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Occurrence and Ecological Impacts of Invasive Aquatic Weeds in Lahore, Pakistan

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Abstract

The present study was conducted to establish baseline information on the diversity, distribution, and ecological implications of aquatic weeds in Lahore and surrounding habitats. Field surveys were carried out between 2021 and 2023 at randomly selected sites including Kasur Road, Raiwind Road, Thokar Niaz Baig, Gajjumatta, and Shahdara, where drains and ponds were sampled and aquatic flora identified using standard floras and expert consultation. Water quality parameters indicated generally eutrophic conditions, with dissolved oxygen ranging from 4.5 to 9.2 mg/L (mean 6.8 ± 1.1 mg/L), electrical conductivity from 300 to 750 µS/cm (mean 520 ± 95 µS/cm), and turbidity between 7 and 36 NTU (mean 21.3 ± 6.7 NTU). A total of six dominant taxa were documented, with Eichhornia crassipes showing the highest frequency (86 ± 4.1%), density (63 ± 5.3 ind./m²), and cover (65 ± 3.8%), followed by Lemna minor (74 ± 6.2% frequency; 88 ± 7.4 ind./m² density; 53 ± 2.9% cover). Emergent species such as Typha angustifolia and Phragmites australis exhibited moderate distribution (57–60% frequency), while Pistia stratiotes (33 ± 3.6%) and Microcystis aeruginosa (25 ± 4.2%) were less abundant. The predominance of free-floating weeds, particularly E. crassipes and L. minor, highlights their adaptability to nutrient-rich and stagnant waters and underscores their role in altering aquatic ecology by reducing light penetration and oxygen availability. This first systematic report from Lahore emphasizes the urgent need for continuous monitoring and integrated management strategies, while also pointing to the potential utilization of invasive weed biomass in sustainable practices such as composting and biochar production.

1. Introduction

Aquatic weeds, often regarded as exotic and undesirable plants, pose significant ecological and socioeconomic challenges in freshwater ecosystems. These plants are notorious for their rapid growth, wide distribution, and diverse modes of propagation, which allow them to proliferate in both natural and artificial water bodies. Their invasion results in obstruction of water channels, degradation of aesthetics, and the creation of favorable habitats for mosquitoes and flies, which are vectors of many diseases (Kawade et al., 2023). The ecological consequences are equally severe: aquatic weeds reduce dissolved oxygen concentrations, promote anoxic conditions conducive to methanogenesis, and contribute to greenhouse gas emissions. Dense mats of weeds block sunlight penetration, suppress aquatic biodiversity, and reduce the recreational and aesthetic value of water resources (Hassan and Nawchoo, 2020).

Their ecological dominance stems from high adaptability, prolific reproduction, and tolerance to contaminated and stagnant waters. Among the major drivers of aquatic weed proliferation, eutrophication stands out as a leading cause. Nutrient enrichment, particularly with phosphorus and nitrogen, often arises from agricultural runoff, untreated sewage, and industrial effluents. While natural eutrophication occurs gradually, anthropogenic activities have dramatically accelerated nutrient loading in water bodies, thereby creating ideal conditions for invasive aquatic weeds to thrive (Awasthi et al., 2019).

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These weeds exhibit remarkable diversity in growth forms, ranging from planktonic algae responsible for algal blooms to free-floating species such as *Eichhornia crassipes* (Mart.), *Pistia stratiotes* (L.), and *Lemna gibba* (L.), and emergent taxa including *Typha latifolia* (L.) and *Phragmites australis* (L.). Alongside this notorious invader, numerous other aquatic plants, including *Alternanthera sessilis* (L.), *Azolla pinnata* (R.Br.), *Bacopa monnieri* (L.), *Ceratophyllum demersum* (L.), *Hydrilla verticillata* (L.f.) Royle, *Marsilea quadrifolia* (L.), *Nelumbo nucifera* Gaertn., *Nymphoides cristata* (Roxb.), *Nymphoides indica* (L.), *Potamogeton nodosus* (L.), and *Polygonum barbatum* (L.), *Typha angustifolia* (L.), have been documented as part of the invasive or dominant aquatic flora in Pakistan's water bodies (Bakhtiar Gul et al., 2017; Mustafa & Hayder, 2021; Rizvi et al., 2024). Lahore hosts a network of freshwater canals, drains, ponds, and slow-moving waters including the Ravi River and Hudiara drain, in addition to water bodies along Bedian, Kasur, and Raiwind roads. These habitats provide favorable environments for invasive aquatic weeds, among which *Eichhornia crassipes*, *Pistia stratiotes*, *Lemna minor*, *Typha latifolia*, and *Phragmites australis* are especially prevalent.

Despite their widespread distribution and well-documented ecological and economic impacts globally, systematic and site-specific baseline data on aquatic weeds in Lahore remain scarce. While past research in Pakistan has recorded aquatic weed species at broader regional or provincial scales, there is a notable lack of focused studies that assess their diversity, ecological impacts, and potential management within this urban center. Without such localized data, developing effective monitoring frameworks and management strategies remains challenging. Establishing a baseline inventory of invasive aquatic weeds in Lahore is therefore critical not only for ecological understanding but also for formulating integrated control measures and exploring biomass utilization pathways.

The current study aims to bridge this knowledge gap by (i) documenting the diversity and distribution of abundant aquatic weeds across selected sites in Lahore and its surroundings, and (ii) providing baseline ecological data to guide future monitoring and management efforts. This represents the first comprehensive baseline survey of invasive aquatic weeds reported from Lahore, Punjab, Pakistan.

Beyond simply cataloguing species, the study underscores the ecological impacts of these weeds and highlights the urgent need for innovative management strategies. In particular, the enormous biomass of aquatic weeds presents opportunities for sustainable utilization. Their conversion into compost or biochar could mitigate environmental hazards while creating value-added products that improve soil fertility and contribute to industrial applications. Moreover, emerging biotechnological tools, including genetic approaches such as CRISPR, offer promising avenues for controlling the invasive potential of these species. By integrating ecological insights with biomass management and advanced biotechnological strategies, this research lays the foundation for a novel, sustainable, and holistic approach to managing aquatic weeds in urban ecosystems with climatic conditions similar to those of Lahore.

In summary, aquatic weeds represent a serious ecological challenge in Lahore, with consequences for biodiversity, ecosystem function, and human well-being. However, through systematic documentation and the exploration of innovative management strategies, including ecological monitoring, biomass bioconversion, and genetic interventions, there is potential to transform this challenge into an opportunity. This study provides the much-needed baseline evidence to support such efforts, positioning it as a critical contribution to aquatic weed ecology and management in the urban landscapes of Pakistan.

2. Materials and Methods

2.1 Study Area

Between 2021 and 2023 (Punjab, Pakistan) surveys were carried out in aquatic ecosystems in Lahore District. The Ravi River floodplain, Thokar Niaz Baig drainage canals, Bedian Road ponds, and Kasur Road marshes, Raiwind Road wetlands and peri-urban industrial drains were used as study sites. These areas are stagnant, low flowing and disturbed water bodies, which are exposed to enrichment of nutrients through urban and agricultural discharges.

2.2 Sampling Design

Aquatic weed surveys were systematic random quadrat. On every site three 1 m 2 quadrats were positioned on 50 m transects that were parallel to the shoreline spaced at 10 m. In ponds, quadrats were placed randomly at the three points at the periphery with the same distance. The aquatic weeds in each quadrat were counted, abundance measured as frequency (%), density (individuals m^{-2}) and cover (%) (Braun-Blanquet scale). At every quadrat GPS-coordinates were measured (latitude/longitude, WGS84) with a Garmin GPSMAP 64s. The in-situ parameters measured in the Hanna multiparameter probe (HI9829) included water quality parameters (pH), electrical conductivity (EC), dissolved oxygen (DO), temperature, total alkalinity (TA), and turbidity.

2.3 Plant Collection and Identification

Aquatic representatives of each were gathered according to the routine herbarium procedures. Specimens were preserved, dried and mounted on herbarium sheets together with complete collection data (GPS, habitat, abundance category, collector name/date). Voucher specimens were deposited in Department of Botany, University of Punjab, Lahore. Recognition of the species was done using regional floras (Flora of Pakistan), dichotomous taxonomic keys and cross-verified with plant net. Nomenclature the Plant List and APG IV (2016).

2.4 GIS Mapping

In ArcGIS Pro 3.0 (ESRI, USA), spatial distribution maps of species have been created. The importation of coordinate data was done in WGS84 projection (EPSG:4326). Occurrence point of species were visualized, to indicate hotspots of abundance.

2.5 Statistical Analyses

Radar charts were generated to illustrate the comparative values of species cover (%), species density (ind./m²), and frequency (%). In addition, polar heatmaps were produced using OriginPro 2024 to depict the relationships between dominant aquatic weeds (*Eichhornia*, *Typha*, *Lemna*, *Microcystis*, *Pistia*, and *Phragmites*) and the measured water quality parameters (pH, EC, DO, temperature, turbidity). This approach enabled visualization of species–environment interactions and provided insights into ecological drivers of species distribution and abundance.

3. Results

3.1 Estimation of eutrophic water quality parameters

The parameters of water quality monitored showed moderate fluctuation in sampling sites (Table 1). DO was found to be between 4.5 and 9.2 mg/L with an average of 6.8 + 1.1 mg/L. These levels are within the limit of supporting most aquatic organisms, meaning that there are usually good oxygen levels, though the lower values indicate that there are times when there is stress on oxygen in some locations. EC ranged 300 to 750 µS/cm with a median of 520 ± 95 µS/cm indicating a moderate ionic strength. These values are common to freshwater bodies affected by domestic runoff or agricultural inputs but are still lower than freshwater classification limits in most international standards. The pH of the water (6.384; mean 7.4 +0.5) showed that the water was either mainly neutral or slightly alkaline, which is in keeping with the environment that supports the growth and existence of various aquatic plants and animals. Some small alkalinity can be explained by carbonate buffering or enrichment of nutrients by the catchments. The temperature was kept at 23-33 ºC with a mean of 27.6 + 2.8 ºC, which is within the ambient climatic conditions of the time of the experiment and gives an appropriate thermal regime of biological activity and nutrient cycling. Turbidity ranged between 7 and 36 NTU (mean 21.3 + 6.7 NTU), with intermittent heavy suspended matter loads, probably precipitated by rain or surface runoff, or phytoplankton yearns. Although moderate turbidity is conducive to nutrient dynamics, high turbidity at certain sites can inhibit light penetration and hence photosynthetic activity. In general, the physico-chemical properties suggest that the examined water bodies were mostly within the acceptable range of ecological operations, but with local variability in the levels of DO and turbidity, there are signs of episodic stress on the aquatic communities.

3.2 Species Composition and Abundance

The survey showed significant differentiation in frequency, density, and cover of the aquatic macrophytes and algal species among the study sites (Table 2 and Figure 1). The highest frequency (86 ± 4.1%), in comparison to the other recorded species, was observed in Eichhornia crassipes (EC, water hyacinth) with a high density (63 ± 5.3 ind./m^2) and cover (65 ± 3.8%). Its summer-autumn cycle (June - October) is an indicator of its invasive growth and expansion and a high vegetative propagation rate, which is in line with it being among the most aggressive aquatic weeds in the world. The second most abundant species was *Lemna minor* (LM, duckweed) with a frequency of 74/62, highest density (88/74 ind./m2) and intermediate cover (53/29). It has an advantage when it comes to its capability to develop thick surface mats in late spring and summer, enabling it to control eutrophic water bodies. *Phragmites australis* (PA, common reed) and *Typha angustifolia* (TA, cattails) were emergent macrophytes with frequency of 57 ± 4.3 and 60 ± 3.9, respectively. Densities (30 ± 3.1 and 24 ± 2.2 ind./m^2) and cover (45 ± 2.4 and 40 ± 3.1) were lower in both species. Such species normally inhabit littoral areas and shallow margins, which serve as an important source of habitat heterogeneity and shoreline stability, but they grow more slowly than free-floating weeds. *Pistia stratiotes* (PS, water lettuce) were less common in frequency (33 ± 3.6%), density (16 ± 1.9 ind./m^2) and extent of cover (22 ± 2.2%). This is an indication of a limited distribution, possibly because of competence with more aggressive intruders like *Eichhornia* and *Lemna*. *Microcystis aeruginosa* (MW, blue-green algae) had the lowest frequency (25 ± 4.2%) and cover (20 ± 3.5%), though being a colonial bloom-forming cyanobacterium, its density could not be measured in the same way as macrophytes. It has been observed to occur in the monsoon period, which implies that the blooms grow because of the presence of nutrient-rich runoff and warm and stagnant waters. Overall, the radar chart in Figure 1 also indicates the predominance of free-floating weeds especially *Eichhornia crassipes* and *Lemna minor* points to the eutrophic nature of the water bodies studied. Emergent macrophytes and cyanobacterial blooms have co-occurred implying there exists an intricate interaction among nutrient enrichment,

Table 1. water quality parameters measurement (n = 14, ± SD = standard deviation)

Parameter	Range	Mean ± SD
Dissolved Oxygen (DO mg/L)	4.5 – 9.2	6.8 ± 1.1
Electrical Conductivity (EC µS/cm)	300 – 750	520 ± 95
pH (1-7 scale)	6.3 – 8.4	7.4 ± 0.5
Temperature (Temp °C)	23 – 33	27.6 ± 2.8
Turbidity (NTU)	7 – 36	21.3 ± 6.7

Table 2. Quantitative abundance of aquatic weeds in Lahore wetlands.

Species	Family	Blooming period	Frequency (%) (n=14)	Density (ind./m²) (n=14)	Cover (%) (n=14)	Common name
EC (*Eichhornia crassipes*)	Pontederiaceae	June–October	86 ± 4.1	63 ± 5.3	65 ± 3.8	Water hyacinth
LM (*Lemna minor*)	Lemnaceae	May–September	74 ± 6.2	88 ± 7.4	53 ± 2.9	Duckweed
TA (*Typha angustifolia*)	Typhaceae	November–February	60 ± 3.9	30 ± 3.1	45 ± 2.4	Cattails
PA (*Phragmites australis*)	Poaceae	July–September	57 ± 4.3	24 ± 2.2	40 ± 3.1	Common reed
PS (*Pistia stratiotes*)	Araceae	June–September	33 ± 3.6	16 ± 1.9	22 ± 2.2	Water lettuce
MW (*Microcystis aeruginosa*)	Microcystaceae	Monsoon/ rainy seaoon	25 ± 4.2	(colonial)	20 ± 3.5 bloom freq.	Blue-green algae

hydrological environment, and competitive dynamics that all influence the structure of aquatic flora.

3.3 Species–Environment Relationships

The polar heatmap (Figure 2) shows the Pearson correlation coefficients (r) between the density of dominant aquatic weed species and the main physico-chemical parameters of the water. The general trend shows species-specific reaction to environmental gradient and points to ecological preferences and possible forces of weed proliferation. *Eichhornia crassipes* (EC) was positively and moderately correlated with electrical conductivity (r = +0.31) and pH (r = +0.26), indicating that it grows better in nutrient-enriched mildly alkaline environments because it can reproduce and grows best in such environmental conditions. Likewise, *Lemna minor* (LM) had a good positive relationship with pH (r = +0.67) and dissolved oxygen (DO, r = +0.15), and a weaker positive relationship with temperature (r = +0.37), indicating it grows well in well-oxygenated, neutral-alkaline waters. Contrasting relations were observed in emergent species. TA (*Typha angustifolia*) was positively correlated with DO (r = +0.20) and turbidity (r = +0.16), which showed weak positive associations, meaning that it can withstand shallow and nutrient-enriched waters where they flourish. However, *Phragmites australis* (PA) was negatively correlated with most parameters (e.g., DO, r ety= -0.58; EC, r = -0.51), which suggests that it grows best in less nutrient-enriched, relatively stable water bodies. *Pistia stratiotes* (PS) among floating weeds was positive, but weakly, correlated with turbidity (r = +0.10) and pH (r = +0.26), which indicates that it is sensitive to suspended solids and buffering conditions. In comparison, Microcystis aeruginosa (MW, cyanobacteria) had only negative or weak correlations, particularly with DO (r = -0.23), which is unsurprising as bloom formation frequently reduces the oxygen content by overgrowing biomass. Taken together, these correlations illustrate that such species as Eichhornia crassipes and Lemna minor are greatly preferential in the presence of eutrophic and alkaline environments, whereas emergent taxa like Phragmites australis reacts adversely to nutrient enrichment. The differing responses highlight the importance of physico-chemical gradients in the organization of aquatic weed assemblages and suggest that changes in water quality and especially conductivity, pH, and DO can act as ecological sieves that control species dominance.

The polar heatmap (Figure 4) illustrates Pearson correlation coefficients (r) between the cover of the prevailing aquatic weed species and the physico-chemical parameters that were measured. There was a clear indication of species-specific responses based on ecological niche and tolerance limit of various taxa. *Eichhornia crassipes* (EC) was positively correlated with the electrical conductivity (r = +0.29) and the pH (r = +0.29) with weak to moderate positive relationships, which indicates that the extensive surface cover is preferred in nutrient-rich and slightly alkaline environments. On the same note *Lemna minor* (LM) showed high positive correlation with pH (r = +0.69) and electrical conductivity (r = +0.47), which further favors eutrophic and alkaline waters in which surface mat is highly developed. Conversely, emergent macrophytes were seen to have weak or negative relationships. The TA exhibited almost neutral reactions to most of the parameters and the PA exhibited a negatie reaction with DO (r = -0.68) and pH (r = -0.60), which indicated a decreased canopy cover under oxygen-rich and alkaline environments. The tendency implies that a dense reed bed might be more stable in comparatively undisturbed or less nutrient-rich waters. *Pistia stratiotes* (PS) was also found to have weak positive correlations with DO (r = +0.19) and turbidity (r = +0.16), indicating opportunistic growth in moderately disturbed, shallow and nutrient-enriched environments. On the other hand, *Microcystis aeruginosa* (MW) cover had a strong and negative correlation with DO (r = -0.68) in accordance with its bloom dynamics which frequently cause oxygen depletion during decay phases. Taken together, the correlation framework highlights nutrient enrichment and buffering capacity (EC and pH) to have a strong effect on floating macrophytes (*Eichhornia crassipes* and *Lemna minor*), which allow large-scale surface cover, and emergent taxa (*Typha* and *Phragmites*), which have lower cover in nutrient-enriched, oxygenated waters. The dominance of cyanobacteria (*Microcystis*) among the water resources was negatively correlated with the oxygen levels, which demonstrated its contribution to the worsening of water quality. These results suggest that changes in physico-chemical gradients, especially pH, EC, and DO, are central forces behind aquatic weed cover and community structure. The polar heatmap (Figure 4) shows Pearson correlation coefficients (r) between species frequency and water quality parameters, which can be used to indicate how the environmental conditions influence the predictable consistency of the aquatic weeds at the sites. There was a weak positive relationship between *Eichhornia crassipes* (EC) and electrical conductivity (r = +0.24) and pH (r = +0.22), and thus, it is necessary to conclude that its prevalence is related to nutrient enrichment and alkalinity buffering, which are eutrophic system characteristics. The *Lemna minor* (LM) also demonstrated positive relationships with pH (r = +0.54), and electrical conductivity (r = +0.37), indicating that high ionic content and strongly alkaline waters favor its extensive distribution amongst the locations. The emergent macrophytes *Typha angustifolia* (TA) and *Phragmites australis* (PA) had opposite relationships. Typha exhibited mostly neutral to weak correlations, and Phragmites exhibited negative correlations with dissolved oxygen (r = -0.53) and pH (r = -0.47). This indicates that commonage of *Phragmites* is inhibited in very oxygenated and alkaline water and this is in line with its favoring relatively stable littoral conditions. *Pistia stratiotes* (PS) was weakly positively correlated with dissolved oxygen (r = +0.12) and turbidity (r = +0.07), which implies that it is

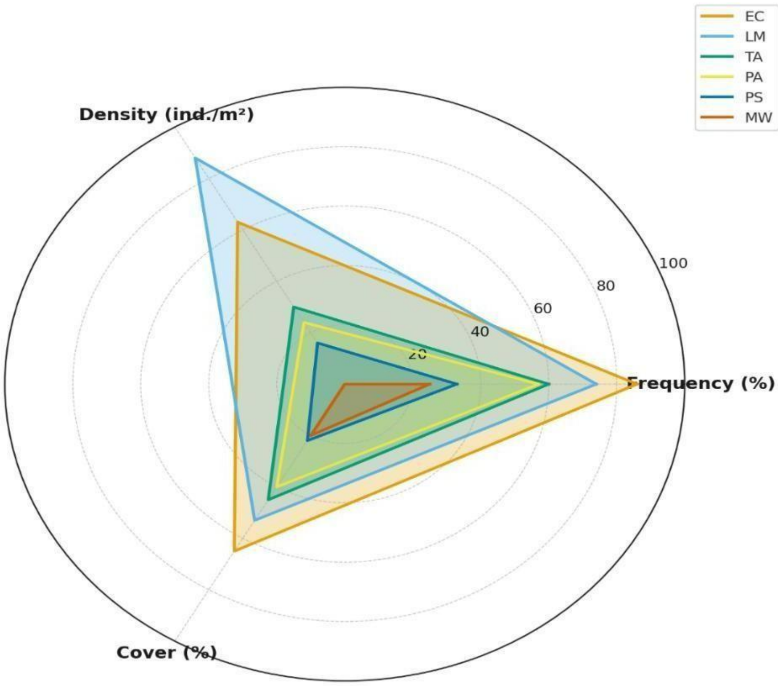

Figure 1. Radar chart showing comparative species cover (%), species density (ind./m^2) and frequency (%)

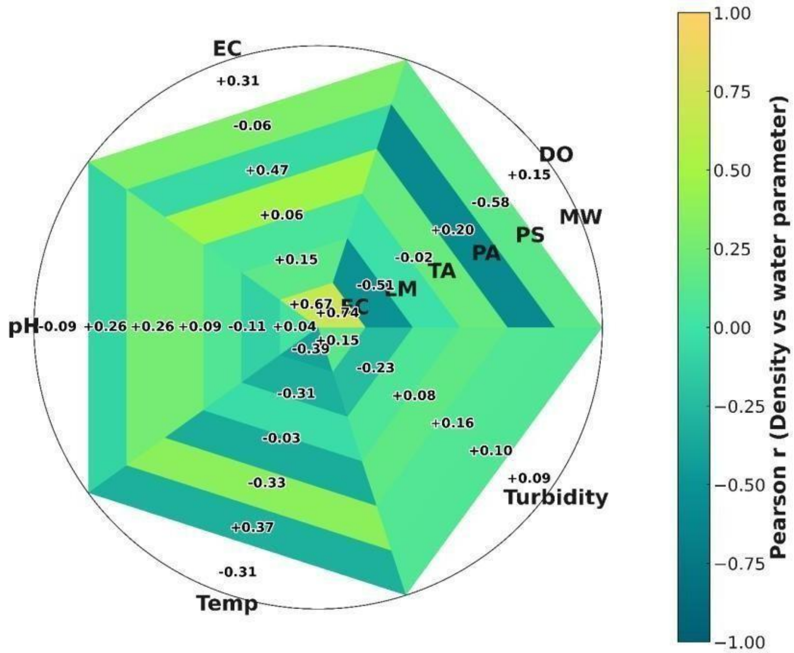

Figure 2. Polar heatmap showing association of species density (%) (EC, LM, TA, PA, PS, MW) with water parameters (pH, EC, DO, TA, Temp).

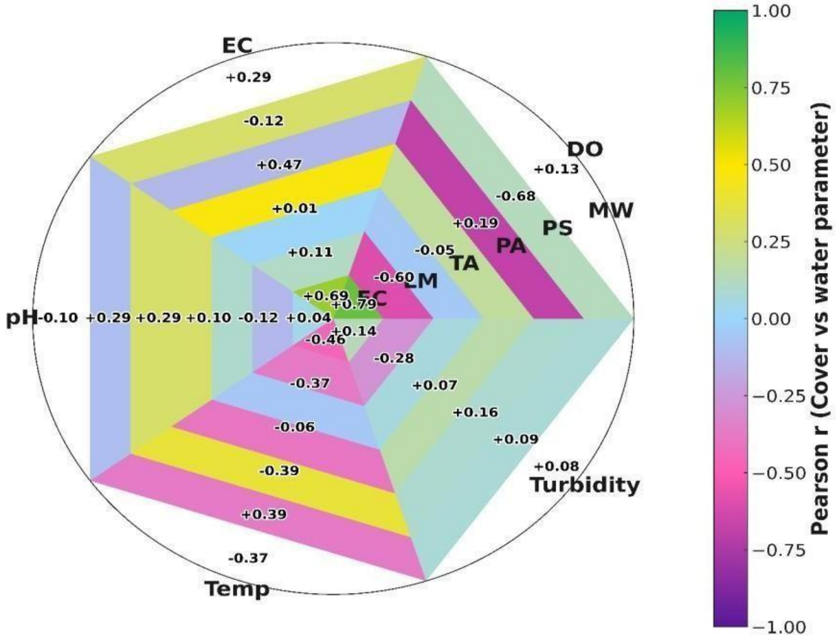

Figure 3. Polar heatmap showing association of species cover (%) (EC, LM, TA, PA, PS, MW) with water parameters (pH, EC, DO, TA, Temp).

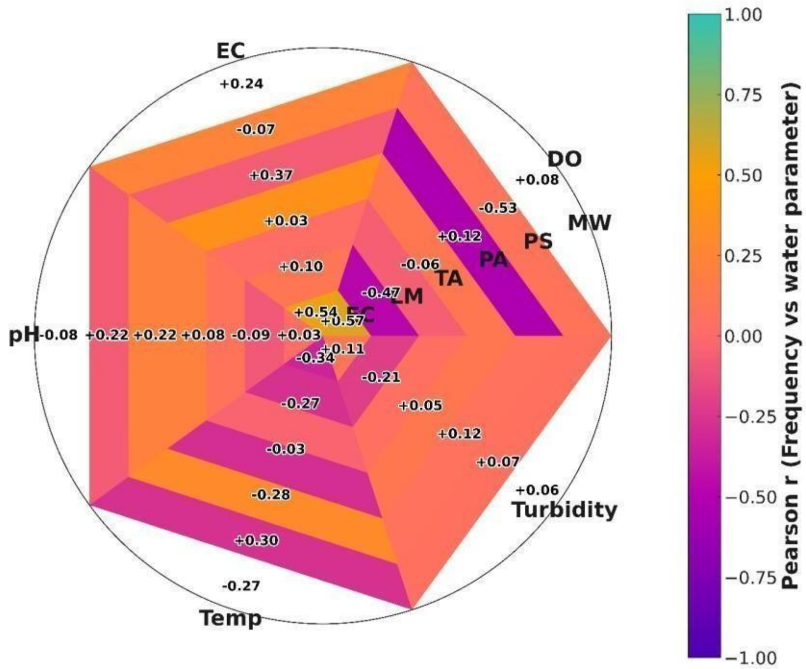

Figure 4. Polar heatmap showing association of species frequency (%) (EC, LM, TA, PA, PS, MW) with water parameters (pH, EC, DO, TA, Temp).

occasionally spread in nutrient-rich shallow environments, but its prevalence was low overall, in comparison with dominant taxa. *Microcystis aeruginosa* (MW), on the contrary, showed a strong negative relationship with dissolved oxygen (r = -0.53), which is in line with its bloom dynamics that lower the oxygen supply and makes it uncommon across locations. In general, frequency-based correlation points to the more reliable distribution of floating weeds (*Eichhornia* and *Lemna*) in nutrient-rich, alkaline, and moderately oxygenated habitats and to the more limited and site-specific distribution of emergent species (*Typha* and *Phragmites*). The occurrence of cyanobacterial blooms (*Microcystis*) was negatively related to oxygen, indicating their frequency patterns depending on the occurrence of blooms. These findings highlight the primary ecological filters of pH, electrical conductivity and dissolved oxygen as the main determinants of persistence and spatial frequency of aquatic weed species in eutrophic systems.

3.4 Spatial Distribution

Figure 5 presents a distribution map of the surveyed sites of dominant aquatic weed species in Lahore and Kasur Tehsils, Punjab in Pakistan. Geo-referencing of the sampling region of the study area along the border between the area and Kasur Tehsil. Such sites are associated with areas of large agricultural runoff and wastewater release, which probably increase nutrient loading and stimulate weed growth. The most widespread species was *Eichhornia crassipes* and *Lemna minor*, which dominated several stagnant ponds and drainage channels as expected based on their known capacity to colonize eutrophic waters very quickly. *Phragmites australis* and *Typha angustifolia* were mainly limited to littoral areas and slow-moving canals, as this species is ecologically adapted to semi-stable and shallow habitats. *Pistia stratiotes* were also relatively less abundant, occurring in only several locations, and there in co-occurrence with other free-floating macrophytes. The inset map gives the geographical setting of the area of study in Punjab province and shows the interconnection of water habitats in Lahore and Kasur. The patchy yet overlapping distributions of the species highlight the role of hydrological conditions as well as anthropogenic inputs in the formation of aquatic weed assemblages. Taken together, this spatial evidence implies that the main drivers of aquatic weed growth in the area are nutrient enrichment and habitat alteration in peri-urban and agricultural landscape.

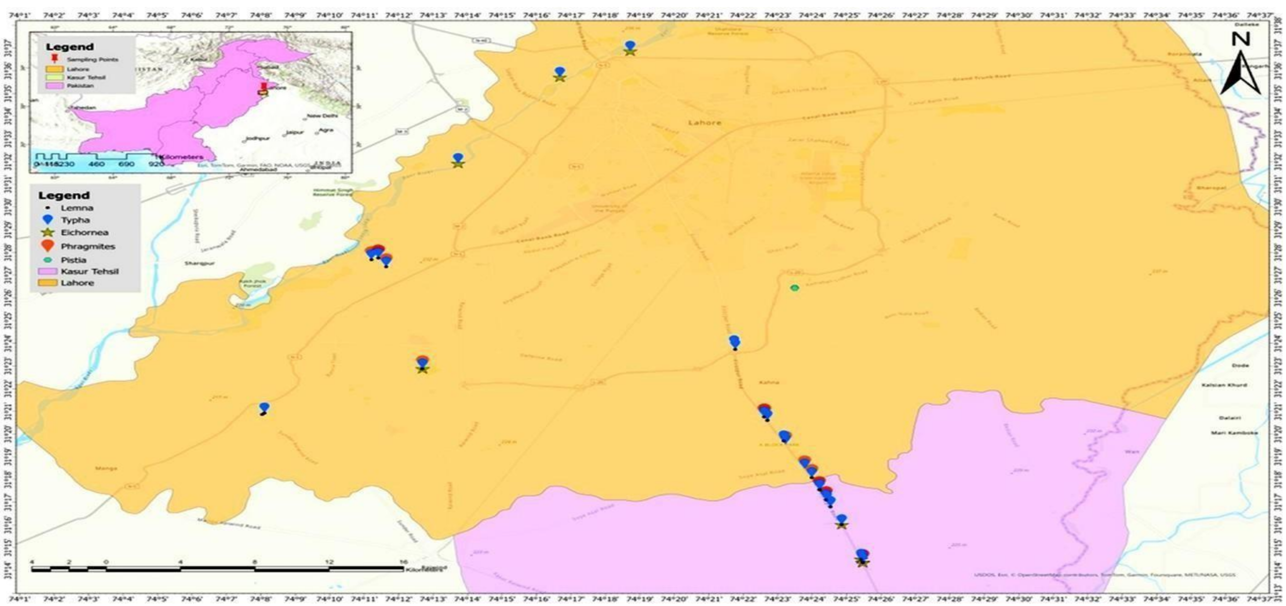

Figure 5. Spatial distribution maps of dominant weeds (ArcGIS Pro, WGS84, KDE hotspots).

points and marking of species presence were done with unique symbols of *Lemna minor*, *Typha angustifolia*, *Eichhornia crassipes*, *Phragmites australis* and *Pistia stratiotes*. The mapped data shows that the aquatic weed infestations are clearly clustered along drainage channels and water bodies of low elevation, especially in the southern

3.5 Diagnostic morphology and field photography of abundant aquatic weeds of Lahore

3.5.1 *Eicchornia crassipes* (Mart.) Solms-Laub.

Morphological characters

Water hyacinth (Figure 6) has fibrous roots which extend down in water several feet below. Stems are spongy due to aerenchyma and form dense mats over water surface. Leaves are thick, waxy, elongated and round (30cm long, 20cm wide). It produces lavender colored flowers with six petals and clusters. They produce asexually by vegetative propagation through runners and rarely sexually by seeds.

3.5.2 *Phragmites australis* (L.)

Morphological characters

The roots of this plant are fibrous. Stems/culms are upright from 2 to 5 meters tall, hollow and jointed, green when young and yellow when mature when mature. Leaves of common reeds are narrow lanceolate, pointed, have parallel venation and long (15-30cm wide, 1-5 wide). Flowers are in the form of panicle inflorescence, feathery upto 30cm long, purplish and produce a high yield of seeds which disperse over long distances (Figure 7).

3.5.3 *Typha angustifolia* (L.)

Morphological characters

This narrow leaf cattail has a rhizomatous root system to stabilize plant in wetland soil (Figure 8). Stems/Culms are tall 1-3 meters long, erect, hollow and smooth generally green but turns brown at maturity help in vegetative propagation. They have narrow, long and linear leaves (1 meter long, 1- 2cm broad) with parallel venation. Flowers make inflorescence of cylindrical spike or catkin type (4-12 inches), brownish in color and produce numerous seeds by wind and water.

3.5.4 *Lemna minor* (L.)

Morphological characters

Duckweed (Figure 9) is a small, free-floating plant that has a thallus-like structure. Its thallus is flattened and resembles leaf (1-5 mm in length, 2-10 mm in width), usually green but appears yellow to brown sometimes. Roots are short and fibrous. Flowers are tiny, unisexual arises from axils of thallus, asexually reproduce by fragmentation and sexually by tiny round seeds.

3.5.5 *Microcystis aeruginosa* (K.)

Morphological characters

This species commonly referred to blue-green algae appears in clusters and colonies in the gelatinous matrix in which cell colonies are protected by mucilage sheath. Colonies form blue scum on the water surface as shown in Figure 10. Cells contain chlorophyll to perform photosynthesis. Colonies show buoyancy due to the presence of gas vesicles which help them to float.

3.5.6 *Pistia stratios* (L.)

Morphological characters

It is 15cm long, light green, spongy and soft leaves (Figure 11). Root length may reach upto 50cm. Flowers are mostly central and invisible due to lack of petals and creamy to yellow in color. They mostly reproduce asexually by stolon. Small fruits (6-10 length, 3-6 width) form in the form of berry containing many seeds which are evidence of sexual reproduction.

4. Discussion

The current research is the first quantitative evaluation of the urban and peri-urban water bodies in Lahore and shows that free-floating macrophytes, especially *Eichhornia crassipes* and *Lemna minor*, prevail in eutrophic and stagnant water bodies. Both species were highly frequent and covered (86% and 65% of *Eichhornia*; 74% and 53% of *Lemna*) and strongly correlated with increased electrical conductivity and alkaline pH, the conditions of nutrient-enriched drains and roadside ponds. *Eichhornia* has also been reported to dominate nutrient-rich waters in Sindh (Akbar et al., 2010) and Khyber Pakhtunkhwa (Marwat et al., 2011; Gul et al., 2017) because of their opportunistic growth in eutrophic waters. *Lemna* has been found to thrive in Punjab wetlands that experienced large amounts of organic input (Ikram et al., 2013, 2014) because they can thrive in alkaline waters with nutrient load. Both species reduce DO while restricting sunlight to penetrate in depth of water because of their dense mats over the water surface, leading to decomposition of organic waste leading to destruction of native fauna and flora and misbalance the aquatic communities. Lahore results are thus consistent with national inventories but differ in that there is a higher proportion of free-floating mats compared with emergent assemblages, probably the result of the hydrology of low flow drains and industrial canals characteristic of the area.

Correlations between species distribution and water chemistry underscore the importance of physico-chemical gradients as ecological filters. *Eichhornia* and *Lemna* had a positive relationship with the conductivity and pH, which validates their established capacity to colonize eutrophic and slightly alkaline water (Patel, 2012; Susheela and Radha, 2015). *Phragmites australis*, in turn, had negative correlations with a dissolved oxygen and pH, which means that it favors comparatively stable littoral areas that are not so affected by nutrient pulses (An et al., 2020; Qiu et al., 2023). *Typha angustifolia* was found to be weakly or neutrally correlated with most parameters due to its ability to survive in a broad range of disturbed wetlands (Nguru and Sabo, 2022) which eventually leads to disturbance of ponds hydrology. The cyanobacterium *Microcystis aeruginosa* exhibited a significant negative relationship with dissolved

Figure 6. Water hyacinth infestation in a local rainy pond

Figure 7. Common reed infestation on the bank of a drainage canal

Figure 8. cattails infestation on shore of a canal

Figure 9. Duckweeds infestation in a local rainy pond

Figure 10. Algal infestation in a roadside drainage waterway

Figure 11. water lettuce infestation in a local rainy pond

oxygen, which validates its dynamics of a bloom that depletes oxygen and increases hypoxia (Du et al., 2017; Wei et al., 2022) which results in production of toxins and destroying water quality making it unfit for native fauna and flora. These species-environment interactions describe the observed spatial clustering, in which the infestations were greatest in the Thokar-Kasur drainage corridor, which is a center of agricultural runoff and untreated effluent.

These weeds have immense ecological effects on the aquatic ecosystems of Lahore. Free floating *Eichhornia* and *Lemna* mats inhibit light penetration, change nutrient cycling and decrease dissolved oxygen resulting in anoxia and fish death (Charudattan, 2001; Wang et al., 2021). Their fast proliferation is superior to native plants, lowers biodiversity and harms ecosystems (Horst et al., 2014; Kriticos and Brunel, 2016). Although they offer some shoreline stabilization, *Phragmites australis* and *Typha angustifolia* are invasive and modify wetland hydrology, replace native macrophytes and pose fire hazards in their senescent state (Engloner, 2009; Aloo et al., 2013; Hassan and Nawchoo, 2020). *Microcysts*, in addition to consuming oxygen, release microcystins, which are very dangerous due to bioaccumulation in aquatic life, livestock, and human health (Xiang et al., 2019; Zhang et al., 2021; Bormans et al., 2023). Less prevalent in this survey, *Pistia stratiotes* also develop thick rosettes that prevent water flow, worsen water quality, and provide habitats to mosquitos, exacerbating ecosystem and health risks to the population (Anuradha et al., 2015; Madeira et al., 2022).

Comparing the assemblage of Lahore with other parts in Pakistan reveals that there are great similarities in the identity of species but dissimilarity in the relative dominance and ecological pressures. Compared to the northern Khyber Pakhtunkhwa or brackish wetland of Sindh, the dominance of Lahore is free-floating, indicating its urban hydrology and sewage and industrial nutrient enrichment (Hussain and Shah, 2012; Akbar et al., 2010). Such a tendency is also consistent with the global patterns of tropical and subtropical systems in which eutrophication, combined with warm stagnant water, strongly prefers floating mats and cyanobacterial blooms (Susheela and Radha, 2015; Prokopuk et al., 2021). Lahore, therefore, offers a local case study of how anthropogenic loads of nutrient reorganize aquatic communities into invasive oxygen-depleting assemblies with far-reaching ecological impacts.

This has management implications: the uncontrolled increase of these weeds is a threat to ecological integrity, fisheries, agriculture, and recreational uses. In Lahore, *Eichhornia* and *Lemna* mats block irrigation canals and drainage systems, raise maintenance expenditures, and worsen navigation, and *Microcystis* blooms degrade water quality and complicate the treatment of drinking supplies. This means that management strategies must focus on nutrient sources reduction, specific elimination in hotspots identified, and the valorization of harvested biomass into value-added products, e.g., compost or biochar as it has been suggested elsewhere (Sarma et al., 2021; Khan et al., 2014). New genetic methods like CRISPR or microbial biocontrol are still hypothetical and must be viewed as future directions of research (Liu et al., 2019; Dong et al., 2021), but immediate response must be taken in the form of locally adapted, ecosystem-based interventions.

Finally, the results underscore the fact that nutrient enrichment and lack of hydrological control are increasingly making Lahore aquatic ecosystems dominated by invasive free-floating weeds and bloom-forming cyanobacteria. These ecological effects are depletion of oxygen, loss of biodiversity, change in hydrology, and the risk to human health, and reflect global invasive weed crises, but with region-specific intensity in industrial and agricultural drains. To overcome these difficulties, combined management, including nutrient abatement, mechanical control, and biomass valorization, is necessary and further research must estimate nutrient budgets, coupled interventions, and reed-bed restoration as buffer zones. This research therefore offers a benchmark on future ecological study and sustainable management of weed in urban freshwater systems in Pakistan.

5. Conclusion

This research gives the baseline on invasive aquatic weeds in wetlands and urban water bodies of Lahore in quantitative terms. The most common species were the free-floating macrophytes *Eichhornia crassipes* and *Lemna minor*, then emergent taxa (*Typha angustifolia* and *Phragmites australis*), *Pistia stratiotes* and *Microcystis aeruginosa*. Their effects on the environment are diminishing the amount of oxygen, restricting light, disrupting the habitat, loss of biodiversity, and interference with fisheries, irrigation, and recreational activities. These results indicate that the weed growth in the aquatic ecosystems of Lahore is mostly triggered by nutrient enrichment and imbalanced hydrology. The current research emphasizes important insights for environmental scientists and policymakers to develop a sustainable solution to conserve native biodiversity, to clean water quality and to address multiple socio-economic issues created by unchecked proliferation of aquatic weeds in Lahore and its outskirts.

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Ethical Approval

This article does not contain any studies with human participants or animals performed by any of the authors. This study does not contain any ecological issues or environmental degradation.

Author Contributions

Muntaha Munir: Data collection, material preparation, and writing—original draft. Aisha Nazir: Conceptualization, methodology, provision of resources, and supervision. Samreen Aslam: Data curation and review. Faiza Irshad: Editing and refinement of the manuscript. All authors read and approved the final version of the manuscript.

Data Availability

All data generated or analyzed during this study are included in the article. No additional datasets were generated or analyzed.

References

Akbar, G., Khatoon, S., Imran, M., Rizwan, N., Khan, M. Z., & Islam, S. (2010). Floristic and phyto-sociological assessment of vegetation of Keenjhar Lake and Surrounding Area (Thatta, Sindh), Pakistan. *International Journal of Biology and Biotechnology*, *7*(3), 197.

Akhter, N., Aqeel, M., Shahnaz, M. M., Alnusairi, G. S., Alghanem, S. M., Kousar, A. & Noman, A. (2021). Physiological homeostasis for ecological success of Typha (Typha domingensis Pers.) populations in saline soils. *Physiology and Molecular Biology of Plants*, *27*, 687-701.

Aloo, P., Ojwang, W., Omondi, R., Njiru, J. M., & Oyugi, D. (2013). A review of the impacts of invasive aquatic weeds on the biodiversity of some tropical water bodies with special reference to Lake Victoria (Kenya). *Biodiversity journal*, *4*(4), 471-482.

An, S., Liu, X., Wen, B., Li, X., Qi, P., & Zhang, K. (2020). Comparison of the photosynthetic capacity of phragmites australis in five habitats in saline–alkaline wetlands. *Plants*, *9*(10), 1317.

Anuradha, J., Abbasi, T., & Abbasi, S. A. (2015). An eco-friendly method of synthesizing gold nanoparticles using an otherwise worthless weed pistia (Pistia stratiotes L.). *Journal of advanced research*, *6*(5), 711-720.

Bakhtiar Gul, B. G., Bilal Khan, B. K., & Haroon Khan, H. K. (2017). Aquatic flora of various fresh water bodies of District Charsadda, Khyber Pakhtunkhwa, Pakistan.

Bormans, M., Legrand, B., Waisbord, N., & Briand, E. (2023). Morphological and physiological impacts of salinity on colonial strains of the cyanobacteria Microcystis aeruginosa. *Microbiology Open*, *12*(3), e1367.

Ceschin, S., Abati, S., Leacche, I., & Zuccarello, V. (2018). Ecological comparison between duckweeds in central Italy: The invasive Lemna minuta vs the native L. minor. *Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology*, *152*(4), 674-683.

Charudattan, R. (2001, November). Are we on top of aquatic weeds. In *Weed problems, control options, and Challenges. A talk presented at an international symposium on the World's Worst Weeds*.

Dong, H., Huang, Y., & Wang, K. (2021). The development of herbicide resistance crop plants using CRISPR/Cas9-mediated gene editing. *Genes*, *12*(6), 912.

Du, Y., Ye, J., Wu, L., Yang, C., Wang, L., & Hu, X. (2017). Physiological effects and toxin release in Microcystis aeruginosa and Microcystis viridis exposed to herbicide fenoxaprop-p-ethyl. *Environmental Science and Pollution Research*, *24*, 7752-7763.

Engloner, A. I. (2009). Structure, growth dynamics and biomass of reed (Phragmites australis)–A review. *Flora-Morphology, Distribution, Functional Ecology of Plants*, *204*(5), 331-346.

Fawad, M., Gul, B., Khan, H., & Khan, Z. (2013). Study and collection of hydrophytes of the district Swabi, Pakistan. *Pakistan Journal of Weed Science Research*, *19*(4).

Gul, B., Khan, B., & Khan, H. (2017). Aquatic flora of various fresh water bodies of district charsadda, khyber pakhtunkhwa, pakistan. *Pakistan Journal of Weed Science Research*, *23*(2).

Han, Y. J., & Kim, J. I. (2019). Application of CRISPR/Cas9-mediated gene editing for the development of herbicide-resistant plants. *Plant Biotechnology Reports*, *13*(5), 447-457.

Hassan, A., & Nawchoo, I. A. (2020). Impact of invasive plants in aquatic ecosystems. *Bioremediation and*

Biotechnology: Sustainable Approaches to Pollution Degradation, 55-73.

Horst, G. P., Sarnelle, O., White, J. D., Hamilton, S. K., Kaul, R. B., & Bressie, J. D. (2014). Nitrogen availability increases the toxin quota of a harmful cyanobacterium, Microcystis aeruginosa. *Water research*, *54*, 188-198.

Hussain, F., Shah, S. M., & Badshah, L. (2012). Floristic and vegetation diversity of some aquatic habitats of mastuj valley, hindukush region, district chitral, pakistan. *Pakistan Journal of Plant Sciences*, *18*(1).

Ikram, S., Bhatti, K. H., & Parvaiz, M. (2014). Ethnobotanical studies of aquatic plants of district Sialkot, Punjab (Pakistan). *Journal of Medicinal Plants Studies*, *2*(1), 58-63.

Ikram, S., Parvaiz, M., Ahmed, M., Ilyas, U., Khalid, A., Munir, M. & Afzal, H. (2013). Aquatic plants of Sialkot district, Pakistan. *World Appl Sci J*, *28*(6), 884-896.

Ishaq, K., Marwat, S. K., & Mandokhel, N. K. (2017). Preliminary study of aquatic and marshland angiosperms of Zhob District, Balochistan, Pakistan. *Pak. J. Bot*, *49*(2), 715-723.

Kawade, S. S., Panchakarla, S., & Sapkale, P. H. (2023). Review on Aquatic Weeds and Their Management. *Environment and Ecology*, *41*(4C), 2900-2908.

Kay, S. H., & Hoyle, S. T. (2001). Mail order, the internet, and invasive aquatic weeds. *Journal of aquatic plant management*, *39*(1), 88-91.

Khan, M. A., Marwat, K. B., Gul, B., Wahid, F., Khan, H., & Hashim, S. (2014). Pistia stratiotes L. (Araceae): Phytochemistry, use in medicines, phytoremediation, biogas and management options. *Pakistan Journal of Botany*, *46*(3), 851-860.

Kriticos, D. J., & Brunel, S. (2016). Assessing and managing the current and future pest risk from water hyacinth, (*Eichhornia crassipes*), an invasive aquatic plant threatening the environment and water security. *PloS one*, *11*(8), e0120054.

Liu, Y., Wang, Y., Xu, S., Tang, X., Zhao, J., Yu, C., & Zhou, G. (2019). Efficient genetic transformation and CRISPR/Cas9-mediated genome editing in Lemna aequinoctialis. *Plant biotechnology journal*, *17*(11), 2143-2152.

Ludwig, D. F., Iannuzzi, T. J., & Esposito, A. N. (2003). Phragmites and environmental management: a question of values. *Estuaries*, *26*(2), 624-630.

Madeira, P. T., Dray Jr, F. A., & Tipping, P. W. (2022). The phytogeography and genetic diversity of the weedy hydrophyte, Pistia stratiotes L. *Biological Invasions*, *24*(8), 2613-2634.

Mal, T. K., & Narine, L. (2004). The biology of Canadian weeds. 129. Phragmites australis (Cav.) Trin. ex Steud. *Canadian Journal of Plant Science*, *84*(1), 365-396.

Martin, L. J., & Blossey, B. (2013). The runaway weed: costs and failures of Phragmites australis management in the USA. *Estuaries and Coasts*, *36*, 626-632.

Marwat, S. K., Ishaq, K., Ullah, I., Khan, A. A., Shaheen, S., Salman, S. & Rehman, A. (2017). Preliminary Study of Aquatic and Marshland Angiosperms of QillaSaifullah Tehsil, District QillaSaifullah, Balochistan, Pakistan. *International Journal of Horticulture*, *7*.

Marwat, S. K., Khan, M. A., Rehman, F. U., Ahmad, M., & Zafar, M. (2011). Biodiversity and importance of floating weeds of Dara Ismail, Khan District of KPK, Pakistan. *African Journal of Traditional, Complementary and Alternative Medicines*, *8*(5S).

Minkina, T., Fedorenko, G., Nevidomskaya, D., Konstantinova, E., Pol'shina, T., Fedorenko, A., & Hassan, T. (2021). The Morphological and functional organization of cattails Typha laxmannii Lepech. and Typha australis Schum. and Thonn. under soil pollution by potentially toxic elements. *Water*, *13*(2), 227.

Mustafa, H. M., & Hayder, G. (2021). Recent studies on applications of aquatic weed plants in phytoremediation of wastewater: A review article. *Ain Shams Engineering Journal*, *12*(1), 355-365.

Nguru, M. I., & Sabo, R. (2022). Origin, Classification and Distribution of Typha Species a Paradigm for Understanding the Biology and Ecology of the Wetland Emergent Plant Species. *Fane-Fane International Multi-Disciplinary Journal*, *6*(2, DEC.), 190-197.

Oz, M. T., Altpeter, A., Karan, R., Merotto, A., & Altpeter, F. (2021). CRISPR/Cas9-mediated multi-allelic gene targeting in sugarcane confers herbicide tolerance. *Frontiers in genome editing*, *3*, 673566.

Patel, S. (2012). Threats, management and envisaged utilizations of aquatic weed Eichhornia crassipes: an overview. *Reviews in Environmental Science and Bio/Technology*, *11*, 249-259.

Prada, O. J., Díaz, O. L., & Tache Rocha, K. (2024). Common duckweed (Lemna minor): food and environmental potential. Review. *Revista Mexicana de Ciencias Pecuarias*, *15*(2).

Prokopuk, M., Zub, L., & Bereznichenko, Y. (2021). A City as a Source of Introduction for Tropical Alien Species (Egeria Densa Planch., Pistia Stratiotes L. & Eichornia Crassipes (Mart.) Solms) in Natural Ecosystems with a Temperate Climate.

Qiu, T., Liu, Z., Li, H., Yang, J., Liu, B., & Yang, Y. (2023). Contrasting patterns of genetic and phenotypic divergence of two sympatric congeners, Phragmites australis and P. hirsuta, in heterogeneous habitats. *Frontiers in Plant Science*, *14*, 1299128.

Rizvi, Z. F., Jamal, M., Parveen, H., Sarfraz, W., Nasreen, S., Khalid, N., & Muzammil, K. (2024). Phytoremediation potential of Pistia stratiotes, Eichhornia crassipes, and Typha latifolia for chromium with stimulation of secondary metabolites. *Heliyon*, *10*(7).

Sarma, H., Islam, N. F., Prasad, R., Prasad, M. N. V., Ma, L. Q., & Rinklebe, J. (2021). Enhancing phytoremediation of hazardous metal (loid) s using genome engineering CRISPR–Cas9 technology. *Journal of Hazardous Materials*, *414*, 125493.

Sesin, V., Davy, C. M., & Freeland, J. R. (2021). Review of Typha spp.(cattails) as toxicity test species for the risk assessment of environmental contaminants on emergent macrophytes. *Environmental Pollution*, *284*, 117105.

Smith, K. E., Cowan, L., Taylor, B., McAusland, L., Heatley, M., Yant, L., & Murchie, E. H. (2024). Physiological adaptation to irradiance in duckweeds is species and accession specific and depends on light habitat niche. *Journal of Experimental Botany*, *75*(7), 2046-2063.

Srivastava, J., Kalra, S. J., & Naraian, R. (2014). Environmental perspectives of Phragmites australis (Cav.) Trin. Ex. Steudel. *Applied Water Science*, *4*(3), 193-202.

Susheela, P., & Radha, R. (2015). Studies on the nutritional constituents and the aquatic insect fauna associated with water hyacinth, Eichornia crassipes in Singanallur Lake, Coimbatore. *International Journal of Fauna and Biological Studies*, *2*(6), 05-07.

Wang, W., Jiang, M., & Sheng, Y. (2021). Glyphosate accelerates the proliferation of Microcystis aeruginosa, a dominant species in cyanobacterial blooms. *Environmental Toxicology and Chemistry*, *40*(2), 342-351.

Wasko, J. D., McGonigle, T. P., Goldsborough, L. G., Wrubleski, D. A., Badiou, P. H., & Armstrong, L. M. (2022). Use of shoot dimensions and microscopic analysis of leaves to distinguish Typha latifolia, Typha angustifolia, and their invasive hybrid Typha x glauca. *Wetlands Ecology and Management*, 1-15.

Wei, S., Zhuang, G., Cheng, L., & Wang, S. (2022). The proliferation rule of Microcystis aeruginosa under different initial pH conditions and its influence on the pH value of the environment. *Environmental Science and Pollution Research*, 1-10.

Xiang, L., Li, Y. W., Liu, B. L., Zhao, H. M., Li, H., Cai, Q. Y., & Li, Q. X. (2019). High ecological and human health risks from microcystins in vegetable fields in southern China. *Environment international*, *133*, 105142.

Xiong, W., Zhang, Y., Xie, D., Liu, J., Liu, Y., Yu, Y. & Feng, Y. (2023). Water lettuce (Pistia stratiotes L.) (Araceae) in China: distribution, introduction pathway, and impacts. *BioInvasions Record*, *12*(4).

Yu, X. B., Hao, K., Ling, F., & Wang, G. X. (2014). Aquatic environmental safety assessment and inhibition mechanism of chemicals for targeting Microcystis aeruginosa. *Ecotoxicology*, *23*, 1638-1647.

Zhang, Y., Whalen, J. K., & Sauvé, S. (2021). Phytotoxicity and bioconcentration of microcystins in agricultural plants: Meta-analysis and risk assessment. *Environmental Pollution*, *272*, 115966.

impact of chromium ion stress on plant growth, developmental physiology, and molecular regulation. *Frontiers in Plant Science*, *13*, 994785.

Shakeel, A., Anjum, L., Ibni Zamir, S., Rizwan, M., Arshad, M., Mehmood, Q., ... & Waqas, A. (2021). Irrigation water quality effects on CO_2 emissions along with crop and soil responses. *Pakistan Journal of Agricultural Sciences*, *58*(2), 637-642.

Sharma, A., Kapoor, D., Wang, J., Shahzad, B., Kumar, V., Bali, A. S., & Yan, D. (2020). Chromium bioaccumulation and its impacts on plants: an overview. *Plants*, *9*(1), 100.

Sohaib, N., Arif, M., Shah, M. N., Mahmood, S., Ali, H., Amjid, M., ... & Anwar, H. (2023). Exploring the Role of Anti-Oxidant on Growth and Yield of Cotton to Mitigate the Heat Stress.

Srivastava, D., Tiwari, M., Dutta, P., Singh, P., Chawda, K., Kumari, M., & Chakrabarty, D. (2021). Chromium stress in plants: toxicity, tolerance and phytoremediation. *Sustainability*, *13*(9), 4629.

Steel, R. G. D., Torrie, J., H. & Dickey, D. A. (1997). Principles and Procedures of Statistics, A Biometrical Approach, 3rd ed.; McGraw-Hill Book Company, Inc.: New York, NY, USA; Toronto, ON, Canada; London, UK, 352–358.

Xing, Y., Zheng, Y., & Wang, X. (2025). Integrated strategies for effective remediation of chromium-contaminated soils: advancements, challenges, and sustainability implications. *Environmental Advances*, 100614.

Yin, F., Li, J., Wang, Y., & Yang, Z. (2024). Biodegradable chelating agents for enhancing phytoremediation: mechanisms, market feasibility, and future studies. *Ecotoxicology and environmental safety*, *272*, 116113.

Zulfiqar, U., Haider, F. U., Ahmad, M., Hussain, S., Maqsood, M. F., Ishfaq, M., & Eldin, S. M. (2023).

Chromium toxicity, speciation, and remediation strategies in soil-plant interface: A critical review. *Frontiers in Plant Science*, *13*, 1081624.