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Integrated floristic, environmental, and hyperspectral characterization of wetland vegetation in lake Manzala: implications for ecosystem functioning

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Introduction: Lake Manzala, the largest coastal lake in the Northeastern Nile
Delta of Egypt, represents a highly disturbed wetland system shaped by strong
environmental gradients and persistent anthropogenic pressure. This study
integrates floristic surveys with field-based hyperspectral measurements to
assess vegetation structure, ecological adaptation, and species-level spectral
discrimination across lake shore, islet, and open-water habitats.

Methods: Floristic analysis of georeferenced stands identified 55 vascular plant
species belonging to 26 families, dominated by perennial taxa and widely
distributed chorotypes. Hyperspectral reflectance data (350–2,500 nm) were
collected using an ASD FieldSpec spectroradiometer to evaluate vegetation
spectral behavior and physiological responses across different wetland habitats.

Results: Vegetation composition varied markedly among habitats, with
emergent and terrestrial species prevailing along lake shores, while floating
and submerged hydrophytes dominated open-water zones. Hyperspectral
measurements revealed strong species discrimination, particularly in the near-
infrared (NIR) and red-edge regions. These wavelengths effectively separated
emergent macrophytes (*Phragmites australis* and *Typha domingensis*) from
submerged species (*Ceratophyllum demersum* and *Potamogeton pectinatus*),
while shortwave infrared (SWIR) bands captured variations in leaf water content
and biochemical composition. Vegetation indices indicated high productivity
in *Cyperus alopecuroides*, *Echinochloa stagnina*, and *P. pectinatus*, whereas
halophytic and stress-tolerant species exhibited lower NDVI and elevated stress
and senescence indicators. One-way ANOVA confirmed significant interspecific
spectral differences ($p < 0.05$).

Discussion: By integrating hyperspectral sensing with plant functional ecology,
this study provides a robust, non-destructive approach for vegetation monitoring,
species-level discrimination, and ecological assessment in complex wetland
environments.

KEYWORDS

floristic composition, hyperspectral reflectance, lake Manzala, Nile delta, vegetation
indices, wetland habitats

1 Introduction

Lake Manzala is a large brackish water body in the northeastern Nile Delta that has historically provided major ecosystem services, particularly fisheries, while simultaneously receiving substantial pollutant loads from surrounding agricultural, industrial, and municipal sources (Zahran and Willis, 2008; Kock Rasmussen et al., 2009; Abdel-Gaber et al., 2015; Haroon, 2022; Kobo et al., 2022). The pronounced loss of lake area documented over recent decades has been linked to drainage and land conversion pressures, which have reshaped shoreline dynamics, water residence time, and habitat availability (Abdel-Gaber et al., 2015; Haroon, 2022). In parallel, northern Egyptian lakes function as important components of regional wetland networks that contribute to carbon sequestration and climate regulation, as wetland vegetation and sediments can act as effective carbon sinks (Tranvik et al., 2009; Villa and Bernal, 2018; Wu et al., 2024). This dual context—high ecological value under persistent anthropogenic stress—makes Lake Manzala a priority system for integrated vegetation assessment and monitoring, particularly using spatially explicit approaches such as GIS and remote sensing frameworks. Wetlands are among the most productive and ecologically significant ecosystems worldwide, acting as transitional environments between terrestrial and aquatic systems and supporting a high diversity of plant species adapted to fluctuating hydrological conditions (Mitsch et al., 2009). The structure and functioning of wetland ecosystems are largely controlled by vegetation, which plays a fundamental role in regulating nutrient cycling, stabilizing sediments, modifying hydrological regimes, and providing habitat for a wide range of organisms (Keddy, 2010). Consequently, the composition, distribution, and physiological status of wetland vegetation are widely recognized as reliable indicators of ecosystem condition and environmental change. Aquatic and semi-aquatic plants exhibit a wide range of morphological, physiological, and phenological adaptations that enable them to survive under conditions of waterlogging, variable salinity, and limited oxygen availability. Such adaptations include aerenchyma development, specialized root systems, altered leaf anatomy, and flexible growth forms that allow plants to tolerate both inundation and exposure (Cronk and Siobhan Fennessy, 2001). Variations in vegetation structure and life-form composition often reflect underlying environmental gradients, particularly those related to hydrology, disturbance, and nutrient availability, making vegetation-based assessments essential for wetland ecological studies (Maltby, 2009). Coastal lakes represent a distinctive type of wetland ecosystem characterized by shallow water depth, strong land–water interactions, and high sensitivity to anthropogenic pressures. In the Nile Delta of Egypt, coastal lakes play a crucial ecological and socioeconomic role by supporting fisheries, biodiversity, and migratory bird populations. However, their proximity to densely populated and intensively cultivated areas renders them particularly vulnerable to environmental degradation, leading to changes in vegetation composition and spatial distribution (Shaltout and Galal, 2007). Lake Manzala, the largest deltaic coastal lake in Egypt, exemplifies these challenges, having undergone extensive ecological transformation driven by drainage inflows, land reclamation, and altered hydrological connectivity. Vegetation

dynamics in Lake Manzala are characterized by pronounced spatial heterogeneity, with emergent, floating, submerged, and terrestrial plant assemblages distributed across lake shore, islet, and open-water habitats. Such heterogeneity reflects complex interactions between hydrological conditions, substrate characteristics, and disturbance regimes. Floristic composition, life-form spectra, and chorological patterns provide valuable insight into the adaptive strategies of plant species and the ecological processes shaping vegetation structure in deltaic lakes (Zahran and Willis, 2008). Accordingly, detailed floristic and ecological analyses form a critical foundation for understanding vegetation responses to environmental stress in Lake Manzala.

Traditional approaches to wetland vegetation assessment have relied primarily on field-based floristic surveys and ecological classification. While these methods provide essential information on species composition and community structure, they are often limited in their ability to detect early physiological stress or subtle functional changes within plant communities. In this context, remote sensing techniques have become increasingly important tools for wetland monitoring due to their capacity to provide spatially explicit, repetitive, and non-destructive observations over large and often inaccessible areas (Klemas, 2001). Among remote sensing approaches, hyperspectral remote sensing represents a significant advancement for vegetation studies. Hyperspectral data consist of hundreds of narrow, contiguous spectral bands spanning the visible (VIS), near-infrared (NIR), and shortwave infrared (SWIR) regions, enabling detailed characterization of plant biochemical and biophysical properties (Curran, 1989). Variations in spectral reflectance are closely linked to pigment concentration, internal leaf structure, and water content, allowing hyperspectral measurements to capture vegetation responses to environmental stress before visible morphological symptoms appear (Peñuelas et al., 1994; Khderiy et al., 2025b). In wetland environments, hyperspectral techniques have demonstrated high potential for species-level discrimination, assessment of vegetation vitality, and detection of stress related to salinity, nutrient enrichment, and disturbance (Gamon et al., 1992; Gitelson et al., 2001). Field-based hyperspectral measurements are particularly valuable as they provide high-quality reference spectra that support the interpretation of airborne and satellite observations, improve vegetation index development, and enhance ecological understanding in structurally complex wetland systems (Khderiy et al., 2025a). Hyperspectral vegetation indices derived from reflectance data offer quantitative indicators of key plant functional traits. Indices sensitive to chlorophyll content and photosynthetic activity, such as the Normalized Difference Vegetation Index (NDVI), Green NDVI (GNDVI), and red-edge-based indices, are widely used to assess vegetation vigor and stress. Water-related indices derived from SWIR wavelengths provide insight into leaf water status and drought or salinity stress, while pigment-specific indices reflect changes in carotenoid and anthocyanin content associated with physiological stress responses (Hunt Jr and Rock, 1989; Gitelson et al., 2003; Khderiy, 2020; Khderiy et al., 2026). Recent studies have emphasized the ecological importance and environmental sensitivity of wetland vegetation under anthropogenic stress (Barinova et al., 2024). The combined use of multiple hyperspectral indices allows for a comprehensive evaluation of vegetation condition across heterogeneous wetland

habitats. Integrating floristic and ecological analyses with hyperspectral observations provides a robust framework for wetland assessment by linking vegetation composition and adaptive strategies with functional and physiological information. In complex deltaic systems such as Lake Manzala, where vegetation patterns are shaped by strong spatial gradients and dynamic environmental conditions, this integrated approach is particularly valuable. It enables improved discrimination among dominant plant species, enhances detection of vegetation stress, and supports evidence-based monitoring and management strategies.

In recent years, hyperspectral remote sensing has rapidly advanced as a powerful method for vegetation studies by capturing hundreds of contiguous narrow spectral bands across the visible, NIR, and SWIR regions. These high-resolution spectral data enable detailed characterization of plant biochemical and biophysical properties, such as pigment composition, canopy structure, and water content, often before visual symptoms of stress appear. Hyperspectral imaging has been widely applied for vegetation mapping, stress detection, species differentiation, and functional trait analysis in both terrestrial and aquatic ecosystems (Aboelghar and Khderi, 2017; Bhargava et al., 2024; Lausch et al., 2024; Matyukira and Mhangara, 2024; Khderi et al., 2025b). Studies using spaceborne hyperspectral platforms have demonstrated improved discrimination of plant species richness and functional diversity through sensitive red-edge and NIR information (Guo et al., 2023; Khderi et al., 2023), while recent field and airborne research shows that hyperspectral indicators can resolve subtle physiological differences linked to vegetation vitality across scales (Yones et al., 2023; Fawcett et al., 2025). Furthermore, hyperspectral approaches have been successfully used to detect early plant stress responses, such as moisture decline and pigment degradation, demonstrating the potential of narrowband spectral data for environmental and agricultural monitoring (Williams et al., 2023). Accordingly, the present study aims to investigate the aquatic and semi-aquatic vegetation of Lake Manzala through an integrated approach combining floristic composition, life-form and chorological analysis, and detailed field-based hyperspectral measurements. This study aims to characterize vegetation structure and spectral behavior across distinct wetland habitats using hyperspectral vegetation indices and statistical analysis. It also evaluates the potential of hyperspectral techniques for species-level discrimination and ecological assessment in degraded coastal lake ecosystems. Although previous studies have investigated wetland vegetation using either ecological approaches or remote sensing techniques, limited attention has been given to the integration of field-based hyperspectral measurements with detailed floristic and ecological analyses at the species level in complex coastal lagoon systems. In particular, the relationship between species composition, ecological traits, and hyperspectral signatures remains insufficiently explored in Egyptian wetlands. This study addresses this gap by combining floristic analysis, life-form and chorological characterization, and high-resolution hyperspectral data to improve species-level discrimination and ecological interpretation. The novelty of this work lies in linking spectral behavior directly to vegetation structure, ecological traits, and environmental gradients within a heterogeneous wetland system, providing a more comprehensive

understanding of vegetation dynamics in Lake Manzala. Unlike previous studies that primarily relied on either remote sensing data or general vegetation analysis, this study integrates field-based hyperspectral measurements with detailed species-level ecological characterization, providing a more precise understanding of vegetation–environment relationships.

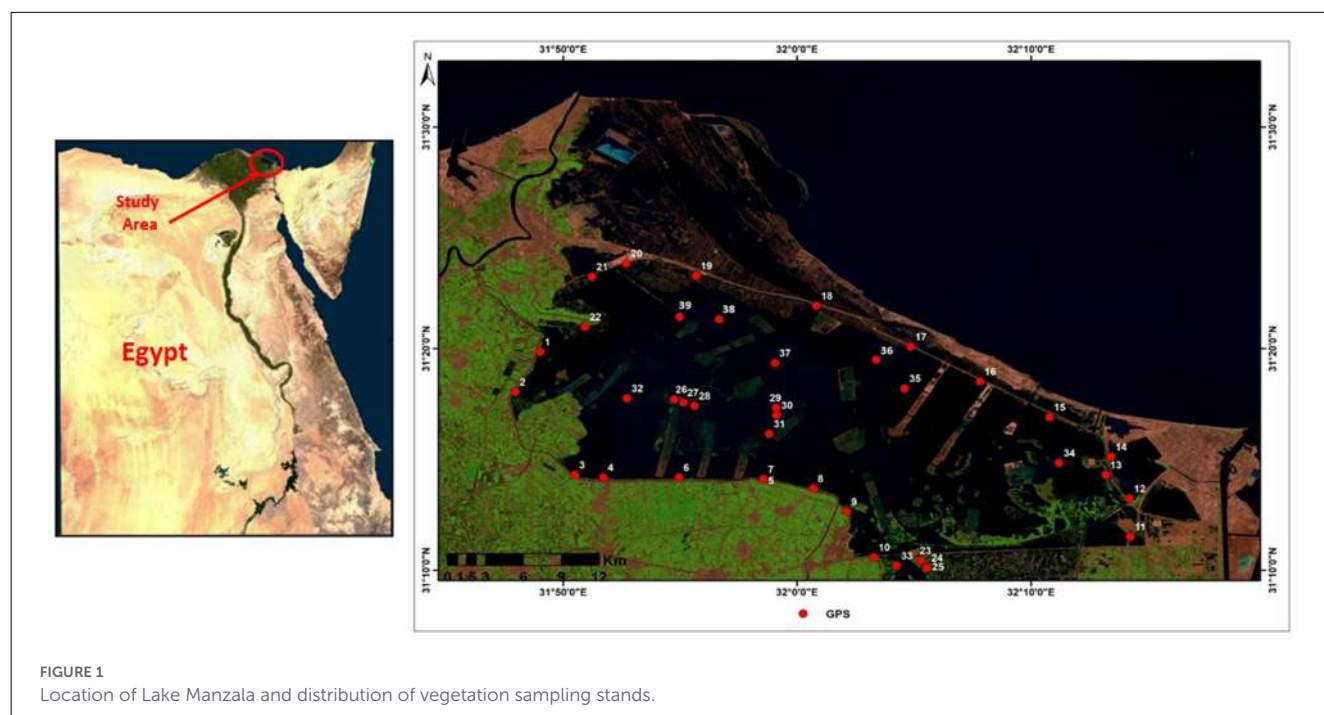
2 Materials and methods

2.1 Study area

Lake Manzala is located in the northeastern Nile Delta, Egypt, and represents the largest deltaic coastal lake in the country. The lake extends approximately between latitudes 31°02'–31°33' N and longitudes 32°18'–33°47' E, and is bordered by the Mediterranean Sea to the north, the Suez Canal to the east, and the Damietta branch of the River Nile to the west. Owing to its shallow nature, with water depths generally ranging from 0.4 to 1.5 m, Lake Manzala supports extensive development of aquatic and semi-aquatic vegetation. The lake comprises a heterogeneous mosaic of wetland habitats, including lake shore zones, lake islets, and open-water areas, which collectively exhibit pronounced spatial variation in vegetation structure and composition. Lake shore habitats are typically dominated by emergent macrophytes, islets support mixed aquatic–terrestrial vegetation, and open-water habitats are characterized mainly by floating and submerged hydrophytes. This habitat diversity provides an appropriate environmental context for vegetation-based ecological and hyperspectral analyses. Vegetation sampling and hyperspectral measurements were conducted at 39 geo-referenced stands distributed across the main habitat types, including 22 lake shore sites, 9 islet sites, and 8 open-water sites (Figure 1). This sampling design was adopted to capture the variability in vegetation composition and spectral behavior across the lake. Climatically, the Lake Manzala region lies within an arid to semi-arid Mediterranean zone, characterized by mild winters, warm summers, low annual rainfall, and high evaporation rates. These climatic conditions, together with the shallow morphology of the lake, strongly influence vegetation growth patterns and seasonal dynamics of aquatic macrophytes. Although this study focuses on Lake Manzala as a representative coastal lagoon system in the Nile Delta, the selected sampling sites were designed to capture the main environmental gradients within the lake, including variations in water depth, salinity, and habitat type. This approach ensures that the dataset reflects a wide range of ecological conditions, allowing for a robust assessment of vegetation–environment relationships within heterogeneous wetland systems. However, the findings are interpreted within the context of this specific ecosystem.

2.2 Vegetation sampling and stand selection

Vegetation sampling was conducted across Lake Manzala using a stratified sampling design to represent the major wetland habitats within the lake. A total of 39 georeferenced stands were selected to



cover the spatial heterogeneity of the study area. These stands were distributed as follows: 22 stands along lake shore habitats, 9 stands on lake islets, and 8 stands within open-water habitats. The selected stands were spatially distributed to capture variations in vegetation composition and habitat characteristics across the lake. Within each stand, vegetation surveys were conducted using five quadrats, each measuring 25 m². All vascular plant species occurring within each quadrat were recorded. Species abundance was estimated using relative frequency values, and the importance value ($IV = 100$) was calculated for each species following standard phytosociological methods described by Westhoff and Van Der Maarel (1978) and Ellenberg and Mueller-Dombois (1974). Plant specimens were collected during the main growing season (March 2022) to ensure accurate identification. Collected specimens were preserved and deposited in the Herbarium of the Botany Department, Faculty of Science, Mansoura University. Species identification and nomenclature followed regional floras and taxonomic references, including Tutin (1964) and Tackholm (1974), and updates by Boulos (1995) and Boulos (1999). From the total floristically recorded taxa, hyperspectral measurements were conducted on a subset of dominant and recurrent plant species rather than on all recorded species. Field spectroradiometric data were acquired for 44 plant species, selected based on their ecological dominance, spatial recurrence across multiple sampling stands (3 stands), and suitability for reliable leaf-level spectral measurements. Several taxa were excluded from hyperspectral acquisition due to limited spatial occurrence, low abundance, highly fragmented populations, or morphological constraints that hinder accurate and repeatable spectral measurements (e.g., very small leaves, submerged growth forms, or inaccessible stands). This selection strategy ensured representative coverage of the main vegetation functional groups and habitat types while maintaining high data quality and consistency in hyperspectral measurements.

2.3 Life-form and chorological analysis

Recorded plant species were classified according to their life span (annual, biennial, perennial) and life-form categories following Raunkiaer's life-form system (Raunkiaer, 1934, 1937). Life-form spectra were used to assess plant adaptive strategies in response to hydrological fluctuation, disturbance, and habitat conditions within Lake Manzala. Chorological affinities of the recorded species were determined based on their global distribution patterns and classified into floristic elements such as Mediterranean, cosmopolitan, pantropical, palaeotropical, and pluri-regional taxa, providing insight into the biogeographical structure of the lake vegetation.

2.4 Field hyperspectral data acquisition and spectral pre-processing

Field-based hyperspectral measurements were conducted to acquire detailed reflectance characteristics of dominant aquatic and semi-aquatic plant species in Lake Manzala. Measurements were performed using an ASD FieldSpec spectroradiometer, covering the full optical spectrum from 350 to 2,500 nm with a nominal output interval of 1 nm. The instrument sampling interval was 1.4 nm in the spectral range of 350–1,050 nm and 2 nm in the range of 1,000–2,500 nm, with automatic interpolation applied by the instrument software to generate continuous spectra across the full wavelength range. Reflectance data were collected under field conditions using a Spectralon® white reference panel for radiometric calibration. A 25° bare fiber optic fore-optic was employed, producing a circular field of view of approximately 3 cm diameter when measurements were acquired at a height of 3 cm above the leaf

surface in a nadir (90°) viewing position. Measurement geometry and illumination conditions were standardized throughout the data acquisition process to minimize variability among observations. To ensure reliable and comparable hyperspectral measurements, data acquisition was conducted under stable atmospheric conditions, and particular attention was given to minimizing the influence of wind, cloud cover, and variable solar illumination angles. Spectral measurement procedures followed established guidelines related to sensor calibration, reference standard use, and experimental design, as outlined by Pfützner et al. (2005). Prior to analysis, spectral regions affected by strong atmospheric water absorption were excluded. The remaining spectral data were segmented into six wavelength regions representing key optical domains relevant to vegetation analysis: blue (350–450 nm), green (451–550 nm), red (551–700 nm), near-infrared (701–1,100 nm), SWIR-I (1,101–1,800 nm), and SWIR-II (1,801–2,500 nm). This segmentation followed standard hyperspectral vegetation analysis protocols described by Underwood et al. (2003) and facilitated interpretation of pigment-related, structural, and water-related spectral features.

2.5 Statistical analysis of hyperspectral data

Statistical analyses were performed to evaluate differences in hyperspectral reflectance and derived vegetation index values among plant species and habitat types. All statistical analyses were conducted using JMP Pro software (version 14.0; SAS Institute Inc., Cary, NC, USA). One-way Analysis of Variance (ANOVA) was applied to test for statistically significant differences across selected spectral regions and hyperspectral vegetation indices. When significant differences were detected at a confidence level of $p < 0.05$, Tukey's Honest Significant Difference (HSD) *post hoc* test was used to identify pairwise differences among species and habitats. To further enhance species-level discrimination based on spectral characteristics, Linear Discriminant Analysis (LDA) was applied to the hyperspectral dataset. This multivariate technique was used to maximize between-class variance relative to within-class variance, thereby improving the separation of dominant plant species across hyperspectral bands and vegetation indices. All spectral pre-processing, vegetation index calculations, and statistical analyses were conducted within the same analytical framework. Mean reflectance spectra, standard deviations, and statistical outputs were generated for each plant species and habitat type prior to interpretation and subsequent ecological analysis. Standard statistical and spectral analysis techniques (e.g., ANOVA, LDA, and vegetation indices) were intentionally applied to ensure interpretability and comparability with previous studies. These approaches provide a robust baseline for evaluating species-level spectral variability while maintaining consistency with established methodologies in ecological and remote sensing research.

2.6 Hyperspectral vegetation indices

Hyperspectral vegetation indices were calculated from field-measured reflectance data to quantify key physiological and biochemical properties of aquatic and semi-aquatic plant species

in Lake Manzala. These indices were selected to represent variations in chlorophyll concentration, photosynthetic activity, biomass, pigment composition, and leaf water status. The use of hyperspectral indices allows for enhanced sensitivity to subtle changes in plant condition compared with broadband indices, particularly in structurally complex wetland environments. Indices sensitive to chlorophyll content and vegetation vigor were used to assess photosynthetic performance, while red-edge-based indices were employed for early stress detection. Water-related indices derived from near- and shortwave infrared wavelengths were applied to evaluate leaf water status. In addition, pigment-specific indices were included to capture variations in carotenoid and anthocyanin content associated with physiological stress responses. All indices were calculated following established formulations reported in the literature and are summarized in Table 1.

3 Results and discussion

3.1 Floristic composition and species distribution

The floristic survey conducted in Lake Manzala resulted in the identification of 55 vascular plant species, representing 41 genera and 26 botanical families, distributed across lake shore, islet, and open-water habitats (Table 2). This relatively high species richness indicates that Lake Manzala still maintains a structurally heterogeneous ecosystem despite long-term environmental pressures, reflecting the coexistence of aquatic, semi-aquatic, and terrestrial vegetation within a confined spatial extent, as also reported for Egyptian wetland systems (El-Alfy, 2015; El-Amier and Abd El-Gawad, 2016). In contrast, lake islets supported 22 species (40.0%), while open-water habitats were floristically poor, containing only 11 species (20.0%), reflecting the restrictive ecological conditions imposed by permanent inundation. Such reduced diversity in open-water habitats reflects strong environmental filtering that limits vegetation establishment to a narrow range of hydrophytic species (Figure 2).

At the family level, Poaceae was the most dominant family, represented by 7 species (12.7%), followed by Asteraceae (6 species; 10.9%) and Chenopodiaceae (5 species; 9.1%). These families collectively accounted for more than one-third of the total flora. The dominance of Poaceae reflects adaptation to wetland conditions, while the presence of Chenopodiaceae indicates the influence of salinity and brackish environments characteristic of Lake Manzala (Quézel, 1978; El-Alfy, 2015).

Other families such as Cyperaceae, Fabaceae, and Polygonaceae showed moderate representation, while the remaining families were represented by one or two species each, indicating a floristically heterogeneous assemblage. This heterogeneity further reflects the role of environmental gradients and disturbance in structuring vegetation composition within the lake ecosystem. This floristic–ecological pattern reflects the influence of multiple anthropogenic pressures acting on Lake Manzala, particularly nutrient enrichment resulting from agricultural drainage and untreated wastewater inputs, which are widely recognized as

TABLE 1 Hyperspectral vegetation indices used for vegetation vitality and stress assessment.

Category	Index	Equation	Explanation	Sources
Canopy water content	Moisture stress index	$MSI = R1599/R819$	Water content	Hunt Jr and Rock (1989)
Dry or senescent carbon	Plant senescence reflectance index	$PSRI = R680 - R500/R750$	Chlorophyll carotenoids ratio	
Broadband greenness	Normalized difference vegetation index	$NDVI = R800 - R680/R800 + R680$	Biomass content	Rouse (1973); Xu et al. (2013)
	Simple ratio	$SR = R800/R680$	General plant condition	Mascarini et al. (2006)
	Enhanced Vegetation index	$EVI = 2.5 * (R800 - R680) / (R800 + 6 * R680 - 7.5 * R450)$	NDVI with a correction of soil reflectance	Peng et al. (2017)
Leaf pigments	Anthocyanin reflectance index	$ARI1 = 1/R550 - 1/R700$	Anthocyanin amount	Gitelson et al. (2001)
Leaf pigments	Anthocyanin reflectance index	$ARI2 = R800 * (1/R550 - 1/R700)$	Anthocyanin amount	Gitelson et al. (2001)
	Carotenoids reflection index	$CRI1 = 1/R510 - 1/R550$	Carotenoids/chlorophyll ratio	Gitelson et al. (2002)
	Carotenoids reflection index	$CRI2 = 1/R510 - 1/R700$	Carotenoids/chlorophyll ratio	Gitelson et al. (2002)
	Cab	$R750 - R705/R750 + R705$	Leaf Cab concentrations	Gitelson et al. (2003)
Red edge vegetation indices	Red edge normalized difference vegetation index	$RENDVI = R750 - R705/R750 + R705$	NDVI based on red edge spectral range	Gitelson and Merzlyak (1994); Sims and Gamon (2002)
	Modified red edge Normalized difference vegetation index	$MRENDVI = R750 - R705/R750 + R705 - 2 * R445$	Modification of RENDVI taking into account leaf specular reflection	Sims and Gamon (2002)
	Modified red edge simple ratio (mSR705)	$MRESR = R750 - R445/R705 - R445$	Red edge modification of SR.	Sims and Gamon (2002); Olofsson et al. (2013)
	Red edge position index	$REPI = (R670 + R780)/2$ $REPI = 700 + 40((R670 - R700)/(R740 - R700))$	Chlorophyll shifts of red edge	Guyot and Baret (1988); Curran et al. (1995)

primary drivers of eutrophication in coastal wetland systems. Under such conditions, vegetation structure is increasingly controlled by environmental filtering processes that favor tolerant and widely distributed species (Pang et al., 2025). The recorded occurrence of submerged macrophytes such as *Ceratophyllum demersum* and *Potamogeton pectinatus* (syn. *Stuckenia pectinata*) further supports this interpretation, as these species are commonly associated with eutrophic to hypertrophic aquatic environments and are frequently used as bioindicators of elevated nutrient levels (Lacoul and Freedman, 2006). This is consistent with the reduced floristic diversity observed in open-water habitats, where only a limited number of hydrophytic species persist under permanent inundation and high nutrient availability. Collectively, these patterns indicate that Lake Manzala is functionally characterized by eutrophic conditions, where vegetation composition and distribution are strongly shaped by nutrient loading, hydrological variability, and disturbance regimes.

3.2 Ecological amplitude and habitat affiliation

Most of the recorded plant species showed restricted ecological amplitude, occurring in a single habitat type, particularly along

lake shores. This pattern is consistent with habitat filtering under strong hydrological and salinity gradients, which are known to structure vegetation distribution in coastal wetlands (Pang et al., 2025). Only a limited number of species displayed wide ecological tolerance and were recorded across more than one habitat. Such broad occurrence reflects greater ecological plasticity under fluctuating wetland conditions (Pang et al., 2025).

Among emergent macrophytes, *Phragmites australis* exhibited the widest ecological amplitude, being recorded in all habitat types with the highest presence value (92.3%), indicating its strong adaptability and dominance within the lake ecosystem. This agrees with recent evidence showing that *Phragmites australis* can persist across contrasting tidal-flat habitats, including high-salinity environments, through marked ecophysiological tolerance. *Typha domingensis* also showed moderate ecological amplitude, occurring mainly in lake shore and islet habitats. Its continued occurrence in Egyptian wetlands also supports its tolerance under stressed and polluted wetland conditions (Soliman et al., 2024).

Floating hydrophytes were generally habitat-restricted. *Eichhornia crassipes* showed relatively broader distribution compared with other floating species, while taxa such as *Lemna minor*, *Azolla filiculoides*, and *Marsilea aegyptiaca* were limited to specific open-water or sheltered zones. The relatively broader spread of *Eichhornia crassipes* is in line with recent assessments

TABLE 2 Floristic composition of vascular plant species recorded in Lake Manzala.

No.	Species	Family	Life span	Life form	Floristic category	Habitat types			P%
						Lake shores	Open water	Lake islets	
A) Hydrophytes									
1. Submerged hydrophytes									
1	<i>Ceratophyllum demersum</i> L.	Ceratophyllaceae	Perennials	Hy	COSM	+	+	–	23.08
2	<i>Potamogeton pectinatus</i> L.	Potamogetonaceae	Perennials	Hy	ME+IR-TR	+	–	–	12.82
2. Floating Hydrophytes									
3	<i>Azolla filiculoides</i> Lam.	Azollaceae	Annuals	Hy	COSM	+	–	–	5.13
4	<i>Eichhornia crassipes</i> (C. Mart.) Solms	Pontederiaceae	Perennials	Hy	NEO	+	+	–	58.97
5	<i>Lemna gibba</i> L.	Lemnaceae	Perennials	Hy	COSM	+	+	–	15.38
6	<i>Lemna minor</i> L.	Lemnaceae	Perennials	Hy	COSM	+	+	–	7.69
7	<i>Ludwigia stolonifera</i> (Guill. & Perr.) P.	Onagraceae	Perennials	He	S-Z	+	+	–	15.38
8	<i>Marsilea aegyptiaca</i> Willd.	Marsileaceae	Perennials	H, He	PAL	+	–	–	5.13
9	<i>Pistia stratiotes</i> L.	Araceae	Perennials	Hy	PAN	+	+	–	30.77
3. Emergent species									
10	<i>Alternanthera sessilis</i> (L.) DC.	Amaranthaceae	Perennials	He	PAN	+	–	–	5.13
11	<i>Bolboschoenus glaucus</i> (Lam.) S.G.Smith	Cyperaceae	Perennials	G	COSM	–	–	+	2.56
12	<i>Cyperus alopecoroids</i> L.	Cyperaceae	Perennials	He	PAN	+	–	–	7.69
13	<i>Cyperus articulatus</i> L.	Cyperaceae	Perennials	G, He	PAN	+	–	–	2.56
14	<i>Cyperus laevigatus</i> L.	Cyperaceae	Perennials	G, He	PAN	+	–	+	5.13
15	<i>Echinochloa colona</i> (L.) Link	Poaceae	Annuals	Th	PAN	+	–	–	5.13
16	<i>Echinochloa stagnina</i> (Retz.) P. Beauv	Poaceae	Perennials	G, He	PAL	+	+	–	20.51
17	<i>Juncus acutus</i> L.	Juncaceae	Perennials	He	ME+IR-TR+ER-SR	+	–	+	10.26
18	<i>Juncus rigidus</i> Desf.	Juncaceae	Perennials	He, G	ME+SA-SI+IR-TR	+	–	+	28.21
19	<i>Juncus subulatus</i>	Juncaceae	Perennials	He, G	ME+SA-SI+IR-TR	+	–	–	5.13
20	<i>Persicaria lapathifolia</i> (L.) Gray	Polygonaceae	Perennials	G	PAL	+	–	–	2.56
21	<i>Persicaria salicifolia</i> (Willd) Assenov	Polygonaceae	Perennials	G	PAL	+	–	–	2.56
22	<i>Phragmites australis</i> (Cav.) Trin. ex Steud	Poaceae	Perennials	G, He	COSM	+	+	+	92.31
23	<i>Ranunculus sceleratus</i> L.	Ranunculaceae	Annuals	Th	ME+IR-TR+ER-SR	+	+	–	12.82
24	<i>Saccharum spontaneum</i> L. Mant. Alt	Poaceae	Perennials	G, He	ME+PAL	+	+	–	10.26

(Continued)

TABLE 2 (Continued)

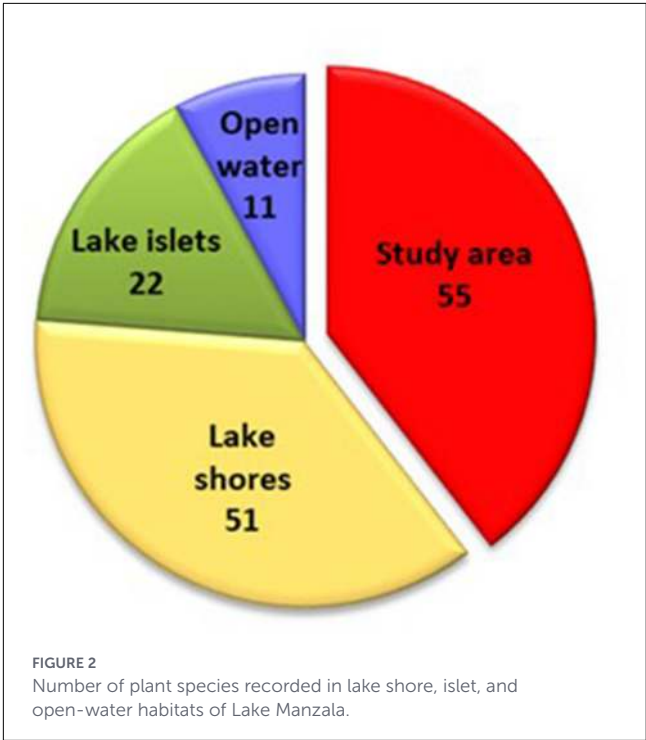
No.	Species	Family	Life span	Life form	Floristic category	Habitat types			P%
						Lake shores	Open water	Lake islets	
25	<i>Typha domingensis</i> (Pers.) Poir. ex Steud.	Typhaceae	Perennials	He	PAN	+	+	–	51.28
B) Halophytic and terrestrial species									
1. Halophytic species									
26	<i>Arthrocnemum macrostachyum</i> _(Moric.)K.Koch	Chenopodiaceae	Perennials	Ch	ME+SA-SI	+	–	+	58.97
27	<i>Atriplex portulacoides</i> L.	Chenopodiaceae	Perennials	Ch	ME+IR-TR+ER-SR	+	–	+	12.82
28	<i>Atriplex prostrata</i> Boucher ex DC.	Chenopodiaceae	Annuals	Th	ME+ER-SR+IR-TR	+	–	+	5.13
29	<i>Bassia indica</i> (Wight) A.J.Scott.	Chenopodiaceae	Annuals	Th	S-Z+IR-TR	+	–	+	25.64
30	<i>Chenopodium album</i> L.	Chenopodiaceae	Annuals	Th	COSM	+	–	+	2.56
31	<i>Chenopodium murale</i> L.	Chenopodiaceae	Annuals	Th	COSM	+	–	+	15.38
32	<i>Cynanchum acutum</i> L.	Asclepiadaceae	Perennials	H	ME+IR-TR	+	–	+	20.51
33	<i>Cynodon dactylon</i> (L.) Pers.	Poaceae	Perennials	G	COSM	+	–	–	10.26
34	<i>Halocnemum strobilaceum</i> (pall) M.Bieb	Chenopodiaceae	Perennials	Ch	ME+IR-TR+SA-SI	+	–	+	51.28
35	<i>Heliotropium curassavicum</i> L.	Boraginaceae	Perennials	Ch	NEO	–	–	+	5.13
2. Terrestrial species									
36	<i>Ipomoea carnea</i> Jacq.	Convolvulaceae	Perennials	Ch	Cult. & Nat.	+	–	–	2.56
37	<i>Limbarda crithmoides</i> (L.) Dumort.	Asteraceae	Perennials	Ch	ME+ER-SR+SA-SI	+	–	+	15.38
38	<i>Malva parviflora</i> L.	Malvaceae	Annuals	Th	ME+IR-TR	–	–	+	2.56
39	<i>Mesembryanthemum crystallinum</i> L.	Aizoaceae	Annuals	Th	ME+ER-SR	+	–	–	7.69
40	<i>Mesembryanthemum nodiflorum</i> L.	Aizoaceae	Annuals	Th	ME+SA-SI+ER-SR	+	–	–	5.13
41	<i>Phyla nodiflora</i> (L.) Greene	Verbenaceae	Perennials	Ch	PAN	+	–	–	2.56
42	<i>Pluchea dioscoridis</i> (L.) DC.	Asteraceae	Perennials	Nph	S-Z+SA-SI	+	–	–	7.69
43	<i>Rumex dentatus</i> L.	Polygonaceae	Annuals	Th	ME+ IR-TR +ER-SR	+	–	–	7.69
44	<i>Salsola kali</i> L.	Convolvulaceae	Annuals	Th	COSM	+	–	–	2.56
45	<i>Senecio glaucus</i> L.	Asteraceae	Annuals	Th	ME+SA-SI+IR-TR	+	–	+	7.69
46	<i>Sonchus oleraceous</i> L.	Asteraceae	Annuals	Th	COSM	+	–	–	5.13
47	<i>Spergularia marina</i> (L.) Griseb.	Caryophyllaceae	Biennials	Th	ER-SR+ME+IR-TR	+	–	+	5.13
48	<i>Suaeda maritima</i> L.	Chenopodiaceae	Annuals	Th	COSM	+	–	–	5.13
49	<i>Suaeda pruinosa</i> Lange	Chenopodiaceae	Perennials	Ch	ME	+	–	+	23.08

(Continued)

TABLE 2 (Continued)

No.	Species	Family		Life span	Life form	Floristic category	Habitat types			P%
							Lake shores	Open water	Lake islets	
50	<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	Chenopodiaceae	Perennials	Ch		ME+SA-SI+ER-SR	-	-	+	5.13
51	<i>Symphoricarichum squamatum</i> (Spreng.) Nesom	Asteraceae	Perennials	Ch		NEO	+	-	+	7.69
52	<i>Tamarix nilotica</i> (Ehrenb.) Bunge	Tamaricaceae	Perennials	Nph		S-Z+SA-SI	+	-	+	38.46
53	<i>Zygophyllum aegyptium</i> hosny	Zygophyllaceae	Perennials	Ch		ME	+	-	-	2.56
54	<i>Zygophyllum album</i> L.	Zygophyllaceae	Perennials	Ch		ME+SA-SI	+	-	+	5.13
55	<i>Zygophyllum coccineum</i> L.	Zygophyllaceae	Perennials	Ch		SA-SI+S-Z	+	-	-	12.82
Number of stands						39	22	8	9	
Number of perennials						39	36	10	16	
Number of biennials						1	1	0	1	
Number of annuals						15	14	1	5	
Total number of recorded species						55	51	11	22	

P, presence; Life-span; Per, perennials; Bi, biennials; Ann, annuals. Life-form: Nph, nanophanerophytes; Ch, chamaephytes; H, hemicryptophytes; G, geophytes; He, helophytes; Hy, hydrophytes; Th, therophytes; Chorotype; COSM, cosmopolitan; PAN, pantropical; NEO, neotropical; PAL, palaetropical; IR-TR, Irano-Turanian; S-Z, Sudano-Zambezian; Cult. & Nat., cultivated and naturalized; ME, Mediterranean; ER-SR, Euro-Siberian; SA-SI, Sahara-Sindian. Bold values indicate the total numbers of stands and recorded species categories across the studied habitats.



describing it as a highly invasive floating macrophyte capable of rapid expansion in suitable aquatic habitats (Yang et al., 2025).

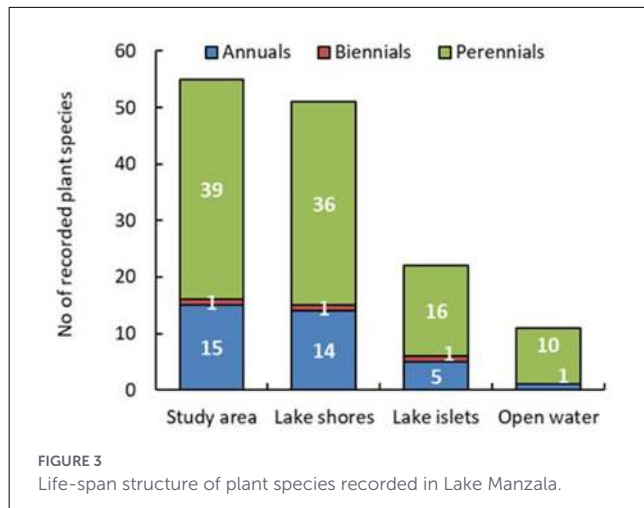
Terrestrial and halophytic species were largely confined to lake shore habitats, reflecting their dependence on periodically exposed substrates and fluctuating moisture conditions. This shoreline confinement is also consistent with recent studies showing that salinity-linked hydrological connectivity strongly controls vegetation patterning in estuarine and coastal wetlands (Pang et al., 2025).

3.3 Life-span structure and life-form spectrum

The combined analysis of life-span structure and life-form spectrum reveals clear patterns in plant adaptive strategies across Lake Manzala habitats (Figure 3). These patterns reflect vegetation responses to environmental gradients and disturbance regimes within wetland ecosystems (Shaltout and Galal, 2007; El-Alfy, 2015; El-Amier and Abd El-Gawad, 2016).

3.3.1 Life-span structure

Perennial species dominate the vegetation, accounting for 39 species (70.9%) of the total flora. Annual species represent 15 species (27.3%), whereas biennial species are rare, with only one species (1.8%) recorded. The dominance of perennial species is consistent with their persistence under fluctuating hydrological conditions and environmental stress typical of wetland systems (Shaltout and Galal, 2007; El-Alfy, 2015; El-Amier and Abd El-Gawad, 2016).



Perennials were present in all habitat types and were particularly dominant in open-water habitats, where they constituted nearly the entire vegetation assemblage. This reflects their ability to maintain growth under permanent inundation conditions. In contrast, annual species were most frequent along lake shore habitats, reflecting the dynamic and disturbed nature of these zones (Shaltout and Galal, 2007; El-Alfy, 2015; El-Amier and Abd El-Gawad, 2016). Lake islets showed an intermediate pattern, with perennials remaining dominant but with a noticeable presence of annual species. This reflects transitional ecological conditions between stable aquatic habitats and disturbed shoreline zones.

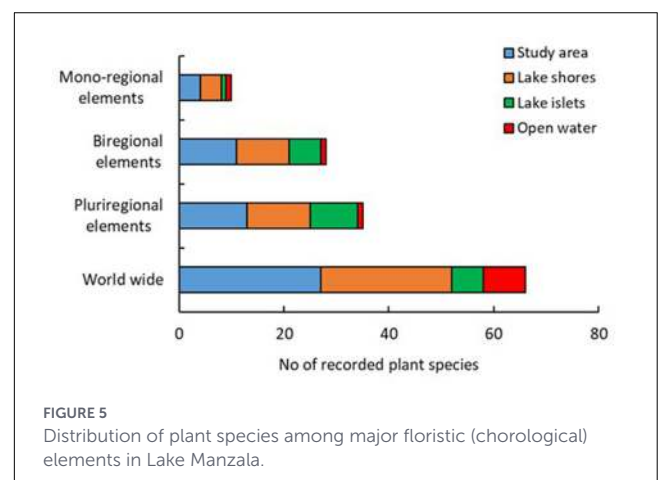
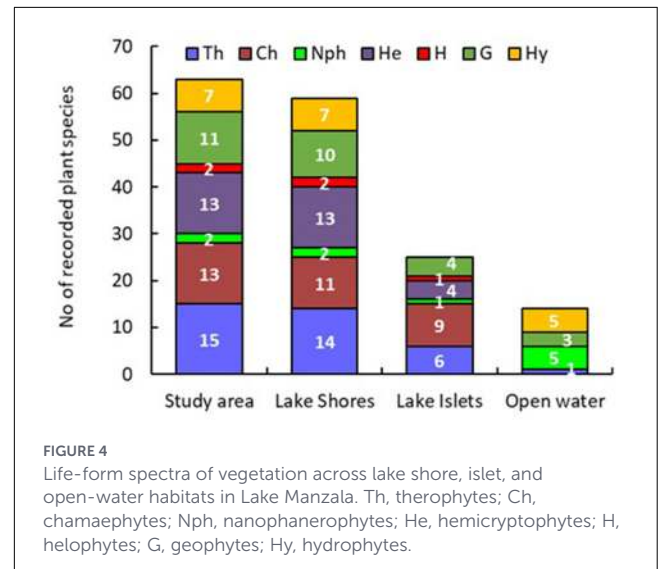
3.3 Life-form spectrum

Seven Raunkiaer life-form categories were identified within the lake vegetation. Therophytes represented the most frequent life-form group (15 species), followed by chamaephytes and helophytes (13 species each). Geophytes were represented by 11 species, while hydrophytes accounted for 7 species (Figure 4). Hemicryptophytes and nanophanerophytes were poorly represented. Such dominance of therophytes and helophytes reflects adaptation to disturbance, salinity, and hydrological variability in coastal wetlands (Midolo et al., 2024).

Life-form composition varied among habitats. Lake shore habitats supported the widest range of life forms, whereas open-water habitats were dominated mainly by hydrophytes and helophytes. This pattern reflects the influence of water depth and substrate availability on vegetation structure. Islet habitats exhibited mixed life-form spectra reflecting their intermediate ecological conditions. Such composition is characteristic of ecotonal habitats influenced by overlapping environmental gradient (Cain and Castro, 1959; Midolo et al., 2024).

3.4 Chorological affinities

Chorological analysis of the vascular plant species recorded in Lake Manzala reveals a clear dominance of widely distributed



floristic elements, reflecting the broad ecological tolerance of the vegetation and the heterogeneous nature of the lake habitats. The analysis indicates that pluri-regional taxa represent the most abundant chorological group, accounting for 23.6% of the total recorded flora. These taxa are characterized by their wide geographical distribution across more than two floristic regions, enabling them to occupy a broad range of environmental conditions within the lake. This dominance of widely distributed taxa is commonly associated with environmental filtering and disturbance-driven ecosystems where generalist species are favored (El Hadidi, 1993). Cosmopolitan species constitute the second most important chorological group, representing 21.8% of the flora. The high proportion of cosmopolitan taxa reflects their strong adaptive capacity and ability to persist under diverse ecological conditions, including fluctuating water levels, variable salinity, and anthropogenic disturbance. These species were recorded across multiple habitat types, particularly along lakeshore and islet habitats. Such a pattern agrees with recent evidence that plant communities in coastal wetlands respond strongly to environmental constraints and disturbance gradients (El-Amier, 2010; El-Amier et al., 2015). Bi-regional elements account for

20.0% of the recorded flora and include species distributed across two major phytogeographical regions. These taxa show moderate ecological amplitude and are mainly associated with transitional habitats within the lake, such as lakeshores and islets, where environmental conditions fluctuate seasonally. This intermediate distribution is compatible with ecotonal conditions where species composition shifts along environmental gradients.

Pantropical taxa represent 14.5% of the flora and are primarily associated with warm climatic conditions. These species were mainly recorded in lake shore habitats and sheltered zones, reflecting their preference for relatively stable thermal regimes and moist substrates. In contrast, palaeotropical taxa (7.3%) and neotropical taxa (5.5%) are less frequently represented (Figure 5). Their limited occurrence indicates a relatively minor contribution of narrowly distributed tropical elements to the overall floristic composition of Lake Manzala (Table 3). This suggests that ecological tolerance plays a stronger role than narrow distributional affinity in structuring the vegetation under lake conditions. Mediterranean and Sudano-Zambezian elements were poorly represented, emphasizing the predominance of broadly distributed taxa over regionally restricted floristic elements. The distribution of chorological categories varies among habitat types. Lake shore habitats support the highest diversity of chorotypes, including cosmopolitan, pluri-regional, and pantropical taxa, whereas islet habitats exhibit a more balanced representation of wide-distribution elements. Open-water habitats are characterized by a limited number of chorotypes, mainly dominated by widely distributed aquatic taxa. This pattern further supports the ecological importance of shoreline habitats as the most heterogeneous part of the wetland system (El-Amier et al., 2015; Yang et al., 2025).

3.5 Spectroscopic parameters and analysis

The field-based hyperspectral reflectance signatures of aquatic and semi-aquatic plant species in Lake Manzala exhibit a common vegetation spectral pattern with pronounced interspecific variability across 350–2,500 nm (Figure 6), enabling clear species-level discrimination, particularly within the red-edge, NIR, and SWIR regions. This agrees with established principles of vegetation spectral behavior controlled by pigment absorption, internal structure, and biochemical composition (Kycko et al., 2014); (Kupková et al., 2017). In the visible region (400–700 nm), all species show low reflectance with absorption features at ~450 nm and ~670 nm due to chlorophyll and accessory pigments. However, variations in reflectance intensity reflect differences in pigment concentration and leaf optical properties. Floating and emergent species exhibit relatively higher reflectance in the green region (~550 nm) compared to submerged taxa, supporting their differentiation based on photosynthetic pigment composition. A pronounced red-edge transition (680–750 nm) represents a key separation zone among species. Emergent macrophytes show a sharper and more distinct red-edge compared to submerged species, indicating higher chlorophyll content and more developed canopy structure, making this region a critical discriminator among vegetation types. The red-edge is widely recognized as

a sensitive indicator of vegetation condition and chlorophyll variability (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025).

In the NIR region (750–1,100 nm), strong interspecific variability is observed. *Phragmites australis* shows the highest reflectance, reflecting dense canopy architecture and enhanced internal leaf scattering, while *Typha domingensis* exhibits slightly lower values, allowing differentiation between emergent species. Submerged macrophytes (*Ceratophyllum demersum* and *Potamogeton pectinatus*) display significantly lower NIR reflectance, forming a distinct spectral group due to reduced internal scattering under submerged conditions. Floating species occupy intermediate positions, with *Eichhornia crassipes* clearly distinguishable by its higher green reflectance and characteristic red-edge behavior. This confirms that NIR reflectance is primarily governed by leaf internal structure and canopy architecture (Cochrane, 2000; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011).

In the SWIR region (1,100–2,500 nm), reflectance decreases across all species, with absorption features at ~1,400 and ~1,900 nm related to water content and around ~2,200 nm linked to biochemical constituents. Emergent species exhibit higher SWIR reflectance than submerged taxa, while halophytic shoreline species (*Atriplex halimus* and *Arthrocnemum macrostachyum*) show enhanced reflectance near 2,200 nm, reflecting adaptations to salinity and water stress. SWIR behavior is strongly linked to plant water content and biochemical composition, enhancing species discrimination (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025).

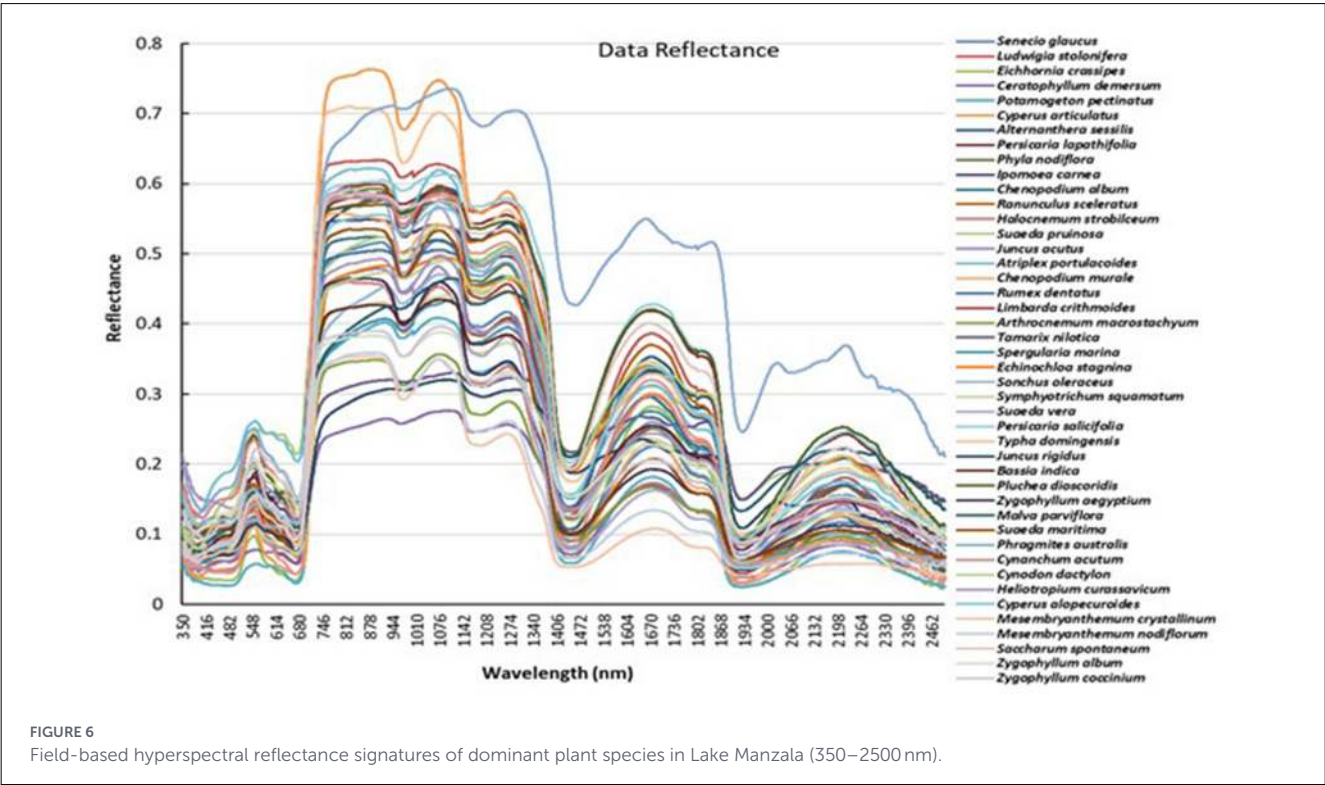
The effectiveness of hyperspectral analysis in this study is strongly linked to the combined use of multiple spectral regions and vegetation indices rather than reliance on single-band information. This integrative approach enhances the detection of species-specific biochemical and structural traits, which are often masked in complex wetland environments.

3.6 Statistical analyses including Tukey's HSD and LDA

One-way Analysis of Variance (ANOVA) revealed statistically significant differences ($p < 0.05$) in hyperspectral reflectance among plant species across most spectral regions (Figures 7, 8), confirming species-specific spectral behavior within the Lake Manzala vegetation assemblage. The variation in discrimination among spectral regions reflects differences in their sensitivity to plant physiological and structural traits. Spectral separability is not uniform across wavelengths because each region responds to different plant properties, including pigment absorption, internal leaf structure, and water content (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). In the visible spectrum, the blue region showed significant differences only for a limited number of taxa, particularly halophytic species (*Atriplex halimus* and *Arthrocnemum macrostachyum*), which

TABLE 3 Number and percentage of plant species belonging to different floristic (chorological) categories across the various habitat types of Lake Manzala.

Floristic category	Study area		Lake shore		Lake islets		Open water		Geographical distribution
	No.	%	No.	%	No.	%	No.	%	
COSM	12	21.82	11	21.57	3	13.64	4	36.36	Worldwide
PAL	4	7.27	4	7.84	—	—	1	9.09	
NEO	3	5.45	2	3.92	2	9.09	1	9.09	
PAN	8	14.55	8	15.69	1	4.55	2	18.18	
ME+IR-TR+ER-SR	6	10.91	6	11.76	4	18.18	1	9.09	Pluri-regional elements
ME+IR-TR+SA-SI	4	7.27	4	7.84	3	13.64	—	—	
ME+ER-SR+SA-SI	3	5.45	2	3.92	2	9.09	—	—	
ME+PAL	1	1.82	1	1.96	—	—	1	9.09	Bi-regional elements
ME+IR-TR	3	5.45	2	3.92	2	9.09	—	—	
ME+ER-SR	1	1.82	1	1.96	—	—	—	—	
ME+SA-SI	2	3.64	2	3.92	2	9.09	—	—	
IR-TR+S-Z	1	1.82	1	1.96	1	4.55	—	—	
SA-SI+S-Z	3	5.45	3	5.88	1	4.55	—	—	
ME	2	3.64	2	3.92	1	4.55	—	—	Mono-regional elements
S-Z	1	1.82	1	1.96	—	—	1	9.09	
Cult. & Nat.	1	1.82	1	1.96	—	—	—	—	
Total	55	100	51	100	22	100	11	100	



exhibited relatively higher reflectance. This is attributed to reduced chlorophyll absorption and structural leaf adaptations in halophytes. However, strong spectral overlap among aquatic species indicates weak discrimination at the species level. The green region provided slightly improved discrimination, where floating species (*Eichhornia crassipes*) exhibited higher reflectance than submerged taxa (*Ceratophyllum demersum*), although overlap among emergent macrophytes persisted. In

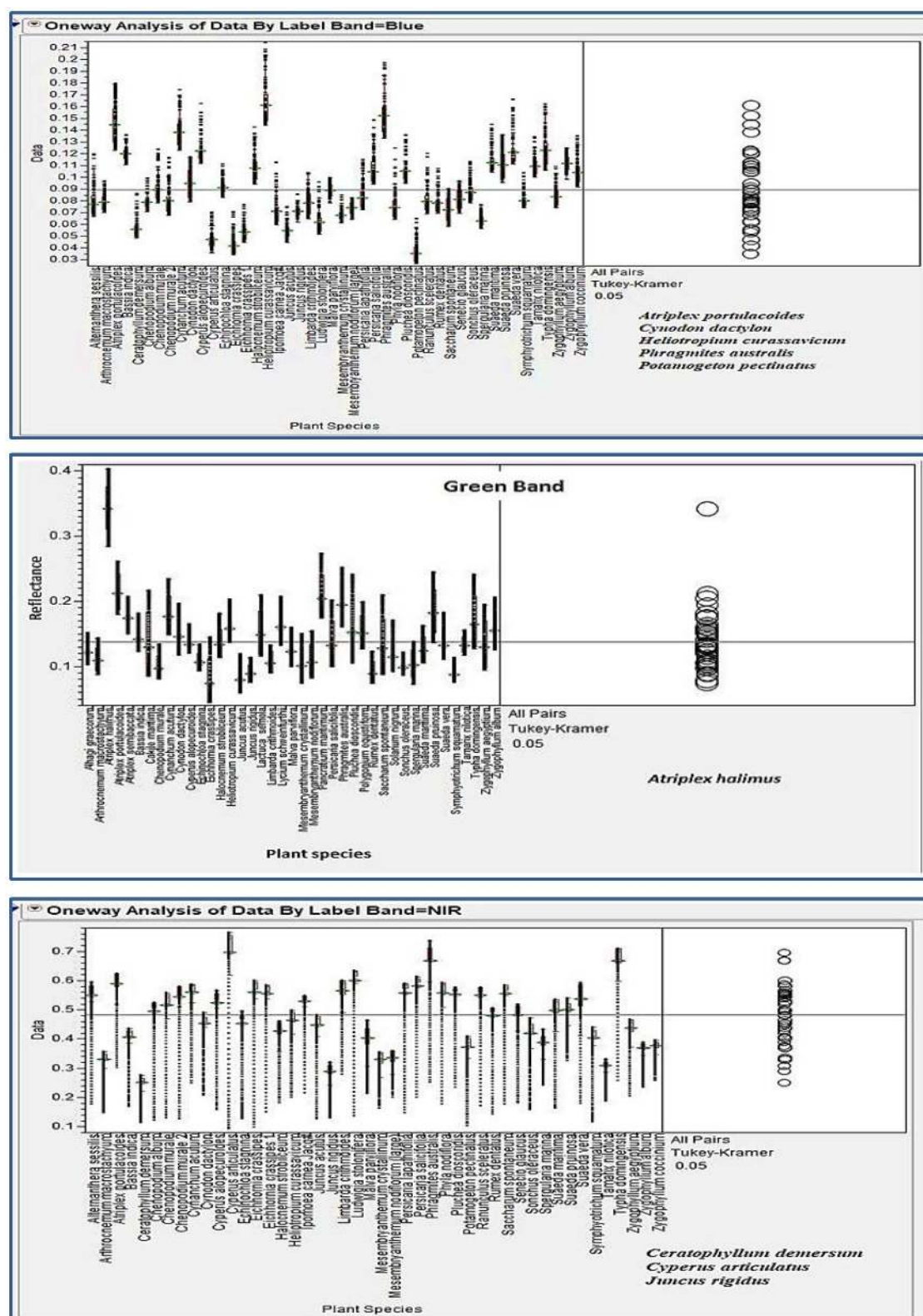


FIGURE 7

ANOVA-based discrimination of dominant plant species across (blue, green and NIR) spectral regions in Lake Manzala.

the red region, reflectance remained consistently low due to strong chlorophyll absorption, limiting discrimination primarily to halophytic and terrestrial taxa. These results demonstrate

that visible bands are predominantly controlled by pigment absorption and are therefore insufficient for reliable species-level discrimination when pigment composition is similar



In contrast, the near-infrared (NIR) region exhibited the highest discriminatory capability, with highly significant differences ($p < 0.05$) clearly separating emergent, floating, and

submerged vegetation types. Emergent macrophytes (*Phragmites australis* and *Typha domingensis*) showed markedly higher reflectance than submerged species (*Ceratophyllum demersum* and *Potamogeton pectinatus*), while floating species occupied intermediate positions. Tukey's HSD test confirmed significant pairwise differences between these vegetation groups. This strong separation is mechanistically linked to differences in internal leaf scattering and canopy architecture, which dominate reflectance in the NIR region and increase with biomass and structural complexity (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). The SWIR regions provided complementary but lower discriminatory power. In SWIR-I, significant interspecific differences were observed, although with higher within-species variability compared to NIR. Emergent macrophytes generally showed higher reflectance than submerged species, while halophytic taxa exhibited distinct responses. In SWIR-II, discrimination remained significant but was weaker and mainly effective in separating halophytic and terrestrial species from aquatic macrophytes. These patterns are associated with variations in leaf water content and biochemical composition, particularly absorption features related to water and organic compounds. Thus, SWIR enhances discrimination by capturing water-related and biochemical variability rather than structural differences, making it complementary to NIR-based separation (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025).

3.7 Wavelength-based discrimination of plant species

The wavelength-based analysis highlights the ability of field hyperspectral data to discriminate among plant species in Lake Manzala, while revealing strong interspecific variability in spectral uniqueness (Table 4). The discriminatory potential of individual wavebands differs among taxa, reflecting variations in pigment composition, canopy structure, and water-related biochemical properties. This confirms that spectral separability is controlled by the combined effects of biochemical and structural plant traits rather than single spectral features (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). The selected vegetation indices were chosen to represent complementary aspects of plant function, including chlorophyll content (NDVI, RECDVI), biomass and canopy structure (SR), pigment composition (PSRI, CRI, ARI), and water status (MSI). This combination allows a comprehensive assessment of plant physiological and ecological variability across wetland habitats.

A subset of species, including *Cyperus articulatus*, *Ipomoea carnea*, *Potamogeton pectinatus*, *Ranunculus sceleratus*, *Saccharum spontaneum*, *Senecio glaucus*, and *Zygophyllum album*, showed strong spectral overlap and lacked distinct diagnostic wavelengths. This indicates limited separability using individual wavebands, as these species share similar optical properties related to chlorophyll absorption and internal leaf structure. Such overlap

demonstrates the limitation of single-band approaches when species exhibit similar pigment composition and structural characteristics (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). In contrast, species such as *Alternanthera sessilis*, *Atriplex halimus*, and *Chenopodium album* exhibited multiple optimal wavelengths across visible, NIR, and SWIR regions, indicating strong spectral distinctiveness. This reflects differences in leaf morphology, canopy structure, and biochemical composition, allowing reliable detection using multispectral and hyperspectral sensors. The presence of multiple diagnostic wavelengths enhances classification accuracy and supports their suitability for spatial mapping and long-term monitoring (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). A third group of species, including *Arthrocnemum macrostachyum*, *Cyperus alopecuroides*, *Echinochloa stagnina*, *Heliotropium curassavicum*, *Ludwigia stolonifera*, *Limbarda crithmoides*, *Persicaria lapathifolia*, *Persicaria salicifolia*, *Rumex dentatus*, *Sonchus oleraceus*, and *Tamarix nilotica*, showed limited spectral uniqueness with only one optimal wavelength or narrow spectral intervals. Although separable at specific wavelengths, their overall similarity to other taxa restricts robust discrimination when relying on narrowband data alone. This highlights the need for multi-band integration or index-based approaches to improve classification reliability (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025).

Across all species, the NIR region emerged as the most informative domain for discrimination, followed by SWIR-I and SWIR-II, particularly for species differing in biomass, leaf structure, and water content. The visible region contributed mainly to species with distinct pigment composition but showed limited effectiveness when used independently. This pattern reflects the dominant role of structural scattering in NIR and water-biochemical absorption in SWIR in enhancing species separability (Cochrane, 2000; Zarco-Tejada et al., 2002; Clark et al., 2005; Wang and Sousa, 2009; Everitt et al., 2011; Sunkur et al., 2024; Fang et al., 2025). Collectively, these results demonstrate that wavelength-based discrimination in complex wetland environments is strongly species-dependent, and that reliable classification requires the integration of multiple spectral regions rather than reliance on individual wavebands.

3.8 Hyperspectral vegetation indices

Hyperspectral vegetation indices derived from field spectroradiometric measurements provide quantitative assessment of plant physiological status, canopy structure, pigment composition, and water content across species in Lake Manzala (Tables 5–7). These indices integrate spectral responses from visible, NIR, and SWIR regions, allowing direct linkage between spectral behavior and plant functional traits (Fawcett et al., 2025). NDVI ranged from 0.366 (*Tamarix nilotica*) to 0.884 (*Cyperus alopecuroides*). High values (>0.80) in *Cyperus alopecuroides* (0.884), *Echinochloa stagnina* (0.879), *Potamogeton pectinatus*

TABLE 4 Optimal wavelengths for discriminating the studied plant species based on hyperspectral reflectance analysis.

Plant name	Optimal wavelength	Spectral range
<i>Alternanthera sessilis</i> (L.) DC.	362- 408- 415- 443- 453- 454- 467- 483- 500- 529- 545- 546- 592- 637- 638- 640- 649- 654- 679- 684- 695- 696- 700- 702- 704- 717- 730- 732- 750- 759- 763- 776- 778- 805- 822- 833- 852- 868- 870- 908- 914- 916- 927- 930- 932- 943- 944- 959- 960- 962- 980- 986- 999- 1001- 1006- 1008- 1017- 1021- 1047- 1052- 1054- 1098- 1100- 1155- 1156- 1158- 1161- 1162- 1164- 1177- 1182- 1183-1185- 1188- 1190- 1192- 1200- 1204- 1205- 1207- 1226- 1229- 1231- 1233- 1234- 1236- 1290- 1291- 1294- 1314- 1325- 1326- 1328- 1337-1340- 1342- 1383- 1386- 1388- 1389- 1391- 1398- 1406- 1410- 1417- 1418- 1443- 1452- 1458- 1466- 1475- 1483- 1498- 1504- 1509- 1510- 1512- 1591- 1604- 1610- 1616- 1626- 1628- 1635- 1636- 1648- 1650- 1713- 1727- 1740- 1742- 1748- 1751- 1759.	Blue–Green–Red–NIR
<i>Arthrocnemum macrostachyum</i> (Moric.) K. Koch	871-912	NIR
<i>Atriplex halimus</i> L.	375-416-457-498-539-580-621-662-703-744-785-826-867-908-949-990-1031-1072-1113-1154-1195-1236-1277-1318-1359-1400-1441-1482-1523-1564-1605-1646-1687-1728-1769-1810-1851-1892-1933-1974-2015-2056-2097-2138-2179-2220-2261-2302-2343-2384-2425-2466	Blue–Green–Red–NIR–SWIRI–SWIRII
<i>Bassia indica</i> (Wight) A. J.Scott	362- 408- 415- 454- 483- 529- 598-885-1049- 1678- 1702- 1751	Red–NIR
<i>Ceratophyllum demersum</i> L.	362-408-41-443-454-500-529-654-700-717- 778- 805- 852- 962- 986- 1001- 1047- 1052 – 1188- 1280- 1291- 1748- 1751- 1759	Blue–Green–Red–NIR
<i>Chenopodium album</i> L.	362-408- 415- 443- 483- 500- 546- 638- 654- 679- 684- 695- 700- 704- 763- 868- 908-930- 944- 960- 980- 1100- 1125- 1144- 1236- 1371- 1382- 1681- 1759	Blue–Green–Red–NIR
<i>Chenopodium murale</i> L.	462-638- 1093- 1164- 1751	Red–NIR–SWIRI
<i>Cynanchum acutum</i> L.	973-1014-1055-1096-1178-1219-1342-1506	11
<i>Cynodon dactylon</i> (L.) Pers.	483-852	Green–NIR
<i>Cyperus articulatus</i> L.	—	
<i>Cyperus alopecuroides</i> Rottb.	1019- 1300	NIR
<i>Echinochloa stagnina</i> (Retz.) P. Beauv.	752	NIR
<i>Eichhornia crassipes</i> (C. Mart.) Solms	631-672-1041-1410-1615-1820-1861-1984-2025-2107-2148-2189-2271-2312-2353-2394-2435-2476	Red–NIR–SWIRI–SWIRII
<i>Halocnemum strobilaceum</i> (Pallas) M. Bieb.	903-1067-1190-1231	NIR–SWIRI
<i>Heliotropium curassavicum</i> L.	1346-1387-1428-1469-1510-1551	SWIRI
<i>Ipomoea carnea</i> Jacq	—	
<i>Juncus acutus</i> L.	578-619-660-701-742-783-824-865-906-947-988-1029	Red–NIR
<i>Juncus rigidus</i> Desf.	761-802-843-884-1909-2032-2114-2155-2196	NIR–SWIRII
<i>Limbarda crithmoides</i> (L.) Dumort.	911	NIR
<i>Ludwigia stolonifera</i> (Guill. & Perr.) P.	1750	SWIRI
<i>Malva parviflora</i> L.	437-847	Blue–NIR
<i>Mesembryanthemum crystallinum</i> L.	569-651-692-774-815-856-897-938-979-1061-1102-2373	Red–NIR–SWIRI–SWIRII
<i>Mesembryanthemum nodiflorum</i> L.	365-406-488-2456-2497	Blue–Green–SWIRII
<i>Persicaria lapathifolia</i> (L.) Gray	1900-1950	SWIRII
<i>Persicaria salicifolia</i> (Willd) Assenov	1292-1333-1374-1415-1456-1497-1538	SWIRI
<i>Phragmites australis</i> (Cav.)Trin.ex	1095-1136-1177-1218-1259-1341-1382	NIR–SWIRI
<i>Phyla nodiflora</i> (L.) Greene	717-1040	
<i>Pluchea dioscoridis</i> (L.) DC.	1091-1132	NIR–SWIRI
<i>Potamogeton pectinatus</i> L.	—	
<i>Ranunculus sceleratus</i> L.	—	
<i>Rumex dentatus</i> L.	1156-1279-1361-1402-1443-1566	SWIRI

(Continued)

TABLE 4 (Continued)

Plant name	Optimal wavelength	Spectral range
<i>Saccharum spontaneum</i> L. Mant. Alt	—	-
<i>Senecio glaucus</i> L.	—	
<i>Sonchus oleraceus</i> L.	1122-1163-1204-1245-1286-1327-1450-1491	SWIRI
<i>Spergularia marina</i> (L.) Griseb.	423-464-587-628-669-710-751-792-833-874-997-1038-1120-1161-1202-2022-2063-2104-2145-2186-2227-2268-2350-2391-2432-2473	Blue-Green-Red-NIR-SWIRI-SWIRII
<i>Suaeda maritima</i> (L.) Dumort	1053-1217-1258	NIR-SWIRI
<i>Suaeda pruinosa</i> Lange	576-617-822	Red-NIR
<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	1086-1209-1250	NIR-SWIRI
<i>Symphyotrichum squamatum</i> (Spren.) Nesom	920-1002-1084-1207-2150	NIR-SWIRI-SWIRII
<i>Tamarix nilotica</i> (Ehrenb.) Bunge	955-996	NIR
<i>Typha domingensis</i> (Pers.) Poir.ex Steud.	1088-1129-1211	NIR-SWIRI
<i>Zygophyllum aegyptium</i> Hosny	600-641-764-928-969-1051-1092-1133-1174	Red-NIR-SWIRI
<i>Zygophyllum album</i> L.	—	—
<i>Zygophyllum coccineum</i> L.	592-704	Red-NIR

(0.840), and *Limbarda crithmoides* (0.813) indicate dense biomass and active photosynthesis, whereas low values in *Tamarix nilotica* (0.366), *Suaeda pruinosa* (0.394), and *Zygophyllum album* (0.429) reflect reduced canopy density and stress-adapted morphology. This pattern confirms that NDVI is primarily controlled by chlorophyll absorption in the red region and NIR scattering, making it a robust proxy for biomass and photosynthetic activity.

SR ranged from 2.153 (*Tamarix nilotica*) to 16.305 (*Cyperus alopecuroides*), with high values in *Cyperus alopecuroides* (16.305), *Echinochloa stagnina* (15.571), and *Potamogeton pectinatus* (11.501), reflecting strong NIR reflectance associated with dense and vertically structured canopies. This indicates that SR enhances sensitivity to canopy structure and leaf area compared to NDVI (Khderiy et al., 2026). PSRI ranged from -0.040 (*Heliotropium curassavicum*) to 0.139 (*Spergularia marina*), with most species showing low values (-0.02 to 0.05), indicating limited senescence. Higher values in *Spergularia marina* (0.139), *Suaeda pruinosa* (0.103), and *Malva parviflora* (0.098) reflect increased pigment degradation. PSRI is strongly linked to the carotenoid-to-chlorophyll ratio and is therefore sensitive to senescence and stress conditions (Khderiy et al., 2026). MSI ranged from 0.236 (*Suaeda vera*) to 0.841 (*Tamarix nilotica*). High values in *Tamarix nilotica* (0.841), *Malva parviflora* (0.799), and *Juncus rigidus* (0.784) indicate reduced water content, whereas low values in *Mesembryanthemum crystallinum* (0.264) and *Cyperus alopecuroides* (0.344) reflect higher water availability. MSI is governed by SWIR absorption features related to leaf water content, making it an effective indicator of plant water status (Hunt Jr and Rock, 1989). CRI1 ranged from 0.877 (*Atriplex halimus*) to 12.712 (*Echinochloa stagnina*), while CRI2 ranged from 1.072 (*Phragmites australis*) to 18.777 (*Potamogeton pectinatus*), indicating strong variability in carotenoid content. High CRI values reflect enhanced photoprotective responses, particularly under high irradiance and environmental stress (Gitelson et al., 2002).

ARI1 ranged from -2.625 (*Cyperus alopecuroides*) to 7.243 (*Potamogeton pectinatus*), and ARI2 from -1.974 to 2.701.

High values in *Ludwigia stolonifera* (3.802), *Ceratophyllum demersum* (3.915), and *Spergularia marina* (3.067) indicate anthocyanin accumulation associated with stress adaptation. Anthocyanins play a protective role against oxidative stress and excess radiation (Khderiy et al., 2025a; Gitelson et al., 2001). Red-edge indices showed strong variability: RENDVI ranged from 0.208 (*Malva parviflora*) to 0.772 (*Phragmites australis*), MRENDVI from -0.070 (*Atriplex halimus*) to 0.605 (*Cyperus alopecuroides*), and MRESR from 1.904 (*Malva parviflora*) to 8.817 (*Cyperus alopecuroides*). REP ranged from 679.8 nm (*Tamarix nilotica*) to 696.8 nm (*Cyperus alopecuroides* and *Persicaria lapathifolia*). The shift of REP toward longer wavelengths is directly associated with increased chlorophyll concentration and canopy density, making red-edge indices among the most sensitive indicators of vegetation vigor (Zarco-Tejada et al., 2002).

Overall, vegetation indices consistently differentiate species based on biomass, pigment composition, and water content, demonstrating that integrating multiple indices provides a robust framework for assessing plant functional variability and stress responses in heterogeneous wetland environments.

Despite the strong discriminatory performance of hyperspectral data, several limitations should be considered. Species discrimination was reduced in cases where taxa exhibited similar pigment composition and structural characteristics, particularly within submerged and morphologically similar species groups. In addition, environmental factors such as water turbidity, mixed backgrounds, and seasonal variability may influence spectral responses under field conditions. Therefore, while the results are robust within the Lake Manzala system, caution is required when transferring these findings to other wetland environments with different ecological and hydrological settings. While advanced machine learning and high-dimensional hyperspectral techniques can further enhance classification performance, the present study focuses on interpretable statistical and index-based approaches

TABLE 5 Vegetation index values (MSI, NDVI, PSRI, SR, and EVI).

No.	Plant species	MSI	NDVI	PSRI	SR	EVI
1	<i>Alternanthera sessilis</i> (L.) DC.	0.553	0.763	−0.003	7.427	2.406
2	<i>Arthrocnemum macrostachyum</i> (Moric.) K. Koch	0.439	0.543	0.002	3.374	1.370
3	<i>Atriplex halimus</i> L.	0.455	0.499	0.012	2.994	2.300
4	<i>Bassia indica</i> (Wight) A. J.Scott	0.548	0.553	−0.016	3.472	1.305
5	<i>Ceratophyllum demersum</i> L.	0.608	0.610	0.029	4.134	1.059
6	<i>Chenopodium album</i> L.	0.515	0.746	−0.008	6.880	2.032
7	<i>Chenopodium murale</i> L.	0.359	0.766	−0.017	7.538	2.125
8	<i>Cynanchum acutum</i> L.	0.454	0.584	−0.008	3.805	2.065
9	<i>Cynodon dactylon</i> (L.) Pers.	0.693	0.544	0.008	3.389	1.804
10	<i>Cyperus articulatus</i> L.	0.555	0.649	−0.012	4.691	1.921
11	<i>Cyperus alopecuroides</i> Rottb.	0.344	0.884	−0.005	16.305	3.425
12	<i>Echinochloa stagnina</i> (Retz.) P. Beauv.	0.404	0.879	0.003	15.571	2.772
13	<i>Eichhornia crassipes</i> (C. Mart.) Solms	0.672	0.672	−0.011	5.103	1.718
14	<i>Halocnemum strobilaceum</i> (Pallas) M. Bieb.	0.333	0.610	−0.016	4.125	1.549
15	<i>Heliotropium curassavicum</i> L.	0.460	0.597	−0.040	3.960	1.229
16	<i>Ipomoea carnea</i> Jacq	0.554	0.768	−0.009	7.630	2.317
17	<i>Juncus acutus</i> L.	0.476	0.739	0.008	6.649	2.121
18	<i>Juncus rigidus</i> Desf.	0.784	0.545	0.007	3.392	1.054
19	<i>Limbarda crithmoides</i> (L.) Dumort.	0.552	0.813	0.002	9.698	2.812
20	<i>Ludwigia stolonifera</i> (Guill. & Perr.) P.	0.380	0.655	0.050	4.790	2.836
21	<i>Malva parviflora</i> L.	0.799	0.438	0.098	2.560	1.922
22	<i>Mesembryanthemum crystallinum</i> L.	0.264	0.601	0.003	4.014	1.474
23	<i>Mesembryanthemum nodiflorum</i> L.	0.332	0.559	0.024	3.534	1.476
24	<i>Persicaria lapathifolia</i> (L.) Gray	0.675	0.773	−0.011	7.800	2.367
25	<i>Persicaria salicifolia</i> (Willd) Assenov	0.661	0.712	−0.013	5.947	2.389
26	<i>Phragmites australis</i> (Cav.)Trin.ex	0.772	0.623	−0.036	4.312	2.256
27	<i>Phyla nodiflora</i> (L.) Greene	0.369	0.786	−0.009	8.353	2.509
28	<i>Pluchea dioscoridis</i> (L.) DC.	0.691	0.667	−0.017	5.011	2.278
29	<i>Potamogeton pectinatus</i> L.	0.415	0.840	0.010	11.501	1.760
30	<i>Ranunculus sceleratus</i> L.	0.583	0.771	−0.009	7.728	2.337
31	<i>Rumex dentatus</i> L.	0.609	0.724	0.006	6.245	2.091
32	<i>Saccharum spontaneum</i> L. Mant. Alt	0.639	0.751	−0.031	7.034	2.342
33	<i>Senecio glaucus</i> L.	0.388	0.636	0.038	4.488	2.128
34	<i>Sonchus oleraceus</i> L.	0.539	0.608	0.027	4.107	1.749
35	<i>Spergularia marina</i> (L.) Griseb.	0.649	0.446	0.139	2.611	2.331
36	<i>Suaeda maritima</i> (L.) Dumort	0.342	0.680	−0.017	5.245	1.928
37	<i>Suaeda pruinosa</i> Lange	0.572	0.394	0.103	2.301	2.669
38	<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	0.236	0.713	−0.027	5.980	2.067
39	<i>Symphyotrichum squamatum</i> (Spreng.) Nesom	0.512	0.696	−0.007	5.572	1.624
40	<i>Tamarix nilotica</i> (Ehrenb.) Bunge	0.841	0.366	0.056	2.153	1.126
41	<i>Typha domingensis</i> (Pers.) Poir.ex Steud.	0.417	0.692	−0.015	5.502	2.774
42	<i>Zygophyllum aegyptium</i> Hosny	0.373	0.633	−0.010	4.444	1.872
43	<i>Zygophyllum album</i> L.	0.558	0.429	0.029	2.503	1.446
44	<i>Zygophyllum coccineum</i> L.	0.490	0.462	0.053	2.715	1.655

TABLE 6 Pigment-related vegetation indices (CRI1, CRI2, ARI1, ARI2) and chlorophyll (a + b) content of the studied plant species in Lake Manzala.

No.	Plant species	ARI1	ARI2	CRI1	CRI2	Chl. a & b
1	<i>Alternanthera sessilis</i> (L.) DC.	0.635	0.356	4.678	5.314	0.421
2	<i>Arthrocnemum macrostachyum</i> (Moric.) K. Koch	0.077	0.027	2.153	2.231	0.332
3	<i>Atriplex halimus</i> L.	0.437	0.269	0.877	1.314	0.282
4	<i>Bassia indica</i> (Wight) A. J.Scott	−0.544	−0.229	1.846	1.302	0.359
5	<i>Ceratophyllum demersum</i> L.	3.915	0.965	4.072	7.987	0.283
6	<i>Chenopodium album</i> L.	−0.312	−0.163	3.545	3.232	0.533
7	<i>Chenopodium murale</i> L.	−0.665	−0.371	3.660	2.995	0.546
8	<i>Cynanchum acutum</i> L.	0.099	0.058	1.605	1.704	0.331
9	<i>Cynodon dactylon</i> (L.) Pers.	0.173	0.079	1.816	1.988	0.310
10	<i>Cyperus articulatus</i> L.	−0.397	−0.217	1.665	1.269	0.475
11	<i>Cyperus alopecuroides</i> Rottb.	−2.625	−1.974	8.913	6.288	0.702
12	<i>Echinochloa stagnina</i> (Retz.) P. Beauv.	−0.749	−0.442	12.712	11.963	0.611
13	<i>Eichhornia crassipes</i> (C. Mart.) Solms	−0.647	−0.303	2.244	1.596	0.503
14	<i>Halocnemum strobilaceum</i> (Pallas) M. Bieb.	−0.131	−0.060	2.278	2.146	0.354
15	<i>Heliotropium curassavicum</i> L.	−0.223	−0.107	1.724	1.501	0.338
16	<i>Ipomoea carnea</i> Jacq	0.415	0.227	5.546	5.960	0.333
17	<i>Juncus acutus</i> L.	0.150	0.070	4.984	5.134	0.485
18	<i>Juncus rigidus</i> Desf.	0.848	0.239	2.637	3.485	0.286
19	<i>Limbarda crithmoides</i> (L.) Dumort.	0.138	0.087	6.089	6.227	0.545
20	<i>Ludwigia stolonifera</i> (Guill. & Perr.) P.	3.802	2.256	2.071	5.873	0.287
21	<i>Malva parviflora</i> L.	1.521	0.583	1.768	3.289	0.208
22	<i>Mesembryanthemum crystallinum</i> L.	0.364	0.128	3.427	3.791	0.289
23	<i>Mesembryanthemum nodiflorum</i> L.	1.318	0.465	3.187	4.505	0.202
24	<i>Persicaria lapathifolia</i> (L.) Gray	−0.395	−0.228	4.442	4.047	0.494
25	<i>Persicaria salicifolia</i> (Willd) Assenov	−0.320	−0.191	3.164	2.844	0.407
26	<i>Phragmites australis</i> (Cav.)Trin.ex	−0.115	−0.076	1.187	1.072	0.363
27	<i>Phyla nodiflora</i> (L.) Greene	−0.050	−0.029	5.312	5.261	0.436
28	<i>Pluchea dioscoridis</i> (L.) DC.	−0.307	−0.174	2.686	2.379	0.340
29	<i>Potamogeton pectinatus</i> L.	7.243	2.701	11.534	18.777	0.451
30	<i>Ranunculus sceleratus</i> L.	−0.400	−0.227	5.409	5.009	0.424
31	<i>Rumex dentatus</i> L.	0.696	0.346	3.831	4.527	0.468
32	<i>Saccharum spontaneum</i> L. Mant. Alt	−1.167	−0.682	3.553	2.386	0.448
33	<i>Senecio glaucus</i> L.	2.390	1.198	2.083	4.473	0.389
34	<i>Sonchus oleraceus</i> L.	1.735	0.722	2.055	3.790	0.362
35	<i>Spergularia marina</i> (L.) Griseb.	3.067	1.157	2.093	5.160	0.143
36	<i>Suaeda maritima</i> (L.) Dumort	−0.245	−0.130	2.250	2.005	0.458
37	<i>Suaeda pruinosa</i> Lange	0.947	0.474	1.343	2.290	0.152
38	<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	−0.323	−0.191	2.531	2.207	0.454
39	<i>Symphyotrichum squamatum</i> (Spreng.) Nesom	−0.052	−0.022	3.100	3.048	0.487
40	<i>Tamarix nilotica</i> (Ehrenb.) Bunge	0.976	0.299	1.160	2.136	0.185
41	<i>Typha domingensis</i> (Pers.) Poir.ex Steud.	0.077	0.054	2.219	2.296	0.385
42	<i>Zygophyllum aegyptium</i> Hosny	0.044	0.020	2.780	2.823	0.315
43	<i>Zygophyllum album</i> L.	0.485	0.183	1.677	2.162	0.182
44	<i>Zygophyllum coccineum</i> L.	0.612	0.236	2.857	3.469	0.147

TABLE 7 Pigment indices and chlorophyll content of the studied plant species in Lake Manzala.

No.	Plant species	RENDVI	MRENDVI	MRESR	REPI
1	<i>Alternanthera sessilis</i> (L.) DC.	0.421	0.280	3.157	688.941
2	<i>Arthrocnemum macrostachyum</i> (Moric.) K. Koch	0.332	0.164	2.998	690.048
3	<i>Atriplex halimus</i> L.	0.282	−0.070	2.665	687.164
4	<i>Bassia indica</i> (Wight) A. J.Scott	0.359	0.113	4.136	691.874
5	<i>Ceratophyllum demersum</i> L.	0.283	0.186	2.255	681.743
6	<i>Chenopodium album</i> L.	0.533	0.373	5.884	695.101
7	<i>Chenopodium murale</i> L.	0.546	0.378	6.132	694.384
8	<i>Cynanchum acutum</i> L.	0.331	0.039	3.023	688.250
9	<i>Cynodon dactylon</i> (L.) Pers.	0.310	0.081	2.786	687.691
10	<i>Cyperus articulatus</i> L.	0.475	0.233	6.364	695.063
11	<i>Cyperus alopecuroides</i> Rottb.	0.702	0.605	8.817	696.807
12	<i>Echinochloa stagnina</i> (Retz.) P. Beauv.	0.611	0.541	5.209	694.783
13	<i>Eichhornia crassipes</i> (C. Mart.) Solms	0.503	0.315	6.976	694.900
14	<i>Halocnemum strobilaceum</i> (Pallas) M. Bieb.	0.354	0.130	3.350	689.435
15	<i>Heliotropium curassavicum</i> L.	0.338	0.049	3.766	688.094
16	<i>Ipomoea carnea</i> Jacq	0.333	0.195	2.339	683.958
17	<i>Juncus acutus</i> L.	0.485	0.370	4.011	692.972
18	<i>Juncus rigidus</i> Desf.	0.286	0.139	2.627	686.084
19	<i>Limbarda crithmoides</i> (L.) Dumort.	0.545	0.423	4.624	693.917
20	<i>Ludwigia stolonifera</i> (Guill. & Perr.) P.	0.287	0.111	2.114	679.768
21	<i>Malva parviflora</i> L.	0.208	0.014	1.904	681.161
22	<i>Mesembryanthemum crystallinum</i> L.	0.289	0.145	2.315	682.933
23	<i>Mesembryanthemum nodiflorum</i> L.	0.34	0.18	2.85	684.5
24	<i>Persicaria lapathifolia</i> (L.) Gray	0.67	0.55	6.90	696.8
25	<i>Persicaria salicifolia</i> (Willd) Assenov	0.64	0.51	6.20	695.1
26	<i>Phragmites australis</i> (Cav.) Trin. ex Steud.	0.59	0.42	4.85	693.4
27	<i>Phyla nodiflora</i> (L.) Greene	0.71	0.60	7.95	697.2
28	<i>Pluchea dioscoridis</i> (L.) DC.	0.61	0.46	5.40	694.6
29	<i>Potamogeton pectinatus</i> L.	0.38	0.12	2.10	681.9
30	<i>Ranunculus sceleratus</i> L.	0.52	0.33	4.10	690.2
31	<i>Rumex dentatus</i> L.	0.63	0.48	5.95	694.1
32	<i>Saccharum spontaneum</i> L.	0.68	0.56	7.30	696.5
33	<i>Senecio glaucus</i> L.	0.46	0.28	3.65	688.7
34	<i>Sonchus oleraceus</i> L.	0.49	0.31	3.90	689.9
35	<i>Spergularia marina</i> (L.) Griseb.	0.41	0.20	2.95	686.1
36	<i>Suaeda maritima</i> (L.) Dumort.	0.57	0.39	4.75	692.3
37	<i>Suaeda pruinosa</i> Lange	0.44	0.26	3.40	687.8
38	<i>Suaeda vera</i> Forssk. ex J.F. Gmel.	0.60	0.44	5.10	693.9
39	<i>Symphyotrichum squamatum</i> (Spreng.) Nesom	0.54	0.36	4.55	691.5
40	<i>Tamarix nilotica</i> (Ehrenb.) Bunge	0.32	0.10	1.95	679.8
41	<i>Typha domingensis</i> (Pers.) Poir. ex Steud.	0.66	0.53	6.70	695.9
42	<i>Zygophyllum aegyptium</i> Hosny	0.48	0.30	3.80	689.3
43	<i>Zygophyllum album</i> L.	0.35	0.14	2.30	682.6
44	<i>Zygophyllum coccineum</i> L.	0.51	0.34	4.20	690.8

to ensure ecological relevance and comparability across wetland systems.

5 Conclusion

The present study demonstrates that Lake Manzala, despite intense anthropogenic pressure, still supports a structurally diverse and functionally heterogeneous wetland vegetation assemblage. The main contribution of this work lies in integrating field-based hyperspectral measurements with detailed floristic and ecological analysis to achieve reliable species-level discrimination and functional characterization in a complex wetland system. The results highlight the strong discriminatory capability of near-infrared and red-edge regions, while shortwave infrared wavelengths provide complementary insights into plant water status and biochemical composition. Despite these findings, species discrimination may be limited in cases of spectral overlap among morphologically and physiologically similar taxa, particularly within submerged and structurally comparable vegetation groups. In addition, environmental factors such as water turbidity and mixed spectral backgrounds may influence hyperspectral responses under field conditions. Future research should explore advanced hyperspectral analytical approaches, including machine learning techniques and multi-temporal analysis, to enhance classification accuracy and extend the applicability of this framework to broader wetland systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

GK: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Software, Validation, Visualization, Resources, Writing – original draft, Writing – review & editing, Supervision. MS: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. NR: Validation, Visualization, Writing – review & editing. HE-B: Project administration, Visualization, Writing – review & editing. YE-A: Conceptualization, Methodology, Investigation, Formal analysis, Validation, Visualization, Writing – original draft, Writing - review & editing, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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