, Abudhabi, UAE.

Abstract

Seasonal pools and ephemeral wetlands are ecologically significant habitats that support diverse flora and fauna. This study, conducted during the 2022–23 monsoon at Nedyenga, Sreekandapuram, Kannur District, Kerala, explores herbaceous plant diversity, soil and water characteristics, and climate trends. A total of 53 vascular plant species from 34 families were documented, with angiosperms accounting for 96% and dicots being dominant. Endemic and threatened species such as *Rotala malabarica* and *Utricularia cecilii* highlight the site's conservation value. Climate data from 2019 to 2023 reveal increasing summer temperatures, warmer winter nights, and erratic monsoon rainfall, indicating shifting ecological conditions. Soil analysis showed slightly acidic pH, with high nutrient variability and elevated iron and manganese levels suggestive of anthropogenic influence. Water analysis revealed low TDS (79-89ppm), acidic pH (5.7-5.8), and slightly improved quality in 2023. These findings emphasize the biodiversity, the endemic plant diversity, ecological sensitivity, and vulnerability to climate change and anthropogenic pressures, calling for urgent, adaptive conservation strategies.



Article History

Received: 26 April 2025

Accepted: 26 May 2025

Keywords

Biodiversity;
Seasonal Pond;
Soil Nutrient Analysis;
Temperature and
Precipitation,
Water Quality
Conservation.

Introduction

Lateritic plateaus, significant geological formations in tropical regions, are ecologically rich and biodiverse.¹ First identified by Francis H. Buchanan in 1807 at Angadippuram, Kerala, laterite is known for its porous structure, reddish color, and nutrient-poor soils.² Formed through chemical weathering, these iron- and aluminium-rich substrates support

ecologically diverse yet nutrient-limited ecosystems. These edaphic limitations support specialized biodiversity, making them globally relevant for conservation. These plateaus are present across tropical zones in South America, Africa, Southeast Asia, and India. In India distribution is along western coast, especially in Kerala.^{3,4} These plateaus serve as critical ecosystems for endemic flora and fauna

CONTACT Sarga Abhijith ✉ ssarga0@gmail.com 📍 Department of Botany, Sree Narayana College, Kannur University, Kerala, India.



© 2025 The Author(s). Published by Enviro Research Publishers.

This is an  Open Access article licensed under a Creative Commons license: Attribution 4.0 International (CC-BY).

Doi: <http://dx.doi.org/10.12944/CWE.20.2.21>

adapted to seasonal and microhabitat variability. Despite their ecological value, they are often misclassified as "wastelands," thus diminishing the conservation efforts or focus.⁴

In northern Kerala, particularly Kannur and Kasaragod districts, lateritic plateaus exhibit unique ecological features such as sacred groves, bushy patches, soil-accumulated rock crevices, and seasonally wet areas.⁵ Sacred groves, protected by community beliefs, support up to 171 flowering plant species.^{6,7} Bushy patches with shrubs like *Hugonia mystax* and climbers such as *Asparagus racemosus* support butterflies, birds, and small mammals. Soil-filled rock crevices house herbaceous species like *Lepidagathis keralensis*, thereby contributing to local biodiversity.

Among those microhabitats, seasonally wet areas tubular potholes, puddles, marshes, and ephemeral ponds are especially dynamic. Tubular potholes or "Thondu" retain water year-round with pH values of 6.5–7.5 and temperatures of 25–30°C⁵. Monsoon puddles and ponds support herbaceous plants like *Bulbostylis densa*, *Cyperus iria*, and endemics such as *Rotala malabarica* and *Utricularia malabarica*.^{8,9} These ephemeral habitats vanish post-monsoon but enable rapid regrowth from dormant seeds.

Seasonal pools, shaped by geology and climate, exhibit varied hydroperiods that influence plant succession and biodiversity.¹⁰ With the monsoon, early species like *Polygala elongata* and *Fimbristylis dichotoma* emerge, followed by blooms of *Utricularia reticulata* and *Eriocaulon lanceolatum*. By September, species like *Isachne globosa*, *Eragrostis unioloides*, and *Eriocaulon sexangulare* dominate.¹¹ These pools also aid in water retention, aquifer recharge and support diverse fauna.

Modern ecological studies increasingly rely on high-resolution climatic and environmental datasets to understand such habitat dynamics. Tools like the ERA5-Land reanalysis data, available through the Copernicus Climate Change Service (C3S) Climate Data Store (CDS), provide accurate long-term climate data.¹² These datasets, accessed via platforms such as Google Earth Engine, allow for the integration of spatial and temporal variables including precipitation, temperature, and evapotranspiration

enhancing ecological interpretation and modeling capacity.¹³ Such tools are invaluable in correlating vegetation patterns in seasonal pools with multi-decadal climate trends, thus supporting evidence-based conservation planning.

However, threats from mining, urbanization, and misclassification jeopardize these ecosystems.¹⁴ New species discoveries like *Dimeria kalerii* and *Rotala thulunadensis* highlight their significance.¹⁵ This study, conducted during the 2022–23 monsoon at Nedyenga, Kannur, explores peak vegetation diversity in seasonal pools and examines its relationship to with water, soil, water, and climatic factors variables, stressing the urgent need for conservation.

Materials and Methods

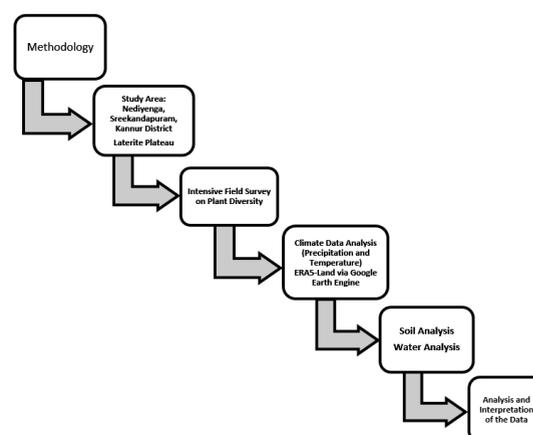


Fig.1: Flowchart of methodology

Selection of Study Area

The Nedyenga, Sreekandapuram, Kannur district was selected as the study area. This village is under Sreekandapuram Municipality (Lat 12.065046°, Long 75.478398°) in the Irikkur Block, Taliparamba Taluk, and Northern Kerala. A major portion of this area is the laterite plateau. This laterite plateau has received limited scientific attention regarding its biodiversity and endemic species. This study focused on the seasonal pools in the area over the monsoon season in 2023 to highlight their unique ecological diversity, particularly the numerous species that emerge during the monsoon.

Field Survey

Intensive field surveys were conducted in the study area and plant specimens were collected for

laboratory studies, identified by standard methods, and documented. Leaves, flowers, fruits, and overall plant structure were used for identification. The identified plant species were recorded with their current status and distribution.

Precipitation and Temperature

Climate data like precipitation and temperature were derived from ERA5-Land (1990–2023), Copernicus Climate Change Service (C3S) Climate Data Store (CDS), with a 9 km spatial resolution. The cloud-based platform Google Earth Engine (GEE) was used extensively to analyze and download climate variables, manage large datasets, and perform comparative analysis of climatic trends over the past five years to understand their influence on the study area.¹⁶

Analysis of Physico-chemical Properties of the Soil

Soil samples were collected during pre-monsoon, monsoon, and post-monsoon seasons from the top 15 cm layer at approximately five different points of the pond in polythene bags to analyze edaphic factors influencing biodiversity.

Determination of Soil pH

The soil pH was determined following the method of Jackson.¹⁷ Ten grams of soil was added to a 100 ml beaker with 25 ml water, stirred intermittently for 30 minutes, and the pH measured after calibration.

Determination of Organic Carbon

Organic carbon content was estimated by Walkley and Black's method.¹⁸ A 0.5 g soil sample was digested using potassium dichromate and sulfuric acid and titrated using ferrous ammonium sulfate with a ferroin indicator.

Determination of Available Phosphorus

Available phosphorus was determined following Jackson.¹⁷ Five grams of soil were treated with Bray's No.1 reagent, and a colorimetric analysis was performed using ascorbic acid and a spectrophotometer at 660 nm.

Determination of Electrical Conductivity (EC)

Electrical conductivity was measured by preparing a 1:2.5 soil-water suspension and recording the EC after 30 minutes of incubation.¹⁷

Determination of Available Potassium

Available potassium was extracted with ammonium acetate and analyzed using a flame photometer standardized with potassium standards.¹⁹

Determination of Exchangeable Calcium and Magnesium

Exchangeable calcium and magnesium were estimated using ammonium acetate extracts titrated with standard EDTA solution using EBT and murexide indicators.¹⁷

Determination of Available Sulfur

Available sulfur was estimated by the method of Massoumi and Cornfield.²⁰ Ten grams of soil were extracted using 0.15% CaCl₂ and the turbidity measured spectrophotometrically at 420 nm.

Determination of Micronutrients (Fe, Mn, Zn, Cu)

Micronutrient contents were determined using 0.1M HCl extracts and measured with an atomic absorption spectrophotometer.²¹

Determination of Available Boron

Boron content was measured using Bingham's method.²² A water extract was treated with azomethine-H and absorbance was read at 420 nm.

Analysis of Physico-chemical Properties of Water

Water samples were collected seasonally in pre-cleaned polyethylene bottles according to standard protocols.²³

Determination of Carbonate and Bicarbonate

Carbonate and bicarbonate were estimated via titration using phenolphthalein and methyl orange indicators with 0.01N sulfuric acid.²⁴

Estimation of pH and EC of Water

Water pH was measured using a calibrated digital pH meter and EC was determined using a conductivity meter.²⁴

Total Dissolved Salts (TDS)

TDS was calculated from EC using the formula:

$$\text{TDS} = \text{EC} \times 640 \text{ (mg/L).}^{24}$$

Estimation of Chloride

Chloride content was determined by titrating the water sample with 0.1N AgNO³ using potassium chromate as indicator until a flesh-red color appeared.²⁴

Result

These analyses were conducted out in the seasonal pond of Nedyenga, Sreekandapuram in Kannur District of Kerala from 2022 to 2023. Seasonal ponds can be widespread in forest landscapes, but how they respond to disturbances in their surrounding upland forests is poorly understood. These ponds offer extremely important ecosystems for native plants that provide all the food, oxygen, and shelter to many other animals. There are 3 zones where pond vegetation grows: the bank side, marsh, and aquatic zone, some plants prefer different water requirements.

Similarly, seasonal ponds are common in forests, however their response to environmental or human disturbance has not been properly documented. A pond, unlike rivers, still contains water and supports native plants, which provide food, oxygen, and shelter for wildlife. Plants grow in distinct zones: species such as great willow herb and meadow sweet thrive in the damp bank-side zone, emergent plants grow near the edge in the marsh zone, and true aquatic plants live in the water, either floating with dangling roots or anchored in the mud.

During the study at Nedyenga, a total of 53 (53%) vascular plants belonging to 47 genera and 34 families were documented. Among these angiosperms were the dominant groups with 51 (96%) members, while pteridophytes were dominant group 2 (3.7%). With respect to their habit, there were 48 (90.5%) herbaceous plants, 3 (5.6%) shrub plants and 2 (3.7 %) climbers(Fig 2). Among angiosperms, dicots comprised 23 families, 34 genera and 38 species while monocots comprised 9 families, 11 genera and 13 species. The dominant family was Rubiaceae with 4 species followed by Linderniaceae, Commelinaceae and Eriocaulaceae with 3 species each. From the seasonal pools 20 (37.03%) plants were identified and rest of the plants were collected from close plant associates. The dominant plant families in the seasonal pools include Eriocaulaceae and Linderniaceae, each represented by three species. These are followed

by Commeliaceae and Lythraceae, with two species each. Other families, including Pontederiaceae, Hydrocharitaceae, Rubiaceae, Boraginaceae, Plantaginaceae, Lentibulariaceae, Acanthaceae, Menyanthaceae, and Marsiliaceae, each contribute one species (Table1, Fig-3).

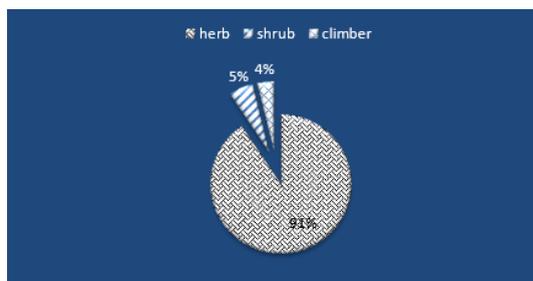


Fig. 2: Distribution of plants based on habit from the study locations in Kerala, India

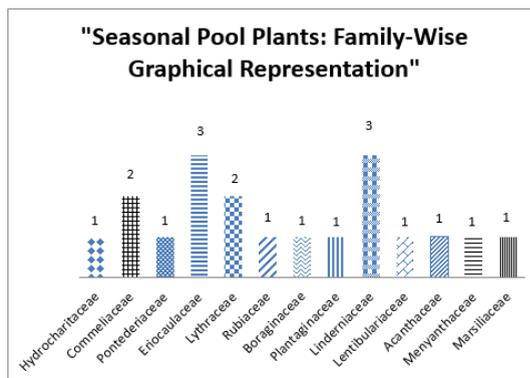


Fig. 3: Family-wise distribution of plant species in the seasonal pools of Nedyenga

The endemic species included *Neanotis subtilis* (Rubiaceae), *Cyanotis burmanniana*, *Murdannia semiteres* (Commelinaceae), *Utricularia cecillii* (Lentibulariaceae), *Eriocaulon eurypeplon*, *Eriocaulon reductum* (Eriocaulaceae), *Rotala malabarica*, *Rotala malampuzhensis* (Lythraceae), *Justicia nagpurensis*, *Lepidagathis keralensis* (Acanthaceae), *Parasopubia hofmanii* (Orobanchaceae), *Polygala elongata* (Polygalaceae), *Impatiens minor* (Balsaminaceae), *Canscorinella stricta* (Gentianaceae), *Hemidesmus indicus* (Apocyanaceae), *Heliotropium marifolium* (Boraginaceae) and *Sesamum indicum* (Pedaliaceae). Species that are confined to Western Ghats include *Cyanotis burmanniana*, *Rotala malampuzhensis*, *Eriocaulon reductum*, *Osbeckia muralis* and *Utricularia cecillii*. According to the IUCN status *Rotala*

malabarica is classified as Critically Endangered, while *Utricularia cecilia* is listed as Endangered. There were 22 least common species and the status of 29 species were not evaluate (Table1).²⁵

Table 1: List of plants at Nediengam, Sreekandapuram

S. No	Species Name	Family	Habitat	Distribution	IUCN status
1	<i>Blyxa octandra</i> (Roxb.) Planch.*	Hydrocharitaceae	Stagnant pool, pond flooded paddy field	Andhra Pradesh , Maharashtra , Kerala	LC
2	<i>Curculigo orchioides</i> Gaertn.	Hypoxidaceae	Forest open grassy slopes	Kerala	NE
3	<i>Asparagus racemosus</i> Willd.	Asparagaceae	Low altitude in shade and tropical climate	Asia, Australia, Africa	NE
4	<i>Cyanotis axillaris</i> (L.) D.Don ex Sweet.*	Commeliaceae	Forest, grassland, Marshy land	Delhi, Arunachal Pradesh, Uttarpradesh	LC
5	<i>Cyanotis burmanniana</i> Wight.	Commelinaceae	Seasonally dry tropical biome	Kerala	NE
6	<i>Murdannia semiteres</i> (Dalzell) Sant.*	Commelinaceae	Terrestrial Fresh -water, Wet rocks, Stream edges	Kerala	LC
7	<i>Monochoria vaginalis</i> (Burm.f.) CPresl.*	Pontederiaceae	Wetlands, Artificial /Aquatic and marine	Kerala	LC
8	<i>Eriocaulon cuspidatum</i> Dalzell.*	Eriocaulaceae	Puddles near forests, fields, roadsides, and plateaus	Karnataka, Kerala, Maharashtra	NE
9	<i>Eriocaulon eurypeplon</i> Korn.*	Eriocaulaceae	Terrestrial fresh water, Rocky areas	Kerala	NE
10	<i>Eriocaulon reductum</i> Ruhland.*	Eriocaulaceae	Marshy areas, Paddy fields and wetlands	Kerala	NE
11	<i>Fimbristylis quinquangularis</i> (Vahl) Kunth.	Cyperaceae	Terrestrial and aquatic	Southern and eastern India	LC
12	<i>Pycreus pumilus</i> (L.) Nees.	Cyperaceae	Marshy areas, Paddy fields and wetlands	Southern and western India	LC
13	<i>Eragrostis uniolooides</i> (Retz.) Nees ex Steud.	Poaceae	Forest, savanna, shrubland, grassland, rocky, desert, marine	Widespread in India	LC
14	<i>Desmodium adscendens</i> (DA) (Sw.) DC.	Fabaceae	Terrestrial, forest, grassland	Widespread in India	LC

15	<i>Geissaspis cristata</i> Wight & Arn.	Fabaceae	Grassland, Rocky areas	Kerala, India	LC
16	<i>Polygala elongata</i> Klein ex Willd.	Polygalaceae	Exposed slops and crevices of rocks from foothills	Kerala	NE
17	<i>Micrococca mercurialis</i> (L.) Benth.	Euphorbiaceae	Forest and plains	Maharashtra, Karnataka, Tamilnadu, Kerala	NE
18	<i>Croton bonplandianus</i> Baill.	Euphorbiaceae	Terrestrial	Kerala	NE
19	<i>Passiflora foetida</i> L.	Passifloraceae	Roadside, open woodland	Widespread in India	LC
20	<i>Rotala malabarica</i> Pradeep, Joseph & Sivar.*	Lythraceae	Seasonal pools on lateritic rocks	Kerala	CR
21	<i>Rotala malampuzhensis</i> R.V. Nair ex C.D.K. Cook.*	Lythraceae	Grassland, wetland, Rocky area, Aquatic and marine, Mountain peaks	Kerala	LC
22	<i>Osbeckia muralis</i> Naudin.	Melastomataceae	Rocky areas and plains	Maharashtra, Tamilnadu, Kerala	NE
23	<i>Melochia corchorifolia</i> L.	Malvaceae	Forest, wetlands, Artificial and marine	Widespread in India	LC
24	<i>Polycarpaea corymbosa</i> L.	Caryophyllaceae	Tropics and subtropic regions, sandy soils, grasslands	Widespread in India	NE
25	<i>Impatiens minor</i> (DC) Bennet.	Balsaminaceae	Moist , shaddy places	Widespread in India	NE
26	<i>Neanotis subtilis</i> (Miq.) Govaerts ex Punekar \$ Lakshmin.*	Rubiaceae	Garden, urban, wet, tropical biome	Widespread in India	NE
27	<i>Oldenlandia corymbosa</i> L., varcorymbosa.	Rubiaceae	Grassland, Shallow soil on rocks, sandy river ridges	Widespread in India	LC
28	<i>Oldenlantia herbacea</i> (L) Roxb.	Rubiaceae	Grassland, Roadside, often on sandy soils	Widespread in India	NE
29	<i>Spermacoce alata</i> Aubl.	Rubiaceae	Humid tropical climate with sandy soil	Assam, Meghalaya, Kerala	NE
30	<i>Canscorinella stricta</i> Shahina \$ Nampy.	Gentianaceae	Seasonally dry biome	Kerala	NE
31	<i>Hemidesmus indicus</i> (L.) R.Br.	Apocynaceae	Terrestrial	Kerala	LC
32	<i>Heliotropium marifolium</i> Retz.*	Boraginaceae	Rocky plateaus and hillocks, Moist places	Kerala	LC
33	<i>Limnophila repens</i> (Benth.) Benth.*	Plantaginaceae	Wetland	Widespread in India	LC

34	<i>Scoparia dulcis</i> L.	Plantaginaceae	Grazed grasslands, Wet waste lands and cultivated lands	Widespread in India	NE
35	<i>Bonnaya ciliata</i> (Colsm.) Spreng.*	Linderniaceae	Forest, Grassland, wetland and fresh water	Kerala	LC
36	<i>Lindernia hyssopioides</i> (L.) Haines.*	Linderniaceae	Terrestrial and freshwater to marine habitats	Widespread in India	LC
37	<i>Torenia crustacea</i> (L.) Cham.*	Linderniaceae	Wetland, Artificial /aquatic and marine	Widespread in India	LC
38	<i>Sesamum indicum</i> L.	Pedaliaceae	Tropical regions	Kerala	NE
39	<i>Rotheca serrata</i> (L.) Steane &Mabb.	Lamiaceae	Forest, mountain slops, valleys	Kerala	NE
40	<i>Leucas aspera</i> (Willd.) Spreng.	Lamiaceae	Dry open sandy soil	Widespread in India	NE
41	<i>Parasopubia hofmannii</i> Pradeep & Pramod var. hofmannii.	Orobanchaceae	Shallow soiled area	Kerala	NE
42	<i>Ramphicarpa fistulosa</i> Benth.	Orobanchaceae	Marshy land	Andhra Pradesh, Kerala	NE
43	<i>Utricularia ceciliai</i> P. Taylor.*	Lentibulariaceae	Wetland, Rocky areas	Kerala	EN
44	<i>Utricularia graminifolia</i> Vahl.*	Lentibulariaceae	Grassland, Rocky areas	Western India	LC
45	<i>Justicia nagpurensis</i> V.A.W.Graham.*	Acanthaceae	Damp places in plains	Kerala	NE
46	<i>Lepidagathis keralensis</i> Madhus. &N.PSingh.	Acanthaceae	Laterite hills, sea coast woody rock stock	Kerala	NE
47	<i>Lantana camara</i> L.	Verbenaceae	Grassland, woodland, and riparian areas	Widespread in India	NE
48	<i>Nymphoides indica</i> (L.)Kuntze .*	Menyanthaceae	Wild aquatic	Kerala, Andhra pradesh	LC
49	<i>Ageratum conyzoides</i> L.	Asteraceae	Terrestrial	Northeast India	NE
50	<i>Emilia sonchifolia</i> (L.) DC.	Asteraceae	Grassland, semi shaded area	Widespread in India	NE
51	<i>Chlorophytum laxum</i> Ker-Gawl.	Liliaceae	Grassland	Widespread in India	NE
52	<i>Marsilea quadrifolia</i> L.*	Marsiliaceae	Shallow freshwater habitats	Kerala	LC
53	<i>Cheliantus tenuifolia</i> (Burm.f.)Sw	Pteridaceae	Terrestrial in rocky coastal woodlands	India	NE

* Plants found in seasonal pond, T: Threatened, CR: Critically endangered, LC: Least concern, EN: Endangered, NE: Not evaluated

From 2019 to 2023, Nediyinga's temperature trends reveal distinct seasonal patterns with subtle shifts in recent years (Fig 4 and 5). Summer (March to May) consistently recorded the highest temperatures, with March 2023 peaking at 36.13°C the highest across the five years. Minimum temperatures during this period also showed a warming trend, particularly in 2023 when May nights were notably warmer at 24.02°C. In contrast, the monsoon season (June to September) stabilized temperatures, with maximums ranging from 28°C to 31°C and minimums hovering

around 22°C. While early monsoons (June) exhibited slight warming over the years, late monsoons (August–September) maintained cooler trends, with 2022 recording the lowest minimum of 21.73°C in September. Winters (October to February) displayed the most significant nighttime cooling in 2019 (18.08°C in January) and 2022 (18.19°C in February), but recent years indicate a gradual warming of minimums, suggesting less extreme winter nights (Fig 5 -6).

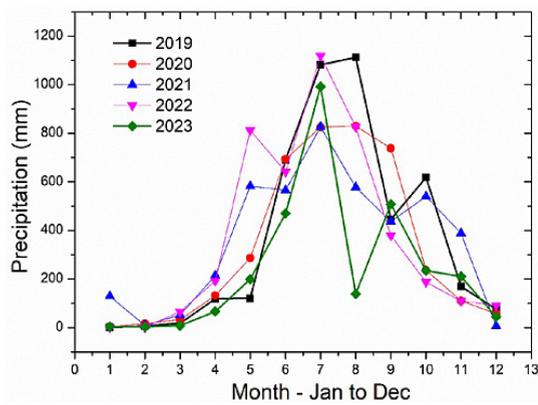


Fig. 4: Precipitation Trends in Nediyinga from 2019 to 2023

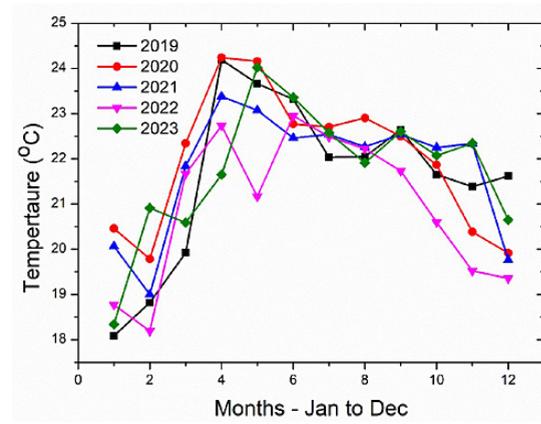


Fig. 5: Minimum temperature trends in Nediyinga from 2019 to 2023

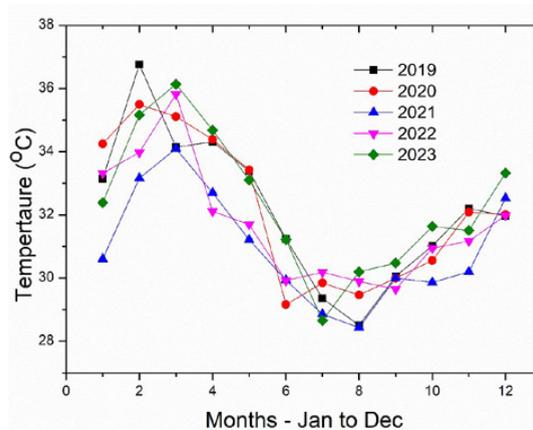


Fig. 6: Minimum temperature trends in Nediyinga from 2019 to 2023

These trends are illustrated in the accompanying charts as the same annual pattern with minor differences. Maxima here are at their best in March and April so onset maxima are evident in summer. If the winters have a wider spacing of minimum

temperatures due to varying overnight cooling, in monsoons a discernible fall in temperature is seen when contrasted with summer. The plots show warming trend in summer nights and early monsoon (june) season (Fig 6).

The precipitation data of Nedyenga for the period from 2019 to 2023 present substantial seasonal and interannual anomalies with several distinct maxima and anomalies. The monsoon months of July (1081.52 mm) and August (1112.22 mm) recorded the maximum rainfall in 2019, while 617.74 mm rainfall was recorded in October. Similarly, 2022 received substantial monsoon rainfall, and was the wettest in Jul (1050.4 mm). (Fig 4). which table or fig is this result?

In contrast, 2021 saw a weaker monsoon, with precipitation in July (826.27 mm) and August (577.54 mm) being significantly less than in 2019 and 2022. 2021 saw the most pre-monsoon rainfall, especially in May (582.43 mm). (Fig 4).

The year 2023 showed a decline in monsoon intensity, with August precipitation dropping to 138.44 mm, but October (234.26 mm) and November (210.67 mm) showed stronger post-monsoon rainfall. (Fig.3).

The physical and chemical characteristics of the Nedyenga soil are given in Table 2. When we analyzed the pH indicate slightly acidic conditions for both years. The standard deviation is higher in 2022 (0.47) than in 2023 (0.25), reflecting greater variability in 2022.

Table 2: Analytical report of soil sample

S. No	Parameter	Pre mon	Mon -soon	Post Mon	Mean ±SD	Pre Mon	Mon -soon	Post Mon	Mean ±SD
		2022	2022	2022	2022	2023	2023	2023	2023
1	pH	5.6	5.4	5.1	5.3±0.25	4.71	4.02	4.93	13.66±0.475
2	Electrical Conductivity (ds/m)	0.12	0.23	0.15	0.16±0.06	0.23	0.27	0.04	0.18±0.123
3	Organic carbon (%)	2.75	3.15	2.55	2.81±0.31	2.75	3.3	1.29	2.44±1.039
4	Phosphorous (kg/ha)	15.1	16.85	13.9	15.28±1.48	30.03	12.57	14.43	19.01±9.589
5	Potassium (kg/ha)	156.6	160	140.2	152.2±10.59	359.92	112	40.9	170.94±167.478
6	Sulphur (ppm)	3.1	3.4	2.8	3.1±0.30	3.65	3	0.41	2.35±1.714
7	Calcium (ppm)	620	622	6.1	416.03±6.43	540	640	621	600.3±53.107
8	Magnesium (ppm)	116	118	113	115.6±2.52	120	124	114	119.3±5.033
9	Boron (ppm)	0.16	0.18	0.14	0.16±0.02	0.13	0.112	0.14	0.127±0.014
10	Zinc (ppm)	12.5	14	11.5	12.66±1.26	10.02	8.8	7.17	8.66±1.430
11	Iron (ppm)	8.7	9.2	7.8	8.56±0.71	10.02	37.9	7.17	18.36±16.979
12	Copper (ppm)	2.72	3.01	2.63	2.81±0.71	3.63	1.38	4.99	3.33±1.823
13	Manganese (ppm)	16.5	17.5	18	17.33±11.15	14.2	15.6	34.18	21.32±11.153

Table 3: Analytical report of water sample

S. No	Parameter	Pre mon -soon 2022	Mon -soon 2022	Post Mon -soon 2022	Mean ±SD 2023	Pre Mon -soon 2023	Mon -soon 2023	Post Mon -soon 2023	Mean ±SD 2023
1	pH	6.1	5.6	5.4	5.7±0.36	6.3	5.6	5.7	5.8±0.38
2	EC (dS/m)	0.18	0.12	0.09	0.13±0.045	0.21	0.12	0.15	0.16±0.060
3	K (ppm)	4.5	3.9	3.2	3.86±0.65	3.8	3.9	3.5	3.73±0.20
4	Carbonate (meq / L)	0.1	0	0	0.03±0.058	0	Nil	0	0
5	Bicarbonate (meq /L)	0.6	0.4	0.3	0.43±0.15	0.5	0.4	0.4	0.43±0.057
6	Chloride (meq/L)	1.3	1	0.8	1.03±0.25	1.2	1	0.9	1.03±0.15
7	Total Dissolved solids (ppm)	98.5	76.8	64.3	79.86±17.30	110	76.8	82.6	89.8±13.89
8	Copper (ppm)	0.031	0.0272	0.022	0.26±0.0045	0.035	0.0272	0.031	0.031±0.0040
9	Iron (ppm)	0.175	0.149	0.135	0.153±0.020	0.165	0.149	0.14	0.151±0.012
10	Zinc (ppm)	0.005	0	0	0.001±0.00029	0.006	Nil	0	0.002±0.0034

The electrical conductivity (EC) is low in both years, with values decreasing post-monsoon in 2022. The standard deviation is for 2023 (0.06) higher than for 2022 (0.12), the 2022 EC measurements show more differentiation. Organic carbon content is higher in 2023 relative to 2022, especially in pre-monsoon and monsoon. The standard deviation for 2022 is larger, indicating greater variation in OC content. Phosphorous in monsoon and post-monsoon of 2022 have considerably reduced. There is a higher amount of variability, in 2022 (SD 9.59), and less in 2023 (1.48) (Table 2).

Potassium content is higher in 2022 compared to 2023. Greater variations in potassium levels are indicated by the greater SD in 2022 (167.48). With somewhat lower levels in the post-monsoon phase in both years, Sulphur concentrations are comparatively constant across years. It flips in 2022, with a greater Sulphur standard deviation (1.71), which indicates more erratic values. While the amount of calcium in each of the years become nearly identical, there is more fluctuation for 2023 (SD = 6.43) than in 2022 (SD = 53.11). In year 2023, variations occur less, at an SD of 2.52 compared with 5.03 in 2022. Low SD in years of both measurements indicates the B contents are relatively constant, with little fluctuations. Zinc shows similar behavior trends

to boron, with extremely stable levels in 2022 and small intermediate fluctuations in 2023. Zinc SD values for the two years were similar. Iron levels fluctuate widely in 2022, especially during the monsoon season, which brings a high standard deviation (16.98).With an SD of 0.71 in 2023, iron levels are more consistent. Both years' copper levels are variable, although 2022's SD is larger (1.82) than 2023's (0.71). Manganese readings are more consistent in 2023 (SD = 0.76),larger (1.82) than 2023's (0.71). Manganese readings are more consistent in 2023 (SD = 0.76), however they show notable fluctuation in 2022 (SD = 11.15)(Table 2).

The physical parameters such as the pH value of Nedyenga The comparative analysis of seasonal water quality for the years 2022 and 2023 at the Nedyenga laterite plateau revealed subtle yet important variations in physico-chemical characteristics, supported by the standard deviation values indicating the degree of fluctuation across seasons. The electrical conductivity (EC) varied slightly more in 2022 (0.12–0.15 dS/m) than in 2023 (0.11–0.13 dS/m), suggesting a marginal decline in dissolved ionic content in 2023, supported by a lower standard deviation; the potassium (K) values were relatively stable, although 2023 showed a slight decrease in mean value and variability, possibly due to lower

agricultural input. The pH values were consistently acidic in both years, ranging from 5.1 to 5.6, with a low standard deviation (~0.2), indicating stable hydrogen ion concentration despite seasonal influences.; carbonate was absent (Nil) in both years, reflecting the persistently acidic conditions; the bicarbonate ranged between 0.2 and 0.4 meq/L, with 2022 showing slightly higher fluctuations; and the chloride levels decreased slightly in 2023, indicating a moderate reduction in seasonal variability (Table 3).

Both years' total dissolved solids (TDS) were continuously low (between 70 and 77 ppm), but 2023's mean and standard deviation were marginally lower, suggesting a more uniform mineral load. Both years had trace levels of micronutrients like copper and iron that stayed within safe bounds; however, 2023 had a somewhat lower average and variation, indicating better water quality. In both years, zinc was continuously undetectable in all seasons, indicating that there was no anthropogenic contamination to be found.

Overall, the standard deviation values across parameters suggest that water quality was more stable and slightly improved in 2023, reinforcing the relatively undisturbed nature of the seasonal pools in this lateritic ecosystem. (Table 3).

Discussion

Lateritic plateaus are characterized by challenging environmental conditions that promote the growth of specialized vegetation adapted to harsh habitats. These conditions shape seasonal vegetation patterns, with many plant species completing their life cycles during the monsoon season. Porembski and Barthlott identified lateritic plateaus as model ecosystems comparable to oceanic islands due to their isolated and unique biodiversity.²⁶ The plateau supports diverse microhabitats, primarily sustaining herbaceous plants. Three distinct seasons pre-monsoon, monsoon, and post-monsoon contribute to specific patterns in vegetation development. Muller noted significant environmental fluctuations on rock outcrops, including lateritic crusts.²⁶ Vegetation on these plateaus resembles that of tropical inselbergs and includes categories such as cryptogamic crusts, epilithic plants, rock pools, and ephemeral flush vegetation.^{27,28}

In our study at Nedyenga, 53 vascular plant species were documented, of which 48 were herbs. Pramod *et al* noted that nearly all species in similar habitats are herbaceous and complete their life cycles rapidly as the pools dry. Of the species found in Nedyenga, 16 (31%) are endemic. Comparatively, 37% of species from the seasonal pools at Madayippara are endemic, with many classified under various threat categories. Notable and dominant seasonal pool species include *Geissaspis* spp., *Isachne veldkampii*, *Murdannia* spp., *Neanotis subtilis*, *Rotala* spp., *Eriocaulon* spp., *Utricularia* spp., *Blyxa* spp., *Drosera indica*, *Lindernia* spp., *Nymphoides krishnakasara*, *Oryza rufipogon*, *Rhamphicarpa longiflora*, *Fimbristylis* spp., and *Wiesneria triandra*.²⁸

The precipitation trends at Nedyenga reflect a monsoon-dominated climate with high interannual and seasonal variability. The significance of the southwest monsoon is demonstrated by the peak rainfall that occurs throughout the monsoon season (June to September), particularly in July and August.²⁹ Peak rainfall in years like 2019 and 2022 exceeded 1000 mm during these months, recharging seasonal reservoirs of water essential for endemic species and agriculture. On the other hand, monsoon decreased in 2021 and 2023, August 2023 saw just 138.44 mm of rainfall indicating changing precipitation patterns that may be related to climate change. This pattern is consistent with Chandran *et al* research that links changes in atmospheric circulation and rising global temperatures to monsoon variability.²⁹ The November 2023 high post-monsoon rainfall of 210.67 mm suggested that precipitation was redistributed seasonally. These variations impact seasonal pools, endemic biodiversity, and water availability, emphasizing the need for adaptive management practices to address shifting rainfall patterns and mitigate ecological and agricultural impacts.^{29,30}

Strong monsoons in 2019 and 2022 and significant pre-monsoon rainfall in May 2021 (582.43 mm) indicated that monsoon currents were periodically intensifying. Seasonal pools benefit during these times because they rely on regular rainfall. Weaker monsoons, like the one in 2021, jeopardise water retention and limit the amount of habitat available for unique species.^{29,30} The management of water

resources and agriculture are also impacted by these variations. Rainfed agriculture is supported by years with high rainfall, but like other Indian regions, they are vulnerable to flooding.³¹ On the other hand, traditional farming may be disrupted by lower monsoonal or shifted post-monsoon rainfall, necessitating the use of adaptive water management techniques.³²

Nediyenga 2019–2023 temperature data highlight the regional and worldwide climate variability. The trend for maximum summer temperatures (March–May) was upward, reaching a high of 36.13°C in March 2023. This is consistent with the IPCC's findings that urbanisation and greenhouse gas emissions are making heat extremes more intense.^{26,33} Due to weaker monsoon systems and disturbed land-sea temperature differences, the early monsoon months (June) also exhibited warming.²⁹ Winters (October–February) and late monsoons (August–September) exhibit more consistent cooling, with lows of about 22°C and a little warming at night. These alterations are in line with regional trends of rising winter minimums and decreasing monsoon rainfall brought on by weakening circulation and warming oceans.³²

The ecological consequences of these shifts are significant. Rising temperatures threaten biodiversity by favoring invasive species and increasing pest and disease outbreaks. Water scarcity and altered crop cycles further complicate ecological balance. As such, integrated adaptive measures, including climate-resilient agriculture and blue-green infrastructure conservation, are essential.³⁴

Maintaining soil nutrient levels is crucial for sustaining vegetation and ecosystem health. Soil analysis revealed slightly acidic pH values in both years (4.02–5.6), with 2023 showing a slight shift toward less acidity. Such pH values are typical of tropical regions with high rainfall and leaching. Certain crops have specific pH preferences, and if not within the optimal range, this could impact plant growth.³⁵ The increased pH in 2023 may indicate reduced leaching or increased base cations. Electrical conductivity (EC) values were low in both years, confirming non-saline conditions, consistent with findings from other tropical high-rainfall soils.³⁵ EC reduction from monsoon to post-monsoon in 2022 reflects the dilution of soluble salts by rain.

Organic carbon levels were higher in 2023, particularly during pre-monsoon (2.75%) and monsoon (3.3%) compared to post monsoon (1.29%) with great variability, suggesting improved soil fertility and microbial activity. Organic carbon levels above 2% are generally considered indicative of good soil fertility in tropical lateritic soils, suggesting that the study site maintains a moderate to high fertility status.³⁶ The fluctuations seen in 2022 likely reflect seasonal instability in organic matter dynamics. Phosphorus content ranged from 13.9 to 16.85 kg/ha in 2022, with a clear drop during the 2022 monsoon. In contrast, 2023 showed a sharp pre-monsoon peak at 30.03 kg/ha, followed by a decrease to 12.57 kg/ha in the monsoon and a slight recovery to 14.43 kg/ha post-monsoon likely due to lower leaching.³⁷ Phosphorus availability is often limited in tropical soils, with typical agronomic thresholds ranging between 10–25 kg/ha. Thus, the pre-monsoon phosphorus in 2023 exceeds the optimal range, potentially indicating recent nutrient input or mineralization of organic matter, while monsoon levels fall at the lower end, consistent with leaching patterns described in tropical agroecosystems. These comparisons highlight the seasonality and fragility of phosphorus retention in lateritic plateau soils.^{37,38}

Potassium content in 2022, 156.6 kg/ha (pre-monsoon), 160 kg/ha (monsoon), and 140.2 kg/ha (post-monsoon) with a standard deviation of 10.59. In contrast, 2023 exhibited a sharp increase to 359.92 kg/ha in the pre-monsoon, followed by significant declines to 112 kg/ha (monsoon) and 40.9 kg/ha (post-monsoon), resulting in a higher standard deviation of 167.478. Potassium's plays a role in plant physiology, noting that it constitutes 1–3% of plant dry weight and is vital for enzyme activation, osmoregulation, and stress tolerance.³⁹ In 2023, the lower levels could indicate better nutrient uptake by vegetation. The observed 2023 fluctuations may reflect rapid plant uptake during early growth stages or leaching losses in the monsoon season.⁴⁰ Sulphur levels were also higher in 2022 3.1 ppm (pre-monsoon), 3.4 ppm (monsoon), and 2.8 ppm (post-monsoon), with a standard deviation of 0.30. In 2023, levels were 3.65 ppm (pre-monsoon), 3.0 ppm (monsoon), and a notable drop to 0.41 ppm (post-monsoon), resulting in a higher standard deviation of 1.714. Sulfur is crucial for protein synthesis and is

primarily taken up by plants as sulfate (SO_4^{2-}), which is highly soluble and prone to leaching, especially in high-rainfall areas. As an essential element for protein synthesis, sulphur levels may have fluctuated due to atmospheric deposition.⁴¹

Calcium and magnesium showed relatively stable concentrations across both years, with 2023 displaying slightly less variability. These nutrients are critical for plant cell walls and enzymatic functions.⁴⁰ The calcium levels observed ranged from 610 to 622 ppm in 2022 and from 540 to 640 ppm in 2023, which fall within the lower end of the general sufficiency range of 1,000–10,000 ppm. Magnesium levels, ranging from 113 to 118 ppm in 2022 and from 114 to 124 ppm in 2023, lie near the threshold of adequacy, typically considered between 100–1,000 ppm.⁴¹ The minor variations observed in 2022 may reflect differences in soil water availability. Zinc levels remained low and stable across seasons, ranging from 11.5 to 14.0 ppm in 2022 and 7.17 to 10.02 ppm in 2023, above the commonly cited sufficiency range of 1.0–5.0 ppm. Zinc is important for enzymatic activity and trace elements fluctuate due to seasonal changes in moisture and uptake.^{42,43}

Iron levels exhibited higher variation in 2022, 7.8 ppm (post-monsoon) to 9.2 ppm (monsoon), with a standard deviation of 0.71, with peaks during monsoon, possibly driven by pH and soil moisture dynamics. Iron supports photosynthesis and respiration, and its availability is highly sensitive to environmental changes.⁴⁴ A more stable supply in 2023 7.17 ppm (post-monsoon) to a monsoon peak of 37.9 ppm (SD = 16.979), may suggest more efficient plant uptake. Iron availability is strongly influenced by environmental factors such as pH and redox conditions, with lower pH enhancing Fe solubility.⁴⁴ The high iron concentration during the 2023 monsoon may thus reflect increased solubilization under more acidic conditions, enhancing uptake but also posing a risk of toxicity if levels persist. Copper concentrations were consistent across both years, with minimal fluctuation. In 2022, values ranged narrowly from 2.63 to 3.01 ppm (SD = 0.71), and in 2023, they ranged from 1.38 to 4.99 ppm (SD = 1.823), showing slightly more fluctuation but within a moderate range. Copper is essential for enzymatic functions and reproductive growth, with optimal soil concentrations typically between 1 and 5 ppm. While the upper value of 4.99

ppm in 2023 approached this threshold, it did not exceed phytotoxic levels.⁴⁵ While essential, copper can be toxic in excess; the observed stability is likely linked to pH effects.³⁹ Manganese showed considerable variation in 2022, during the post-monsoon season, increasing from 16.5 ppm (pre-monsoon) and 17.5 ppm (monsoon) to 18.0 ppm (post-monsoon), with a high standard deviation of 11.15. This pattern suggests that seasonal changes in soil moisture and redox potential strongly influenced Mn availability. In 2023, manganese levels ranged from 14.2 ppm (pre-monsoon) to an unusually high 34.18 ppm post-monsoon (SD = 11.153), further highlighting the element's sensitivity to hydrological shifts. Manganese is essential for photosynthesis and oxidative stress defense. Its levels can fluctuate based on microbial activity and redox conditions, both influenced by seasonal soil moisture.⁴⁶ Overall, the high levels of pH, iron, and manganese, coupled with low potassium, sulfur, and boron, may indicate ongoing anthropogenic influence on the plateau.

Water quality assessment at Nediya from 2022 to 2023 demonstrated temporal variations influenced by climate and the underlying geology. The water remained slightly to moderately acidic, with pH ranging from 5.4 to 6.3. The marginal pH increase in pre- and post-monsoon periods of 2023 suggests reduced acidification. Such conditions are typical in lateritic regions with minimal buffering due to the absence of carbonates.⁴⁷ The low carbonate and bicarbonate levels confirm this, underscoring the pools' sensitivity to rainfall and organic acid inputs.⁴⁸

EC and total dissolved solids (TDS) values across the seasonal pools ranged from 0.09 to 0.21 dS/m and 64.3 to 110 mg/L, respectively, indicating minimal salinity and affirming their freshwater nature. These values are consistent with or slightly lower than those reported in similar Indian wetland studies. For instance, EC in Charan Beel, Assam ranged from 64.20 to 88.30 $\mu\text{S}/\text{cm}$ with TDS between 122 and 345 mg/L, while in Ropar Wetland, Punjab, EC ranged from 200 to 450 $\mu\text{S}/\text{cm}$ and TDS from 102 to 161 mg/L. In the Pokkali wetlands of Kerala, EC fluctuated seasonally due to seawater intrusion and rainfall dynamics. The dilution effect of monsoon rains was evident, particularly in 2022. However, higher EC and TDS in 2023 during monsoon and post-monsoon may be due to slower leaching,

reduced runoff, or increased ionic input. This reflects interannual differences in hydrological regimes.^{48,49}

Potassium levels in the seasonal pools declined across seasons in 2022 (from 4.5 ppm pre-monsoon to 3.2 ppm post-monsoon), likely due to leaching, which is common in tropical regions with high rainfall and porous lateritic substrates.⁴⁸ In 2023, potassium levels were more stable (ranging from 3.8 to 3.5 ppm), possibly reflecting reduced leaching intensity or enhanced nutrient uptake by aquatic and semi-aquatic vegetation. Similar seasonal potassium leaching patterns have been documented in tropical wetlands, where heavy rains contribute to nutrient washout, in the freshwater wetlands of Tamil Nadu.⁴⁹ Chloride concentrations ranged from 1.3 to 0.8 meq/L in 2022 and from 1.2 to 0.9 meq/L in 2023, showing seasonal dilution during monsoon and gradual concentration afterward. Bicarbonate levels followed a similar pattern, with values declining from 0.6 to 0.3 meq/L in 2022 and maintaining a narrower range (0.5 to 0.4 meq/L) in 2023. These concentrations fall within ecologically acceptable limits for freshwater wetlands and align with observations from other Indian wetland systems such as the Bhitarkanika mangroves and the Charan Beel in Assam.^{48,49} The seasonal variation in these ions underscores the dynamic hydrological and geochemical processes at play in lateritic wetland ecosystems.

Micronutrients such as iron and copper remained within ecologically safe limits across seasons in both years, with iron ranging from 0.175 to 0.135 ppm in 2022 and 0.165 to 0.140 ppm in 2023, and copper varying slightly from 0.031 to 0.022 ppm in 2022 and 0.035 to 0.031 ppm in 2023. Minor fluctuations in iron levels were likely driven by redox reactions at the soil–water interface, a common feature in tropical freshwater systems where alternating wet and dry conditions affect the solubility of iron compounds.⁵⁰ Copper concentrations remained low and stable, consistent with findings from lateritic pools where minimal anthropogenic input limits heavy metal enrichment.^{48,49} Zinc was undetectable during the monsoon and post-monsoon seasons in both years, which may be due to rapid uptake by biota or precipitation under acidic pH conditions (~5.4–5.7). Such seasonal zinc depletion is often associated with high biological demand or reduced

solubility, particularly in nutrient-poor systems.^{50,51} The absence of detectable zinc during critical growth periods may suggest micronutrient limitations for aquatic flora and fauna, potentially influencing primary productivity and trophic interactions.

Based on the provided parameters, the water from Nedyenga appears to be of relatively good quality. However, local water quality standards and regulations must be considered to determine whether the values meet the specified criteria for various uses, such as drinking water or agricultural purposes.⁵² Additionally, periodic monitoring is essential to ensure continued water quality.

Conclusion

Lateritic plateaus like Nedyenga in northern Kerala harbor rich, endemic herbaceous biodiversity but remain underrepresented in floristic studies and conservation efforts. However, increasing anthropogenic pressures including mining, construction, unauthorized roads, and seasonal fires have severely threatened the region's plant diversity and ecological integrity. Between 2019 and 2023, Nedyenga exhibited clear seasonal and interannual variation in temperature and precipitation, with peak rainfall during the monsoon months, especially July and August, exceeding 1000 mm in 2019 and 2022. The monsoon was weaker in 2021 and 2023, while pre-monsoon rains peaked in May 2021 and post-monsoon rainfall was higher in 2023. Summer temperatures consistently reached highs, with a maximum of 36.13°C in March 2023, though monsoon periods provided cooling effects. Soil analysis at Nedyenga revealed acidity and nutrient imbalances that affect plant types, highlighting the need for targeted soil management. While water quality was generally good, regular monitoring is essential to sustain its use and support broader environmental benefits. The rich biodiversity of the Nedyenga habitats is under serious threat from a number of environmental pressures. These ecosystems are highly sensitive, and their unique microclimatic conditions are irreplaceable via any artificial or in vitro conservation methods. It is therefore vital that relevant authorities recognize the urgency of this situation and take urgent and planned and action. Protecting Nedyenga's exceptional and rare biodiversity is not just a local responsibility it is a global imperative.

Acknowledgement

We express our gratitude to Sree Narayana College Kannur, Kerala for their generous support in facilitating our research activities. We would like to acknowledge the support provided by Dr. Aparna P., Head of the Department of Botany, for his invaluable guidance and assistance. We would like to express our gratitude to Dr. K. P. Prasanth for his valuable assistance during the revision of the manuscript.

Funding Sources

The corresponding author received financial support for the research, from Council of Scientific & Industrial Research (CSIR), Govt. of India, (File No. 08/377/(0001)/2021-EMR-I). for publication of this article.

Conflict of Interest

The authors do not have any conflict of interest.

Data Availability Statement

The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

This study did not involve human participants, and therefore, informed consent was not required.

Permission to Reproduce Material from other Sources

Not Applicable

Author Contributions

- **Sarga Abhijith:** Conceptualization, Writing, Data analysis.
- **Jeeshna Meethale Valappil:** Proofreading, review & editing
- **Sreelakshmi Thachan:** Proofreading, review & editing.
- **Greeshma Kadamboor Surendran:** Proofreading, review & editing.
- **Asha Embrandiri:** Proofreading, review & editing.

Reference

1. Pramod C, Pradeep AK. Habitat and floristic diversity of Madayippara, a South Indian lateritic plateau. 2018;:50–53.
2. Roy Chowdhury MK, Datta NP, Goel IC. Laterite Soils of India. New Delhi: Indian Council of Agricultural Research; 1965.
3. Banerjee SK. Geomorphology and laterite formations of Kerala. *Indian Journal of Landscape Systems and Ecological Studies*. 1998;21(2):122-128.
4. Jayarajan PR. Laterite of Kerala: Geo-Environmental Perspectives. Trivandrum: Centre for Earth Science Studies; 2004.
5. Biju P. *Flora of Shallow Ponds in the Low Altitude Laterite Plateaus of Kerala and Konkan Coast*. MG University; 2020.
6. Unnikrishnan E. Sacred groves of Kerala: An ecological and cultural study. *Journal of Ecological Studies*. 1995;8(1):23-27.
7. Chandran MDS, Joshi NV, Gadgil M. Sacred groves of the Western Ghats of India: Ecology, culture, and conservation. *Social Ecology*. 2005;1(2):350-366.
8. Porembski S, Watve A. Ephemeral plant habitats on lateritic plateaus in India. *Phytocoenologia*. 2005;35(1):1-12.
9. Prasad SN, Joseph S, Nair VJ. Wetland plant diversity in lateritic plateaus of Kerala. *Tropical Ecology*. 2012;53(1):29-39.
10. Yadav SR, Joshi SP, Deokule SS, et al. Seasonal wetlands on lateritic plateaus of Maharashtra: Ecological importance and conservation. *Aquatic Botany*. 2009;90(3):229-232.
11. Lekhak MM, Yadav SR. Plant succession and diversity in seasonal pools on laterite plateaus in southwestern India. *Journal of Threatened Taxa*. 2023;15(3):11721–11732.
12. Munoz Sabater J. ERA5-Land hourly data from 1981 to present. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. Published 2019. doi:10.24381/cds.e2161bac
13. Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. Google Earth Engine: Planetary-scale geospatial analysis for

- everyone. *Remote Sensing of Environment*. 2017;202:18-27.
14. Thorpe R, Watve A. India's lateritic plateaus: Misunderstood habitats at conservation risk. *Conservation Science and Practice*. 2023;5(1):e1268.
 15. Biju SD, Gower DJ, Wilkinson M. New species discoveries from laterite habitats of southwestern India. *Zootaxa*. 2023;5271(1):1-18.
 16. Copernicus Climate Change Service (C3S). ERA5-Land data. Climate Data Store. Published 2023. <https://cds.climate.copernicus.eu>
 17. Jackson ML. *Soil Chemical Analysis*. New Delhi: Prentice Hall of India; 1958.
 18. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci*. 1934;37(1):29-38.
 19. Pratt PF, Norman AG. Potassium. In: Black CA, ed. *Methods of Soil Analysis: Part 2—Chemical and Microbiological Properties*. Madison, WI: American Society of Agronomy; 1965:1022–1030.
 20. Massoumi A, Cornfield AH. Assessment of soil sulfur status. *Soil Sci*. 1962;93:215-221.
 21. Sims JT, Johnson GV. Micronutrient soil tests. In: *Micronutrients in Agriculture*. 2nd ed. Madison, WI: Soil Science Society of America; 1991:427–476.
 22. Bingham FT. Boron. In: Page AL, ed. *Methods of Soil Analysis: Part 2*. Madison, WI: ASA and SSSA; 1982:431–448.
 23. Arnold EG, Lenore SC, Eaton AD, eds. *Standard Methods for the Examination of Water and Wastewater*. 18th ed. Washington, DC: American Public Health Association; 1992.
 24. Thermo Scientific. *Expert pH and Conductivity Meter User Guide*. Thermo Fisher Scientific; 2020.
 25. IUCN. 2019. *Guidelines for Using the IUCN Red List Categories and Criteria. Version 14*. Prepared by the Standards and Petitions Subcommittee. <https://www.iucnredlist.org/documents/RedListGuidelines/>.
 26. Porembski S, Watve A, Barthlott W. Lateritic plateaus of Western Maharashtra: A fragile ecosystem. *J Ecol*. 2005;93(5):823-832.
 27. Banerjee AK. Studies on ecological differentiation on rock outcrops. *Environ Ecol*. 1998;16(2):321-325.
 28. Yadav SR, Gaikwad SP, Shende D, Lekhak MM. Vegetation of rock outcrops in the northern Western Ghats of India. *J Threat Taxa*. 2009;1(11):545-552. doi:10.11609/JoTT.o2134.545-52
 29. Lekhak MM, Yadav SR. Diversity and ecology of ephemeral flush communities on lateritic outcrops of Maharashtra. *Indian J Plant Sci*. 2023;12(1):45-57.
 30. Chandran MDS, Joshi NV, Gadgil M. Biodiversity and ecological history of the Western Ghats. *Curr Sci*. 2005;89(7):1019-1027.
 31. Unnikrishnan N. Hydrology and ecology of ephemeral water bodies in the lateritic regions of Kerala. *Kerala Environ Stud*. 1995;4:32-39.
 32. Jayarajan P. *Geography of Kerala*. Thiruvananthapuram: State Institute of Languages; 2004.
 33. IPCC. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press; 2021.
 34. Roy Chowdhury N, Datta NC, Goel SN. Climate and vegetation dynamics in the lateritic zones of India. *Indian For*. 1965;91:441-446.
 35. Rengel Z. Soil pH, soil health and climate change. In: Lal R, Stewart BA, eds. *Soil-Specific Farming: Precision Agriculture*. CRC Press; 2015:67-94.
 36. Yang Y, Fang J, Ji C, Han W. Changes in soil organic carbon and nitrogen in China's forests during 1980s–2000s. *Sci Rep*. 2016;6:19568. doi:10.1038/srep19568
 37. Vance CP, Uhde-Stone C, Allan DL. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource. *New Phytol*. 2003;157(3):423-447. doi:10.1046/j.1469-8137.2003.00695.x
 38. Sattari SZ, Bouwman AF, Giller KE, van Ittersum MK. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. *Proc Natl Acad Sci U S A*. 2012;109(16):6348-6353. doi:10.1073/pnas.1113675109

39. Ayoub AT, Mermut AR, Eswaran H. *Sustaining the Soil: Indigenous Soil and Water Conservation in Africa*. Food and Agriculture Organization; 2018.
40. Mengel K, Kirkby EA. *Principles of Plant Nutrition*. 5th ed. Kluwer Academic Publishers; 2001.
41. Haug W. Sulphur in soil and its impact on vegetation. *Soil Sci Rev*. 2011;38(1):112-127.
42. Alloway BJ. *Zinc in Soils and Crop Nutrition*. 2nd ed. International Zinc Association and IFA; 2008.
43. Cakmak I. Enrichment of cereal grains with zinc: Agronomic or genetic biofortification? *Plant Soil*. 2008;302:1-17. doi:10.1007/s11104-007-9466-3
44. Garbeva P, van Veen JA, van Elsas JD. Microbial diversity in soil: Selection of microbial populations by plant and soil type and implications for disease suppressiveness. *Annu Rev Phytopathol*. 2004;42:243-270. doi:10.1146/annurev.phyto.42.012604.135455
45. Liu WJ, Xu WH, He YF, et al. Copper uptake and its toxicity in plants: A review. *Environ Exp Bot*. 2013;88:1-13. doi:10.1016/j.envexpbot.2012.07.002
46. Tiburcio AF, Alcázar R, Altabella T, Borrell A. Polyamines and plant adaptation to environmental stress. *J Plant Sci*. 2015;237:3-16.
47. Yadav SR, Lekhak MM, Gaikwad SP. Ecology and plant diversity of rock outcrops in peninsular India. In: Joshi R, ed. *Conservation of Fragile Ecosystems*. New Delhi: Scientific Publishers; 2019:105-122.
48. Kumar A, Sinha S, Kumar S. Physicochemical characterization of water in lateritic seasonal pools. *Ecohydrol Hydrobiol*. 2020;20(1):94-102. doi:10.1016/j.ecohyd.2019.10.006
49. Saravanan K, Ravikumar S, Thajuddin N. Hydrological and nutrient dynamics of freshwater seasonal wetlands in India. *Wetlands Ecol Manage*. 2015;23(2):203-216. doi:10.1007/s11273-014-9360-2
50. Singh S, Pandey R. Nutrient dynamics in tropical freshwater ecosystems: Implications for ecosystem functioning. *Aquat Ecol*. 2021;55(3):581-595. doi:10.1007/s10452-021-09850-6
51. Sharma BK, Raju NS. Micronutrient dynamics in water bodies of India: Iron and copper variations. *Indian J Environ Prot*. 2013;33(5):405-412.
52. World Health Organization (WHO). *Guidelines for Drinking-Water Quality*. 4th ed. WHO Press; 2017.