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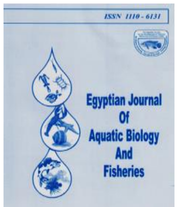

Influence of Weather and Water Quality Parameters on Aquatic Plant Production in Different Freshwater Ponds: Understanding Through Multiple Linear Regression Analysis

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ABSTRACT

Bangladesh is endowed with rich water resources and favorable climate conditions and ranks among the leading global countries of fish production. Despite this, the aquaculture industry of the country focuses mainly on finfish and shellfish, overlooking the potential of aquatic plants. Integrating aquatic plants into aquaculture in Bangladesh could promote sustainability, innovation, and ecological balance. To explore this potential, a six-month study was conducted using a 1m² standard quadrat sampling method across aquaculture, non-aquaculture, and derelict ponds to assess aquatic plant diversity and abundance. Employing a multiple linear regression (MLR) model, the study examined the relationship between plant abundance and environmental variables, including weather and water quality parameters. Thirteen aquatic plant species from ten taxonomic families were identified, with *Pistia stratiotes* (50%) being the most dominant, followed by *Lemna minor* (20%) and *Spirodela polyrrhiza* (7%). Free-floating species accounted for 78.2% of all plants observed, with the highest abundance found in derelict ponds. The MLR model had R^2 values of 0.670, 0.780, and 0.922 for aquaculture, non-aquaculture, and derelict pond, respectively. The independent variable (Number of plants/quadrat) showed a significant relationship with dependent variables, including rainfall, air temperature, water temperature, water depth, pH, dissolved oxygen, transparency, and for non-aquaculture and the derelict ponds, excluding the aquaculture pond. These findings indicate that aquatic plant diversity and abundance vary across water body types and are influenced by both climatic and physicochemical factors. Moreover, the results suggest that aquatic weeds hold considerable potential for integration into aquaculture systems through Integrated Multi-Trophic Aquaculture (IMTA) approaches.

INTRODUCTION

Aquaculture is one of the fastest-growing sectors in global food production, having overtaken capture fisheries as the leading source of aquatic foods

(Azra *et al.*, 2021). In Bangladesh, it plays a critical role in advancing food security **(Sarà *et al.*, 2022)**. The country's abundant water resources and favorable climatic and geographic conditions have positioned it among the top fish-producing nations in the world **(Alam *et al.*, 2025)**. Aquaculture now accounts for 57.39% of the total fish production of Bangladesh **(DoF, 2022)**, reflecting its increasing significance within national food systems. Traditionally practiced, the sector has seen substantial commercialization aimed at boosting yields and profitability. With 410,600 ha under pond-based aquaculture and an annual production of 2.16 million MT **(DoF, 2022)**, Bangladesh ranks as the world’s fifth-largest aquaculture producer **(FAO, 2024)**. However, the intensification of production through high stocking densities and increased feed inputs has introduced challenges such as nutrient accumulation and water quality deterioration **(Uddin *et al.*, 2018)**. In response, the integration of aquatic plants is being explored as a potential mitigation strategy.

Bangladesh faces challenges in global aquaculture competitiveness, primarily due to limited export opportunities and a continued reliance on traditional pond-based farming systems **(Alam *et al*., 2024a)**. These systems often underutilize the potential of multi-trophic integration of different aquatic organisms, which could otherwise enhance overall biomass productivity **(Alam *et al.*, 2024b)**. In contrast, countries such as China, Vietnam, and Malaysia have successfully cultivated and exported aquatic plants like *Ipomoea aquatica* (locally known as Kolmi in Bangladesh) as fresh vegetables, showcasing both economic and ecological advantages of plant-fish co-culture **(Bablee *et al.*, 2024)**. Despite the widespread cultivation and cultural significance of aquatic plants across Asia, including in Bangladesh, they remain largely absent from official agricultural statistics **(FAO, 2020)**. Globally, the trade in aquatic plants has expanded significantly from US$ 65 million in 1976 to over US$ 1.3 billion in 2018. Major exporters such as Indonesia, Chile, and the Republic of Korea supply key markets in China, Japan, and the United States **(FAO, 2020)**. In some regions, species like *Eichhornia crassipes*, originally introduced as ornamental plants, have proliferated and contributed to local economies **(Wu & Ding 2019; Huang *et al.*, 2020)**.

Aquatic plants are integral components of freshwater ecosystems, functioning as primary producers, habitat providers, biological indicators, and enhancers of biodiversity **(Jonsson *et al.*, 2009; Othman *et al.*, 2015; Ansari *et al.*, 2017; Mitu *et al.*, 2019)**. They contribute to ecosystem stability by producing oxygen, sequestering carbon dioxide, and synthesizing essential organic compounds such as lipids, carbohydrates, and proteins **(Adhikary *et al.*, 2018; Alam *et al.*, 2020)**. Their ecological importance is further underscored by their capacity to remove pollutants and heavy metals from aquatic environments **(Eid *et al.*, 2020)**. For instance, *Lemna* species have been shown to remove up to 88.2% of arsenic from contaminated water within 21 days of exposure and are occasionally classified as hyperaccumulators due to their remarkable ability to concentrate on heavy metals in their tissues **(Vaillant *et al.*, 2004; Mokhtar *et al.*, 2011)**.

Beyond their environmental benefits, aquatic plants hold considerable economic potential due to their rapid reproduction rates and favorable biochemical characteristics, making them promising candidates for biofuel production **(Mahija *et al.*, 2018; Moshood *et al.*, 2021; Koley *et al.*, 2023)**. Their high hemicellulose content, compared to traditional compost, also supports their use in biogas production and as bio-fertilizers in agriculture **(Matache *et al.*, 2020; Rashad, 2021)**. Aquatic plants are utilized as animal feed, offering a cost-effective alternative to conventional crops and potentially reducing reliance on traditional feed sources in aquaculture nutrition **(Gatlin *et al.*, 2007)**. Certain species, such as duckweeds, have long been consumed as human food in various countries and are valued for their high protein content, comprising 20–30% of dry weight **(Appenroth *et al.*, 2017; Azra *et al.*, 2021)**. Despite these diverse applications, aquatic plants in Bangladesh are often regarded as nuisance weeds and are routinely removed from aquaculture systems due to concerns over nutrient competition and interference with routine activities such as netting. Although several studies have documented the diversity and ecological functions of aquatic plants in Bangladesh **(Chakraborty, 2014; Basak *et al.*, 2015; Kaisar *et al.*, 2016; Islam *et al.*, 2017; Hasan *et al.*, 2018; Hasan *et al.*, 2021; Laskar *et al.*, 2021; Sultana *et al.*, 2021; Ame *et al.*, 2022)**, comprehensive research on their practical applications and economic potential within aquaculture remains limited.

To address this gap, it is crucial to explore the abundance, diversity, and functional roles of aquatic plant species, with a particular focus on their integration into sustainable production models such as Integrated Multi-Trophic Aquaculture (IMTA). Such research holds promise for unlocking the cultural, ecological, and economic value of aquatic plants, particularly in Bangladesh, where aquaculture remains a key pillar of national food production. Accordingly, this study aimed to assess the diversity of aquatic plants in selected pond ecosystems and to analyze their relationships with weather and water quality parameters, providing insights into their potential contributions to sustainable aquaculture development.

MATERIALS AND METHODS

Description of the study area

This study was conducted from July to December 2023 at the Field Laboratory Complex of the Faculty of Fisheries, Bangladesh Agricultural University, Mymensingh (24°43′26″ N, 90°25′48″ E). Three types of ponds were selected for sampling: aquaculture, non-aquaculture, and derelict ponds. The aquaculture pond was actively used for fish farming, regularly fed, and managed using standard aquaculture practices. In contrast, the non-aquaculture pond had been previously used for fish culture but was no longer managed and had begun to rewild, allowing aquatic plants to colonize naturally.

The derelict pond, which had never been used for aquaculture, received nutrient inputs primarily from the drainage system of the field laboratory complex.

Sampling of aquatic plants

Aquatic plant samples were collected from the ponds during each sampling date, always in the morning. Various methods are commonly used to assess plant diversity, including the quadrat, transect, loop, and point methods. In this study, the randomized quadrat method described by **Stromberg (1993)** was employed. A 1×1 m^2 wooden quadrat was placed in selected areas of each pond, with a minimum of three replications. The average abundance of aquatic plants was calculated as the number of plants per quadrat. Sampling was conducted in three distinct locations within each pond, based on water depth: near the water's edge, at an intermediate distance from the edge, and at the center of the pond. All plants within each quadrat were manually collected.

Identification of aquatic plants

The collected aquatic plants were identified through visual observation, supported by standard reference books, monographs, and digital tools such as Google Lens **(Campbell *et al.*, 2010; Calvert & Liessmann 2014)**. Particular emphasis was placed on using the *Encyclopedia of Flora and Fauna of Bangladesh* **(Ahmed *et al.*, 2008)**. All aquatic plant specimens collected on each sampling date were identified to the species level.

Weather and water quality parameters assessment

Monthly weather data, including air temperature and rainfall, were obtained from the local weather station of the Bangladesh Meteorological Department located on the BAU campus. Water quality parameters were measured on-site in the selected ponds during each sampling date, between 9:00 am and 11:00 am. The observed parameters included water temperature, depth, transparency, pH, and dissolved oxygen (DO). Water temperature was measured using a digital thermometer (SMART Sensor AR 867), and water depth was determined using a rope attached to a marked plastic pipe. Transparency was measured using a Secchi disc. A digital pH meter (Lutron PH-222) was used to measure water pH, while dissolved oxygen was measured using a portable DO meter (Lutron POD-520).

Data analysis

Multiple Linear Regression (MLR) was conducted using SPSS (Statistical Package for Social Science), Version 26, to assess the relationship between the dependent variable, aquatic plant abundance, and a set of independent variables, including climatic and water quality parameters. MLR analysis was performed for each pond type using six months of longitudinal data to assess the relationship between aquatic plant abundance and associated weather and water quality parameters. During the analysis, water temperature (x_1), water depth (x_2), water transparency (x_3), dissolved oxygen (x_4), pH

(x_5), air temperature (x_6), and rainfall (x_7) data were considered as independent variables and number of plants per quadrat (y) data as the dependent variable. The data were analyzed separately for aquaculture, non-aquaculture, and derelict ponds. The equation for MLR is:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots + \beta_7 x_7 + \varepsilon$$

Where, y is the dependent or predicted variable (the number of aquatic plants recorded per quadrat), β_0 is the intercept value, x_i is the seven independent variables, βi is the regression coefficients representing the change in y relative to a one-unit change in x_i and ε is the model's random error (residual) term, i.e. the variation of our estimate of y concerning the real value. All the statistical analyses were conducted at a 0.05% level of significance. Collinearity diagnostics were performed to assess the absence of multicollinearity among the independent variables. The Durbin-Watson test was conducted to evaluate the independence of the residuals. Additionally, Cook's distance was used to identify any potential outliers in the data.

RESULTS

Diversity of aquatic plant species

A total of 13 different aquatic plant species were recorded across all three types of ponds, representing diverse families and life forms that contribute to the ecological diversity of aquatic ecosystems (Table 1). Among them, free-floating species such as *Eichhornia crassipes* (Kachoripana), *Pistia stratiotes* (Topapana), *Lemna minor* (Khudi pana), and *Spirodela polyrrhiza* (Sonapana) dominate, indicating their adaptability to different ponds. Emergent species, including *Mikania mycrantha* (Japani lota), *Ipomoea aquatica* (Kolmishak), and *Trapa natans* (Panifol), suggest the presence of shallow or marshy habitats (Fig. 1). Additionally, *Nymphoides aquatica* (Chadmala) represents a floating anchored form, showing its rooted nature with floating leaves. The diversity in plant families, such as Pontederiaceae, Araceae, Poaceae, and Amaranthaceae, highlights the broad taxonomic representation of aquatic plants. The highest diversity of aquatic plants was found in derelict ponds, followed by non-aquaculture and aquaculture ponds (Table 1).

Table 1. Available species found during the study period in different types of ponds

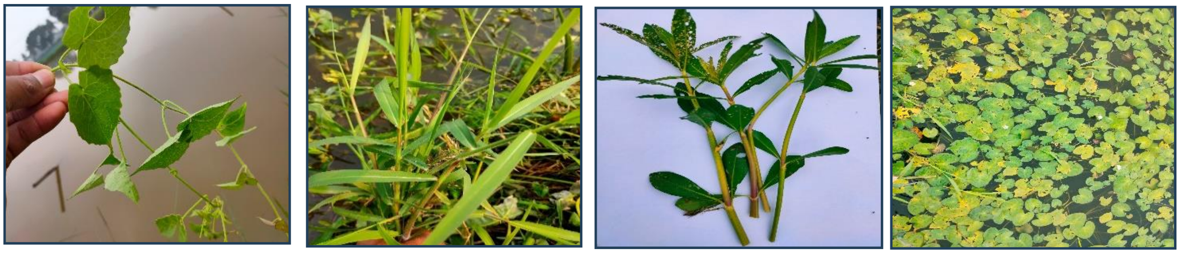
Scientific Name	**Local name**	**Presence of aquatic plants**			**References**
		AQ*	**NAQ***	**DE***	
Eichhornia crassipes	Kachoripana	×	×	✓	**(Ahmed *et al.*, 2008)**
Pistia stratiotes	Topapana	✓	✓	✓	**(Siddiqui *et al.*, 2007)**
Lemna minor	Khudi pana	✓	✓	✓	**(Siddiqui *et al.*, 2007)**

Spirodela polyrrhiza	Sonapana	×	✓	✓	**(Ahmed *et al.*, 2008)**
Mikania mycrantha	German lota	✓	✓	✓	**(Siddiqui *et al.*, 2007)**
Hygroryza aristata	Dol	✓	✓	✓	**(Ahmed *et al.*, 2008)**
Alternanthera philoxerodies	Malancha	✓	✓	✓	**(Siddiqui *et al.*, 2007)**
Nymphoides aquatica	Chadmala	×	✓	✓	**(Ahmed *et al.*, 2008)**
Commelina appendiculata	Kanaidoga	✓	✓	✓	**(Siddiqui *et al.*, 2007)**
Ipomoea aquatica	Kolmishak	✓	✓	✓	**(Ahmed *et al.*, 2008)**
Trapa natans	Panifol	×	×	✓	**(Siddiqui *et al.*, 2007)**
Scirpus mucronatus	Chechra	✓	✓	✓	**(Ahmed *et al.*, 2008)**
Colocasia esculenta	Kochu	✓	✓	✓	**(Siddiqui *et al.*, 2007)**

*AQ= Aquaculture Pond, NAQ= Non- Aquaculture Pond and DE= Derelict Pond

✓ = Present and × = Absent.

Eichhornia crassipes *Pistia stratiotes* *Lemna minor* *Spirodela polyrrhiza*



Mikania mycrantha *Mikania mycrantha* *Alternanthera philoxerodies* *Nymphoides aquatica*

Commelina appendiculata *Ipomoea aquatica* *Trapa natans* *Scirpus mucronatus*

Colocasia esculenta

Fig. 1. Photographs of aquatic plants found in the studied ponds (Taken by first author of the article)

Seasonal abundance of aquatic plants in different types of ponds

In the aquaculture pond (Table 2), the abundance of aquatic plant species (number of plants/quadrat) varied across the months, with the highest recorded in July (42) and August (43), followed by a gradual decline from September (36) to December (10). *Pistia stratiotes* showed the highest presence, peaking in September (27) before sharply declining in the following months. *Lemna minor* disappeared after August, while *Mikania* *micrantha*, *Hygroryza aristata*, and *Alternanthera philoxeroides* fluctuated in low numbers.

Table 2. Monthly diversity and abundance of aquatic plants (number of plants/ quadrat) in the aquaculture pond

Scientific Name	July	August	September	October	November	December
Pista stratiotes	16	21	27	05	03	01
Lemna minor	09	06	00	00	00	00
Mikania micrantha	03	01	00	00	01	02
Hygroryza aristata	02	02	03	01	00	02
Alternanthera philoxerodies	03	02	03	01	02	01
Commelina appendiculata	02	01	01	00	00	00
Ipomoea aquatica	04	06	01	01	00	01
Scirpus mucronatus	03	02	01	01	02	02
Colocasia esculenta	00	02	00	02	01	01
Total	42	43	36	11	09	10

The seasonal abundance of aquatic plants in non-aquaculture ponds shows a peak during the monsoon months (July–September), with the highest total abundance recorded in September (291), mainly driven by the dominance of *Pistia stratiotes* and *Lemna minor* (Table 3). These free-floating species thrive in warm, nutrient-rich waters. A sharp decline is observed from October (147) to December (34), likely due to decreasing temperatures and reduced water availability. By winter, most species exhibit significantly lower abundance, with some, such as *Lemna minor* and *Spirodela polyrrhiza*, nearly disappearing. However, a few resilient emergent species, including *Mikania micrantha*, *Scirpus mucronatus*, and *Colocasia esculenta*, persist at low levels.

Table 3. Monthly diversity and abundance of aquatic plants (number of plants/ quadrat) in the non-aquaculture pond

Scientific Name	July	August	September	October	November	December
Pista stratiotes	90	213	215	83	28	08
Lemna minor	65	25	32	38	00	13
Spirodela polyrrhiza	05	07	06	00	00	04
Mikania micrantha	07	04	01	02	02	01
Hygroryza aristata	06	04	09	02	01	03
Alternanthera philoxerodies	08	09	09	04	03	02
Nymphoides aquatica	03	03	06	07	01	01
Commelina appendiculata	00	01	03	02	01	00
Ipomoea aquatica	00	02	00	00	02	01
Scirpus mucronatus	05	03	09	07	04	01
Colocasia esculenta	01	01	01	02	02	00
Total	190	272	291	147	44	34

In the derelict pond, the seasonal abundance of aquatic plants shows a clear decline from the monsoon (July–September) to the winter months (November–December). The highest total abundance was recorded in July (341), primarily driven by the dominance of *Pistia stratiotes*, *Lemna minor*, and *Spirodela polyrrhiza*, which thrive in warm, nutrient-rich waters (Table 4). As the season progresses, a gradual decrease is observed, with a notable drop in November (65) and December (60), (Table 4) likely due to lower temperatures and reduced water levels. Free-floating species like *Lemna minor* and *Spirodela polyrrhiza* nearly disappear by winter, while a few emergent species such as *Nymphoides aquatica*, *Trapa natans*, and *Scirpus mucronatus* persist at lower densities.

Table 4. Monthly diversity and abundance of aquatic plants (number of plants/ quadrat) in the derelict pond

Scientific Name	July	August	September	October	November	December
Eichhornia crassipes	13	08	07	08	04	02
Pista stratiotes	130	80	83	81	28	13
Lemna minor	95	41	37	34	00	19
Spirodela polyrrhiza	35	42	30	21	00	09
Mikania micrantha	00	00	00	01	01	00
Hygroryza aristata	09	07	03	08	01	01
Alternanthera philoxerodies	06	02	06	05	03	02
Nymphoides aquatica	12	16	13	13	05	03
Commelina appendiculata	03	03	01	03	02	02
Ipomoea aquatica	06	06	05	04	04	03
Trapa natans	17	19	16	15	09	02
Scirpus mucronatus	13	08	11	09	05	03
Colocasia esculenta	02	02	01	03	03	01
Total	341	234	213	205	65	60

Weather and water quality parameters

The seasonal variation in weather and water parameters shows distinct trends influencing aquatic ecosystems (Table 1). Rainfall was highest in October (477.6 mm) and lowest in November (3.4 mm), reflecting the transition from the monsoon to the dry season (Table 5). Air and water temperatures followed a decreasing trend, peaking in July–September (~30°C for air, ~29°C for water) and dropping significantly in December (21.9°C and 20.63°C, respectively). Water depth was highest in October (117 ± 14.9 cm) due to heavy rainfall and declined thereafter. Water transparency remained relatively stable but increased slightly in December. Water pH remained near neutral with minor fluctuations, while dissolved oxygen (DO) peaked in August (7.78 ± 1.01mg/L) and declined in December (6.61 ± .770 mg/L), indicating seasonal changes in biological activity and decomposition processes (Table 5).

Table 5. Monthly variation in weather and water quality parameters in all the ponds

Variable	**July**	**August**	**September**	**October**	**November**	**December**
Rainfall* (mm)	346.4	463.2	219.6	477.6	3.4	26.5
Air temperature (°C)	30.5 ± 3.1	29.9 ± 2.8	30.2 ± 4.1	27.8 ± 3.75	25.1 ± 5.55	21.9 ± 4.5
Water temperature (°C)	28.67 ± 0.40	28.37 ± .09	29.17 ± .125	26.67 ± .12	24.53 ± .29	20.63 ± .249
Water depth (cm)	94 ± 6.48	106 ± 7.87	102.33 ± 11.6	117 ± 14.9	96 ± 13.49	82.33 ± 9.46
Water Transparency (cm)	34.46 ± 6.03	31.34 ± 5.53	33.3 ± 6.02	33.87 ± 7.3	33.9 ± 10.2	35.43 ± 13.92
Water pH	7.72 ± 0.121	7.64 ± .068	7.57 ± .11	7.73 ± .040	7.51 ± .154	7.55 ± .141
Water DO (mg/L)	7.10 ± .833	7.78 ± 1.01	7.467 ± 1.09	7.32 ± 1.17	6.81 ± .851	6.61 ± .770

*Monthly total rainfall (mm) was collected from the local weather station of the Bangladesh Meteorological Department located within Bangladesh Agricultural University.

Influence of weather and water quality parameters on the abundance of aquatic plants

The multiple linear regression (MLR) model, using seven weather and water quality predictors (rainfall, transparency, water depth, water temperature, dissolved oxygen, pH, and air temperature), explains approximately 67% of the variance in the number of plants per quadrat ($R^2 = 0.670$) in aquaculture ponds, with an adjusted R^2 of 0.440. This indicates a moderate fit, accounting for the number of predictors in the model (Table 6). The standard error of the estimate is 31.119, suggesting moderate dispersion of observed values around the predicted values. The regression sum of squares (19,688.133) is considerably larger than the residual sum of squares (9,683.645), and the resulting F-statistic is 2.904 with a *P*-value of 0.062. Although this *P*-value is slightly above the commonly accepted significance level of 0.05, it approaches statistical significance, indicating that the model is moderately effective in explaining variation in plant abundance.

Table 6. Model summary of the aquaculture pond

Model	**R**	**R^2**	**Adjusted R square**	**Std error of the estimate**	**Sum of squares**	**Degree of freedom**	**Mean square**	**F**	**Sig.**
Regression	.819[b]	.670	.440	31.119	19688.133	7	2812.590	2.904	0.062[b]
Residual					9683.645	10	968.365		
Total					29371.778	17			

a. Dependent Variable: No. of plants/quadrat

b. Predictors: (Constant), Rainfall, Transparency, Water depth, Water temperature, DO, pH, Air temperature.

The regression coefficients indicate varying contributions of the environmental variables to plant abundance, though most are not statistically significant. Water depth is the only significant predictor (*P*= 0.003), with a negative coefficient (B= -2.763), suggesting that as water depth increases, the number of plants per quadrat decreases. Other variables, including water temperature, transparency, pH, dissolved oxygen (DO), air temperature, and rainfall, DO not show significant effects (*P*> 0.05). Notably, water temperature and transparency have very low tolerance values (0.002 and 0.010, respectively) and extremely high Variance Inflation Factors (VIFs of 438.150 and 96.488), indicating severe multicollinearity. Similarly, air temperature shows extreme multicollinearity (VIF = 875.880). These high VIF values suggest that multicollinearity may be distorting the estimates of individual predictors, and caution is needed in interpreting their individual effects. Overall, water depth appears to be the most reliable predictor of plant abundance in this model.

Table 7. Standardized and unstandardized coefficients with *P*-values of the MLR analysis with collinearity statistics

Variable	**Unstandardized Coefficients**		**Standardized Coefficients**	**T**	***P*-value**	**Collinearity Statistics**	
	B	**Std. Error**	**Beta**			**Tolerance**	**VIF**
(Constant)	-1320.754	1527.588		-.865	.408		
Water Temperature	-32.785	50.652	-2.460	-.647	.532	.002	438.150
Water depth	-2.763	.694	-.943	-3.982	.003	.588	1.700
Transparency	-33.725	30.501	-1.972	-1.106	.295	.010	96.488
pH	238.308	228.396	.614	1.043	.321	.095	10.496
DO	-6.755	37.605	-.104	-.180	.861	.099	10.118
Air temperature	57.564	69.087	4.477	.833	.424	.001	875.880
Rainfall	.050	.095	.235	.523	.612	.163	6.132

The statistics of MLR reveal that the model, which includes seven weather and water quality predictors (rainfall, transparency, water depth, water temperature, dissolved oxygen, pH, and air temperature), explains 78% of the variance in the number of plants per quadrat ($R^2 = 0.780$) in non-aquaculture pond, with an adjusted R^2 of 0.626. This indicates a strong overall model fit (Table 8). The standard error of the estimate is 110.074, and the regression sum of squares (429,870.420) is substantially larger than the residual sum of squares (121,162.025), suggesting that much of the variability in plant abundance is accounted for by the predictors. The F-statistic is 5.068 with a *P*-value of 0.011, which is statistically significant at the 0.05 level.

Table 8. Model summary of non-aquaculture pond

Model	**R**	**R^2**	**Adjusted R square**	**Std. error of the estimate**	**Sum of square**	**Degree of freedom**	**Mean square**	**F**	**Sig.**
Regression	.883^b	.780	.626	110.074	429870.420	7	61410.060	5.068	0.011^b

Residual	121162.025	10	12116.202
Total	551032.444	17	

a. Dependent Variable: No. of plants/quadrat

b. Predictors: (Constant), Rainfall, Trans, Water depth, Water temperature, DO, pH, Air temperature.

The regression results show that water temperature has a strong positive effect (B = 409.238, *P*= 0.015), while water depth (B= -13.136, *P*= 0.001) and air temperature (B = -408.036, *P*= 0.020) have significant negative effects (Table 9). This suggests that higher water temperatures are associated with greater plant abundance, whereas deeper water and higher air temperatures are linked to reduced plant abundance. The other variables, transparency, pH, DO, and rainfall, do not show statistically significant contributions (*P*> 0.05). However, several predictors, including air temperature, water temperature, and rainfall, exhibit extremely high VIFs (VIFs above 100 in some cases), indicating severe multicollinearity. This multicollinearity may compromise the reliability of individual coefficient estimates, and corrective steps such as variable reduction or regularization may be needed for a more stable model.

Table 9. Standardized and unstandardized coefficients with *P*-values of the MLR analysis

Variable	**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**p-value**	**Collinearity Statistics**	
	B	**Std. Error**	**Beta**			**Tolerance**	**VIF**
(Constant)	-1949.751	11433.465		-.171	.868		
Water temperature	409.238	140.510	6.849	2.913	.015	.004	251.462
Water depth	-13.136	2.747	-1.117	-4.783	.001	.403	2.480
Transparency	4.835	38.436	.033	.126	.902	.310	3.222
pH	147.412	1457.282	.132	.101	.921	.013	77.769
DO	338.893	380.426	.687	.891	.394	.037	27.043
Air temperature	-408.036	148.025	-7.327	-2.757	.020	.003	321.361
Rainfall	.725	1.425	.789	.508	.622	.009	109.611

The regression analysis indicates a strong model fit, with the independent variables collectively explaining 92.2% of the variance in the number of plants per quadrat ($R^2 = 0.922$) in derelict pond and an adjusted R^2 of 0.867 (Table 10). The standard error of the estimate is relatively low at 59.980, suggesting that the predicted values closely match the observed data. The regression sum of squares (423,708.817) is much higher than the residual sum of squares (35,976.127), reinforcing the model's explanatory power. The F-statistic of 16.825 is highly significant (*P*= 0.000), indicating that the environmental variables rainfall, transparency, water depth, water temperature, dissolved oxygen, pH, and air temperature collectively have a statistically significant effect on plant abundance in aquaculture ponds. Overall, the model demonstrates excellent predictive strength and reliability.

Table 10. Model summary of the derelict pond

Model	R	R^2	Adjusted R square	Std. error of the estimate	Sum of square	Degree of freedom	Mean square	F	Sig.
Regression	.960[b]	.922	.867	59.980	423708.817	7	60529.831	16.825	0.000[b]
Residual					35976.127	10	3597.613		
Total					459684.944	17			

a. Dependent Variable: No. of plants/quadrat
b. Predictors: (Constant), Rainfall, Trans, Water depth, Water temperature, DO, pH, Air temperature.

The regression results reveal that water depth, rainfall, and dissolved oxygen (DO) are statistically significant predictors of plant abundance in aquaculture ponds. Water depth shows a strong negative effect (B = -16.724, *P*< 0.001), indicating that plant abundance decreases with increasing water depth. Rainfall has a significant positive influence (B = 0.813, *P*= 0.002), suggesting that higher rainfall is associated with greater plant density. DO also shows a significant negative effect (B= -225.626, *P*= 0.044), implying that higher DO levels may reduce plant abundance. The other variables, water temperature, transparency, pH, and air temperature, are not statistically significant (*P*> 0.05). However, the collinearity statistics raise concerns, especially for air temperature (VIF= 133.323) and water temperature (VIF= 113.763), indicating severe multicollinearity. Transparency (VIF = 16.747) and rainfall (VIF = 7.403) also exhibit high multicollinearity. Such high VIF values suggest that some predictors are highly correlated, which may distort coefficient estimates and reduce the reliability of individual variable effects. To improve model stability, multicollinearity should be addressed through variable selection or dimensionality reduction techniques such as principal component analysis or stepwise regression

Table 11. Standardized and unstandardized coefficients with *P*-values of the MLR analysis with collinearity statistics

Variable	Unstandardized Coefficients		Standardized Coefficients	t	*P*-value	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	230.483	5244.499		.044	.966		
Water Temperature	55.768	50.059	1.051	1.114	.291	.009	113.763

Water depth	-16.724	1.975	-1.299	-8.466	.000	.332	3.009
Transparency	-16.273	10.768	-.547	-1.511	.162	.060	16.747
pH	359.919	708.590	.137	.508	.623	.108	9.267
DO	-225.626	97.893	-.451	-2.305	.044	.205	4.887
Air temperature	-35.052	51.954	-.689	-.675	.515	.008	133.323
Rainfall	.813	.202	.970	4.031	.002	.135	7.403

DISCUSSION

This study provides a comprehensive understanding of aquatic plant diversity, seasonal variation, and the influence of weather and water quality parameters across three types of ponds-aquaculture, non-aquaculture, and derelict ponds in a subtropical freshwater ecosystem in Bangladesh. A total of 13 aquatic plant species were recorded during the study period, encompassing various life forms and plant families, thereby reflecting the ecological richness of these lentic habitats.

Free-floating species such as *Pistia stratiotes*, *Eichhornia crassipes*, *Lemna minor*, and *Spirodela polyrrhiza* were dominant across all pond types, highlighting their ecological plasticity and ability to thrive under a wide range of environmental conditions **(Jewell *et al.*, 2023)**. However, *Lemna minor* appeared less frequently in aquaculture ponds, likely due to management practices such as pond cleaning and water exchange. The dominance of these free-floating species can significantly influence the distribution patterns of other aquatic plant types. Emergent and floating-anchored species, including *Mikania micrantha*, *Ipomoea aquatica*, and *Nymphoides aquatica*, were more frequently observed in shallow or marshy zones, indicating the presence of microhabitat heterogeneity within and among pond systems **(Wang, 2022)**. These species are common globally in ponds and wetlands, performing important ecological functions **(Jewell *et al.*, 2023)**. Notably, no submerged plant species were recorded in any pond type during the study period, likely due to the dominance of surface-floating plants that limit light penetration to the benthic zone. Routine pond management practices such as liming, fertilization, and fish activity in aquaculture ponds can resuspend sediments, further hindering the establishment of submerged vegetation. Similarly, in derelict ponds, accumulated organic matter, elevated turbidity, and agricultural pollutants likely have comparable effects. Overall, reduced water transparency and frequent fishing activities, including netting, in both aquaculture and non-aquaculture ponds, impede the growth of submerged plants.

Seasonal changes had a noticeable impact on the abundance of aquatic plants across all pond types studied. The highest abundance of aquatic plants was observed during the monsoon season (July–September), likely due to favorable conditions such as increased water availability, warmer temperatures, and greater nutrient levels **(Hossain *et***

***al.*, 2024)**. In contrast, during the winter months (November–December), a significant decline was observed in plant abundance because of lower water temperatures, reduced water levels, and lower oxygen availability **(Debbarma *et al.*, 2021)**. When comparing different pond types, derelict ponds consistently supported the highest diversity and abundance of aquatic plants, followed by non-aquaculture and then aquaculture ponds. Differences in aquatic plant abundance are also evident across various pond types, particularly in relation to the intensity of human management **(Cannucci *et al.*, 2025)**. Derelict ponds, which have minimal human intervention, provide ideal conditions for abundant, unwanted plant growth. On the other hand, aquaculture ponds had fewer plants due to frequent cleaning, netting, and active water management practices aimed at optimizing conditions for fish production, as these practices restrict plant proliferation and growth **(Yang *et al.*, 2022)**. The species-wise abundance trends also varied seasonally. *Pistia stratiotes* remained dominant across all months, especially in non-aquaculture and derelict ponds, though its abundance declined during winter. *Lemna minor* was observed only during the initial months of the study. In derelict ponds, all 13 species were present in October, with *Spirodela polyrrhiza* peaking in August and *Trapa natans* showing stability in the first half of the study before declining. These findings corroborate earlier studies in similar lentic systems, although species richness here (13 species) was lower than in the Field Laboratory Complex of BAU (36 species; **Islam *et al.*, 2017)**. However, it was comparable to other regional studies **(Harney *et al.*, 2013)**.

To further understand the drivers of plant abundance, multiple linear regression (MLR) models were applied separately for each pond type. In aquaculture ponds, the model explained 67% of the variance (adjusted R^2= 0.440), with only water depth emerging as a statistically significant predictor (β= -2.763, *P*= 0.003). The negative relationship suggests that greater depth limits light penetration and reduces surface contact, decreasing plant growth **(Lacoul & Freedman, 2006)**. Reduced abundance in aquaculture ponds is also linked to regular management interventions such as pond cleaning and dyke maintenance **(Hill *et al.*, 2024)**.

In non-aquaculture ponds, the model showed stronger predictive power (R^2= 0.780; adjusted R^2= 0.626). Significant predictors included water temperature (β= 409.238, *P*= 0.015), air temperature (β = -408.036, *P* = 0.020), and water depth (β = -13.136, *P*= 0.001). These findings align with ecological theory, where warm water enhances plant metabolic activity while excessive heat stress and deeper waters inhibit growth. The concurrent significance of both air and water temperature underscores their interactive influence on aquatic macrophyte proliferation **(Rooney & Kalff, 2000; Hossain *et al.*, 2024; Jiang *et al.*, 2024)**.

The derelict pond model had the highest explanatory strength (R^2= 0.922; adjusted R^2= 0.867), with rainfall (β= 0.813, *P*= 0.002), water depth (β= -16.724, *P*< 0.001), and dissolved oxygen (DO) (β= -225.626, *P*= 0.044) as significant predictors. The negative association with DO may reflect dense vegetative cover that leads to microbial decomposition and subsequent oxygen depletion. Rainfall positively influenced plant abundance by expanding habitat area and enhancing nutrient inflow trends supported by previous studies on hydrological regulation and nutrient dynamics **(Bornette & Puijalon 2010; Rameshkumar *et al.*, 2019; Gaberščik & Zelnik 2021; Zhou *et al.*, 2023)**.

However, multicollinearity among predictors, particularly between air and water temperature, was noted in all models. High Variance Inflation Factors (VIFs) suggest interdependence among variables, which may reduce the reliability of individual coefficient estimates. This issue is common in ecological datasets with limited observations and highly interrelated parameters. To improve model robustness, future research should consider increasing sample size and applying dimension-reduction techniques such as principal component analysis or ridge regression.

In summary, the study reveals that water depth, temperature (both air and water), rainfall, and DO are key environmental drivers of aquatic plant abundance in subtropical freshwater ponds. The patterns vary depending on pond type and management intensity, with derelict ponds offering favorable conditions for macrophyte proliferation due to low disturbance and high nutrient loads. The growing scientific interest in integrating extractive plant species into aquaculture highlights the relevance of these findings. These findings have important implications for aquatic ecosystem management and the potential integration of macrophytes into productive systems such as Integrated Multi-Trophic Aquaculture (IMTA), where aquatic plants can play functional roles in nutrient uptake and habitat structure.

CONCLUSION

This study highlights the significant yet underexplored role of aquatic plants in enhancing sustainable aquaculture practices in Bangladesh. Despite the leading position of the country in global fish production, its aquaculture sector remains narrowly focused on fin fish, neglecting the diverse benefits aquatic plants offer. The study aimed to evaluate the relationship between the diversity of aquatic plants and weather and water quality parameters using multiple linear regression analysis. The research reveals a rich diversity of aquatic plants, particularly in derelict ponds, and establishes meaningful relationships between plant abundance and key environmental parameters in non-aquaculture and derelict settings. The findings suggest that integrating aquatic plants into aquaculture, particularly through technologies like IMTA, can not only bolster ecological balance but also unlock new avenues for economic development. Embracing this potential could pave the way for more resilient, innovative, and sustainable aquaculture systems in Bangladesh.

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Conflict of interest

The authors declare that they have no conflict of interest.

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