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Spatial and seasonal dynamics of aquatic macroinvertebrates and fish communities in relation to water quality variation in the Nile Valley, Egypt

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The assessment of freshwater ecosystem health is essential for sustainable water management amid increasing environmental stress. Aquatic macroinvertebrates and fishes serve as key bioindicators, providing integrated insights into the impacts of water quality and habitat degradation. This study investigated the spatial and seasonal patterns of aquatic invertebrate and fish communities in relation to water quality variation in two contrasting sites of the Nile Valley, Egypt (Kafr Saad and Abu Rawash areas). Sampling was conducted across different freshwater habitats, including canals, irrigation channels, ditches, and pools. A total of 73 aquatic taxa belonging to 30 families and 11 orders were recorded. Community composition and total abundance differed markedly between sites, with the Kafr Saad area exhibiting higher diversity and a greater representation of pollution-intolerant taxa, whereas pollution-tolerant groups dominated Abu Rawash. Seasonal variation significantly influenced aquatic community structure, with higher abundance and diversity observed during the warmer season. Fish taxa, particularly Poeciliidae, were more prevalent in habitats characterized by normal and good water quality. Canonical correspondence analysis (CCA) revealed that plant communities, temperature, nitrate concentration, and electrical conductivity were the main environmental drivers structuring aquatic communities. Based on integrated physicochemical and biological indicators, water quality was classified as good in the Kafr Saad area and moderately good in the Abu Rawash area. These findings highlight the value of combining aquatic macroinvertebrates and fishes in spatiotemporal biomonitoring frameworks for freshwater quality assessment in the Nile Valley.

Keywords Aquatic macroinvertebrates, Biodiversity, Bioindicators, Physicochemical parameters

Freshwater is an important natural resource that supports human societies and ecosystems all over the world[1]. In Egypt, the Nile River and its tributaries play a central role in supporting agriculture, industry, fisheries,

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hydropower generation, and domestic activities, making freshwater availability and quality critical for socioeconomic stability and public health[2,3]. However, increasing population pressure, urban expansion, and agricultural intensification have led to the degradation of freshwater resources through untreated wastewater discharge, agricultural runoff, and industrial effluents, posing a major environmental challenge, particularly in developing countries[4–7].

To better understand these environmental challenges within a real-world context, the present study focuses on selected freshwater sites located within the Nile Delta and Nile Valley regions in Egypt, which represent one of the most intensively utilized and ecologically stressed freshwater systems in the country. These irrigation and drainage networks represent a unique and ancient anthropogenic ecosystem, where high population density and intensive agriculture create complex stress patterns rarely found in natural riverine systems. These sites are characterized by their direct connection to the Nile River network and are influenced by a combination of natural and anthropogenic factors, including agricultural drainage inputs, domestic wastewater discharge, urban expansion, and industrial effluents. The climate of the region is generally arid to semi-arid, with high temperatures during the summer and limited rainfall, which further intensifies the concentration of pollutants and affects water quality dynamics. Moreover, seasonal fluctuations in temperature and hydrological conditions are expected to play a critical role in shaping water quality and biological responses in these systems, yet such dynamics remain insufficiently explored in many Nile-based studies. The selection of these sites was based on their ecological significance, variation in pollution pressure, and their representation of contrasting environmental conditions ranging from relatively less disturbed locations (e.g., Kafr Saad) to heavily impacted areas (e.g., Abu Rawash). This gradient provides a valuable opportunity to assess how environmental stressors influence aquatic community structure and ecosystem health across spatially varying conditions. In Nile Valley ecosystems, aquatic biodiversity, particularly macroinvertebrates and fish, serves as a critical indicator of environmental shifts and anthropogenic impacts on water quality[8]. Among these groups, macroinvertebrates especially aquatic insects serve as fundamental indicators for ecological health[9–12]. Most contemporary freshwater studies prioritize this group owing to their diverse sensitivity levels to organic pollution and habitat degradation, which allows researchers to assess the ecological health of freshwater systems more effectively[13–15]. These organisms play fundamental roles in freshwater food webs, energy transfer, and nutrient cycling, serving as prey for many aquatic vertebrates and macroinvertebrates and contributing to ecosystem functioning across multiple trophic levels[16–18].

Macroinvertebrates are highly sensitive to alterations in water quality and habitat structure due to their close ecological dependence on specific environmental conditions throughout their life cycles. Consequently, changes in macroinvertebrate community composition, particularly the replacement of pollution-intolerant taxa with more pollution-tolerant species, have been widely recognized as reliable indicators of environmental degradation and anthropogenic disturbance[19,20]. Due to their specialized ecological requirements, aquatic macroinvertebrates, serve as exemplary bioindicators for monitoring habitat integrity and the extent of anthropogenic pressures on freshwater and riverine ecosystems[21,22].

The effectiveness of aquatic macroinvertebrates in biomonitoring programs is further enhanced by their broad geographical distribution, relatively long-life cycles, and well-resolved taxonomy, which collectively enable the detection of both short- and long-term environmental changes. In addition, many taxa, particularly aquatic insects, exhibit species-specific tolerances to physicochemical stressors, making them particularly valuable for diagnosing the type and intensity of environmental stress[23,24].

Aquatic insect communities respond rapidly to changes in physicochemical parameters, especially in environments contaminated with heavy metals, pesticides, and other pollutants that alter water quality[25,26]. As a result, ecological indices such as species richness, diversity, evenness, and abundance have been widely employed to evaluate community structure and habitat integrity. While these metrics provide essential information on biodiversity patterns, their integration with physicochemical water quality parameters and specialized biotic assessments is crucial for a comprehensive evaluation of ecological stress. In this study, these indices were utilized in conjunction with multivariate statistical analyses (e.g., Canonical Correspondence Analysis) to effectively correlate biological assemblages with environmental variables and assess the overall water quality status. Variations in these indices often reflect the degree of environmental disturbance and pollution pressure[27–29]. Ecosystems subjected to frequent disturbances, chemical contamination, or reduced habitat heterogeneity typically exhibit lower species diversity and a simplified community structure dominated by tolerant taxa[30]. Collectively, these characteristics point out the importance of aquatic insects as sensitive and cost-effective bioindicators for assessing freshwater ecosystem health and guiding environmental management and conservation strategies.

Previous studies have demonstrated strong relationships between aquatic insect distribution and habitat characteristics across different freshwater systems. For example, Hofmann and Mason[31] and Butler and Demaynadier[32] highlighted the influence of environmental variables and habitat integrity on dragonfly assemblages Specifically, these studies demonstrated that factors such as water temperature, dissolved oxygen levels, and the complexity of aquatic vegetation significantly dictate species distribution. They observed that habitat degradation and alterations in flow regimes led to a decline in specialist species, thereby emphasizing the value of aquatic insects as sensitive indicators of ecological health in riverine and lake ecosystems. Similar patterns have been documented in both tropical and temperate freshwater ecosystems, emphasizing the general applicability of these ecological responses across different environmental contexts.

Freshwater ecosystems are subjected to multiple pollution sources, including agricultural runoff, wastewater discharge, and various chemical contaminants such as heavy metals.[33,34]. Heavy metals originate from multiple anthropogenic sources, including industrial discharges, urban runoff, antifouling coatings, and atmospheric deposition, and tend to persist in aquatic environments due to their non-biodegradable nature[35,36]. As a result, changes in physicochemical water properties associated with anthropogenic activities can significantly influence the structure and functioning of aquatic communities.

Changes in physicochemical parameters, like temperature, dissolved oxygen, nutrient levels, and conductivity, have a direct impact on the distribution and number of aquatic organisms. This includes invertebrate communities that are very sensitive to changes in the environment[13,37]. Integrating physicochemical measurements with biological indicators provides a robust framework for evaluating freshwater ecosystem conditions.

Fish communities also respond to environmental degradation and have been widely recognized as effective bioindicators due to their sensitivity to water quality changes and their capacity to accumulate contaminants[38]. Physiological and morphological responses in fish populations reflect habitat quality across spatial scales, supporting their complementary use alongside aquatic macroinvertebrates in freshwater monitoring and management programs. Importantly, fish communities often integrate longer-term environmental changes, whereas macroinvertebrates can reflect more immediate and localized responses, making their combined use particularly valuable in spatiotemporal assessments.

In this study, water quality assessment is based on an integrated ecological framework that combines physicochemical measurements, community-based diversity indices, and multivariate statistical analysis (CCA). This approach allows for a comprehensive evaluation of environmental conditions by linking biological responses to specific physicochemical gradients, providing a more robust and context-specific assessment compared to the use of single biotic indices alone. Despite the ecological importance of the Nile River system and its associated freshwater branches, systematic ecosystem-based management frameworks and long-term biomonitoring programs remain largely underdeveloped or inconsistently implemented in many affected regions. Integrated assessments that concurrently amalgamate physicochemical parameters with multi-trophic biological indicators, such as aquatic macroinvertebrates and fish communities, remain limited in numerous regions of the Nile Delta and Valley. Furthermore, most previous studies have focused primarily on spatial variation, while seasonal dynamics remain underrepresented, despite their ecological significance. This lack of coordinated monitoring approaches limits the ability to accurately diagnose ecological status, track environmental change, and support evidence-based management decisions. Therefore, there is a clear need for comprehensive baseline studies that integrate biological and physicochemical assessments to fill this knowledge gap and support future conservation and management strategies.). The selection of Kafr Saad and Abu Rawash as study sites presents a typical contrast in aquatic ecosystems in the Nile Delta and its valley, reflecting different human pressures. Kafr Saad represents a predominantly agricultural system, while Abu Rawash reflects combined agricultural, domestic, and industrial impacts. This spatial contrast, when coupled with seasonal variability, provides a robust framework for disentangling the relative influence of environmental gradients and temporal dynamics on aquatic communities. Accordingly, this study was designed to achieve the following objectives: (a) to assess the spatial and seasonal variation in macroinvertebrate and aquatic fish populations in selected freshwater habitats in the Nile Valley; (b) to evaluate the relationship between the physical and chemical properties of the water and the structure of aquatic communities; (c) to determine the effectiveness of incorporating macroinvertebrates and fish as complementary bioindicators of water quality. Based on these objectives, the study tested the following hypotheses: (1) the composition and diversity of aquatic communities are significantly influenced by seasonal variations and environmental gradients; (2) key physical and chemical properties, particularly water temperature, nitrate concentration, and electrical conductivity, are key factors in shaping community structure; (3) sites with better water quality support higher biodiversity and a greater proportion of pollution-sensitive species compared to more affected sites.

Materials and methods

Ethical approval and sampling permits

All water-sampling activities were carried out in accordance with the national regulations and guidelines governing water resources and environmental protection in Egypt, under the supervision of the relevant local authorities and in alignment with the policies of the Ministry of Water Resources and Irrigation (MWRI) and the Egyptian Environmental Affairs Agency (EEAA). All experimental protocols were reviewed and approved Ethical committee of the Faculty of Science, Benha University. All methods were carried out in accordance with the relevant guidelines and regulations for the care and use of animals in research.

Study area

The study area is located in the Greater Cairo region, at the interface between the Nile Delta and the southern Nile Valley. The region is generally flat with some hills and valleys, and land use shifts from predominantly agricultural areas in Qalyubiya and Giza Governorates to more arid desert margins toward the outskirts. Climatically, the area is characterized by an arid to semi-arid regime, with mean annual temperatures ranging between 21 and 25 °C and average annual precipitation typically below 50–100 mm, most of which occurs during the winter months. The area extends approximately 120 km east and west of the Nile banks and lies between latitudes 27° 04′ N and 03° 03′ N and longitudes 27° 02′ E and 31° 55′ E.The study was conducted at two contrasting freshwater sites. The Kafr Saad area located approximately 55 km northeast of Cairo within the Qalyubiya Governorate (30°28′59″N, 31°11′40″E), represents a predominantly agricultural area characterized by fertile sandy clay soils and extensive irrigation networks. The area contains multiple freshwater habitats, including canals, ditches, drainage channels, ponds, and marshy areas associated with agricultural activities. Seasonal water stagnation, particularly during winter, is common due to agricultural drainage and prolonged irrigation periods.

The Abu Rawash area, which is about 10 km southwest of Cairo in Giza Governorate (30°04′16″N, 31°04′30″E), is a semi-arid desert. The area is on a limestone plateau that formed during the Cretaceous period. It gets water from the Nile's tributaries, irrigation canals, and underground wells. The area lacks a modern sewage network and is influenced by nearby industrial activities, despite the presence of a wastewater treatment facility. These characteristics contribute to contrasting environmental conditions between the two studies (Fig. 1).

Sampling design

Sampling was conducted in two geographically distinct areas, Kafr Saad and Abu Rawash, focusing on small-scale freshwater microhabitats including : canals, defined here as primary or secondary permanent waterways with a wider cross-section and managed flow, and irrigation channels, which refer to the smaller tertiary distributaries (locally known as mesqas) that deliver water directly to individual farm plots and often exhibit intermittent flow. These were further compared alongside agricultural drains, designed to collect excess irrigation runoff, and stagnant pools. These habitats are characterized by shallow, slow-moving or stagnant waters, often influenced by agricultural runoff and varying levels of anthropogenic activity. A hierarchical sampling design was implemented, utilizing sixteen sites in total, with eight sites distributed within each study area (two sites for each habitat type). To account for seasonal variability, sampling was carried out across two distinct periods in 2024: Spring–Summer and Autumn–Winter. At each site, two independent samples were collected per season to ensure adequate taxonomic representation. To minimize sampling bias, aquatic fauna were captured using a modified D-shaped dip net equipped with a fine-mesh lining, specifically designed to retain smaller invertebrates and small-bodied fish. For statistical purposes, each sampling site was treated as an independent experimental unit, while the two samples per site served as technical replicates. This design yielded a total of 32 sampling units (16 sites × 2 seasons), providing a robust baseline for analyzing the community structure across these diverse aquatic environments. Mean values for all physicochemical parameters and biotic indices were calculated separately for each sampling season (Spring–Summer and Autumn–Winter 2024) to capture temporal variations. For comparative purposes between study areas, grand means across both seasons were also reported where indicated, accompanied by their respective Standard Deviations (± SD) 2).

Physicochemical water parameters

Water samples were collected simultaneously from the same four fixed sampling sites (canals, drains, streams, and pools) where mosquito larvae were obtained, ensuring direct correspondence between physicochemical parameters and biological data. Sampling was conducted during the spring–summer and autumn–winter of

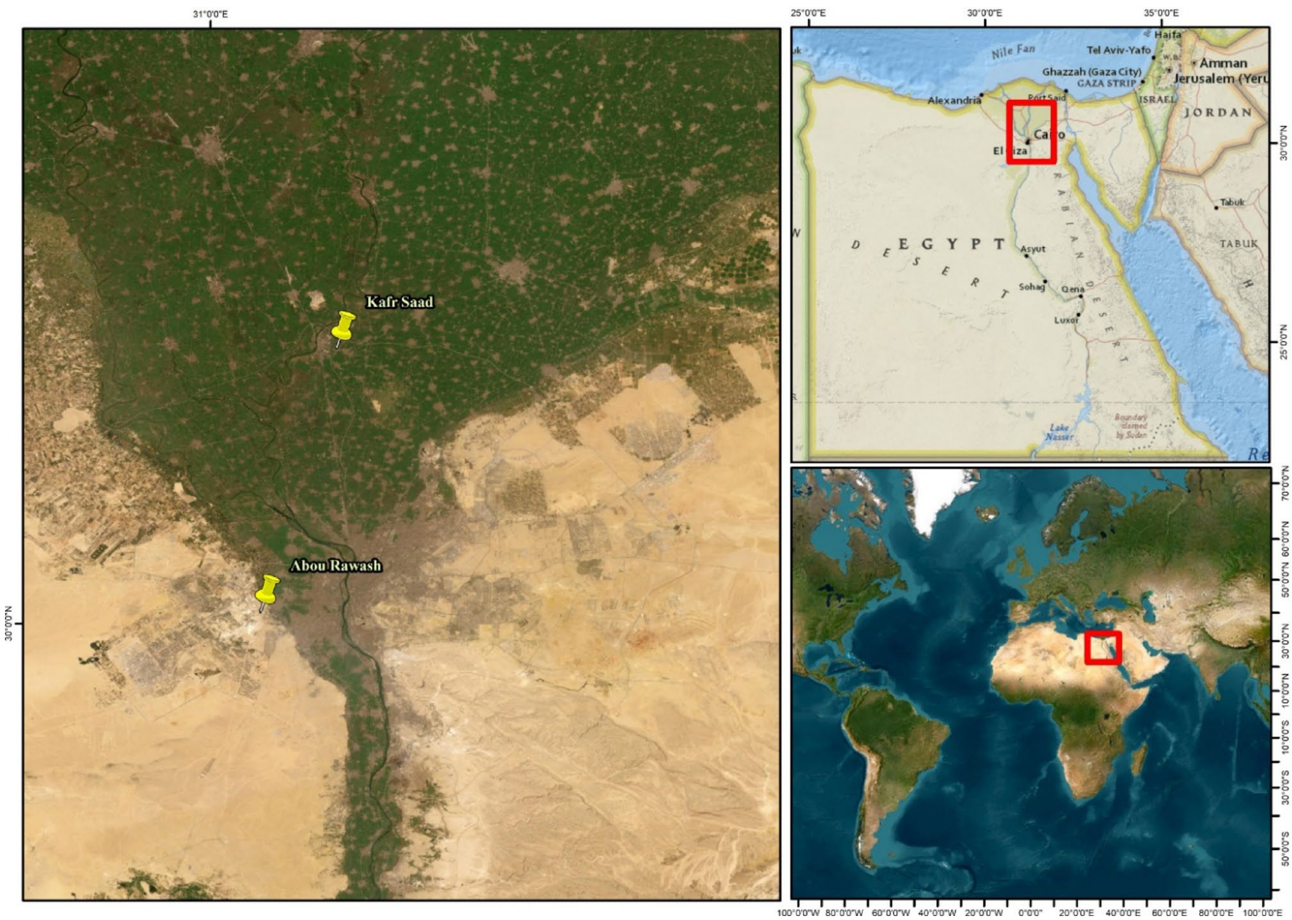

Fig. 1. A map of the study area at Qalyubiya and Giza Governorates, Egypt. The map was generated by the authors using ArcMap software version 10.8 (Esri, Redlands, CA, USA; https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview (esri.com in Bing)).

2024. Collected water samples were placed in labeled 150-mL plastic containers that had been pre-rinsed with nitric acid to eliminate potential contamination. Samples were transported to the laboratory in an insulated cooler and analyzed immediately to determine their physicochemical properties.

Water temperature (°C) was measured in situ using a mercury thermometer (0–100 °C). pH was measured using a portable pH meter (Hanna HI98150). Dissolved oxygen (DO, mg/L), total dissolved solids (TDS, ppt), turbidity (NTU), and electrical conductivity (μS/cm) were measured using calibrated portable meters, including a DO meter, TDS meter, turbidity meter, and conductometer (EC LYTIC-AQUA), respectively. Chemical variables, including ammonia (NH_3) and nitrate (NO_3), were determined colorimetrically using a UV–visible spectrophotometer (Lambda EZ201) according to the Standard Methods for the Examination of Water and Wastewater.

Aquatic macrophytes present along the water margins were recorded as an environmental characteristic of the studied habitats. Macrophytes were classified into three functional groups: floating-leaved, emergent, and submerged plants, following Ameka and Ernest[39].

All physicochemical measurements were conducted following standard environmental monitoring protocols using calibrated instruments. A summary of all measured environmental variables and their units is provided in Table 1. Laboratory analyses were performed at the National Water Research Center, Qanater El-Khairia, Egypt.

Sampling and identification of aquatic macroinvertebrates and fishes

Aquatic macroinvertebrates and fishes were sampled during two seasonal periods in 2024: spring–summer (5 April–29 July) and autumn–winter (2 October–27 February) to assess seasonal variation in aquatic community composition. Sampling was conducted using a D-shaped dip net (33 cm width, 0.8 mm mesh size), which was slightly modified by inserting a finer-mesh lining inside the primary net to enhance the capture efficiency of smaller specimens. At each sampling location, the net was towed for approximately 1 m along the water margin to standardize sampling effort across sites and seasons. This sampling technique was deemed effective and sufficient due to the nature of the habitats, which primarily consisted of narrow canals, shallow drains, and confined pools. In such restricted environments, the mobility of aquatic fauna, including small-sized fish, is relatively limited, allowing for representative collection.

Upon collection, all macroinvertebrate specimens were thoroughly sorted from debris in the field and preserved in 70% ethanol. Samples were then transported to the laboratory for taxonomic identification and authentication by Prof. Dr. Yasser Afifi El-Sayed, Professor of Taxonomy, Benha University, using standard morphological keys. Aquatic macroinvertebrates were identified following Ebrahim and Salem[40], Azari-Hamidian and Harbach[41], Bybee, et al.[42] and Thomson[43]. Fish taxa were identified according to Carella, et al.[44]. In this study, water quality assessment is based on an integrated ecological framework that combines physicochemical measurements, community-based diversity indices, and multivariate statistical analysis (CCA). This approach allows for a comprehensive evaluation of environmental conditions by linking biological responses to specific physicochemical gradients, providing a more robust and context-specific assessment compared to the use of single biotic indices alone.

Statistical analysis

Statistical analyses were performed using SPSS software (version 23; IBM Corp., USA). Differences in physicochemical parameters and biological variables among sampling sites and seasons were analyzed using two-way analysis of variance (two-way ANOVA), with habitat/site and season as fixed factors. When significant effects were detected, Tukey's HSD post hoc test was applied to identify pairwise differences among means. Statistical significance was accepted at $P < 0.05$. To evaluate community responses to environmental gradients, an integrated ecological approach was applied, combining diversity indices and multivariate analysis rather than relying on fixed biotic indices (e.g., ASPT or BMWP). Specifically, the Shannon–Wiener index (H'), Simpson dominance index (D), and Pielou's evenness index (J) were calculated using PAST software to characterize the structural diversity of the aquatic communities. This approach is better suited to reflect the ecological dynamics of the Nile Valley's unique environmental conditions and allows for a more flexible interpretation of biological responses to specific stressors, such as pollution or habitat alteration, which can vary significantly across different areas of the valley. Multivariate statistical analyses were conducted using PAST software to examine relationships between aquatic insect community composition and environmental variables. Canonical Correspondence Analysis (CCA) was applied using sampling sites as independent units of replication. The analysis was based

Equipment	Analytical method	Unit	Parameter
Mercury thermometer (0–100 °C)	In situ measurement	°C	Water Temperature
Portable pH meter (Hanna HI98150)	In situ measurement	-	pH Value
Calibrated portable DO meter	In situ measurement	mg/L	Dissolved Oxygen (DO)
Calibrated portable TDS meter	In situ measurement	ppt	Total Dissolved Solids (TDS)
Calibrated portable turbidity meter	In situ measurement	NTU	Turbidity
Conductometer (EC LYTIC-AQUA)	Conductometric in lab.	μS/cm	Electrical Conductivity (EC)
UV–Vis Spectrophotometer (Lambda EZ201)	Colorimetric in lab.	mg/L	Ammonia (NH_3)
UV–Vis Spectrophotometer (Lambda EZ201)	Colorimetric in lab.	mg/L	Nitrate (NO_3)

Table 1. Equipment used in the physicochemical water quality parameters.

on 16 sampling sites, each sampled across two seasons, resulting in a total sample size of $n = 32$ sampling units (sites × seasons), in accordance with established ecological multivariate analysis protocols[45,46]. The classification of taxa into pollution-tolerant and pollution-sensitive groups was based on previously published ecological tolerance values reported in the literature, rather than on a single standardized biotic index. This ensures that ecological interpretations are grounded in established biomonitoring knowledge while remaining adaptable to local environmental conditions.

Results

Spatial and seasonal variation of aquatic fauna

A total of 4158 aquatic organisms were recorded from Kafr Saad (Qalyubiya Governorate), while 3848 organisms were collected from Abu Rawash (Giza Governorate) across four freshwater habitat types: ditches, canals, irrigation channels, and pools (Table 2; Fig. 2). The recorded fauna comprised 11 orders and 30 families, including aquatic macroinvertebrates (insects, crustaceans), and fishes.

. The analysis of the aquatic community structure showed a clear numerical disparity between the studied groups. Aquatic invertebrates exhibited a marked dominance, accounting for 90.8% and 96.7% ($n = 3776$ and 3721) of the total recorded organisms, whereas fish taxa represented only 9.2% and 3.3% ($n = 382$ and 127) in Kafr Saad and Abu Rawash, respectively. This quantitative distribution provides a baseline for the taxonomic richness and community composition in the habitats of Kafr Saad and Abu Rawash.Diptera represented the

		Kafr Saad					Abu Rawash				
Order	**Family**	**Ditch**	**Canal**	**Ir. channel**	**Pool**	**Total***	**Ditch**	**Canal**	**Ir. channel**	**Pool**	**Total**
I. Aquatic insects											
Diptera	Culicidae	370	115	155	240	880 (21.2)	650	150	210	370	1380 (35.9)
	Chironomidae	33	66	45	25	169 (4.1)	4	21	20	9	54 (1.4)
	Stratiomyidae	7	0	2	1	10 (0.2)	98	32	66	78	274 (7.1)
	Syrphidae	8	0	1	2	11 (0.3)	66	18	45	75	204 (5.3)
	Tabanidae	2	3	4	8	17 (0.4)	24	8	19	15	66 (1.7)
	Ephydridae	16	2	9	13	40 (1.0)	106	52	65	87	310 (8.1)
	Tipulidae	5	2	11	4	22 (0.5)	21	9	12	14	56 (1.5)
	Psychodidae	11	0	0	5	16 (0.4)	14	3	15	28	60 (1.6)
Coleoptera	Dytiscidae	56	14	25	33	128 (3.1)	120	75	32	85	312 (8.1)
	Gyrinidae	41	65	24	71	201 (4.8)	0	2	7	0	9 (0.2)
	Hydrophilidae	10	12	7	11	40 (1.0)	75	55	40	22	192 (5.0)
	Hydroscaphidae	2	5	2	6	15 (0.4)	0	1	0	0	1 (0.03)
Collembola	Entomobryidae	3	2	5	2	12 (0.3)	1	0	0	0	1 (0.03)
	Poduridae	1	1	0	0	2 (0.05)	0	0	0	0	0
Hemiptera	Notonectidae	88	65	77	45	275 (6.6)	7	5	6	12	30 (0.8)
	Corixidae	66	75	120	57	318 (7.6)	11	5	25	2	43 (1.1)
	Blestomatidae	55	26	32	55	168 (4.0)	76	73	90	86	325 (8.4)
	Nepidae	4	2	13	5	24 (0.6)	1	0	2	5	8 (0.2)
	Gerridae	53	70	35	45	203 (4.9)	30	12	9	19	70 (1.8)
	Veliidae	1	3	1	5	10 (0.2)	0	2	0	3	5 (0.1)
Odonata	Coenagrionidae	28	23	63	15	129 (3.1)	5	7	24	15	51 (1.3)
	Libellulidae	43	13	25	14	95 (2.3)	6	3	11	3	23 (0.6)
	Agrionidae	13	5	9	11	38 (0.9)	5	6	2	1	14 (0.4)
	Aeshnidae	7	3	9	3	22 (0.5)	3	2	1	5	11 (0.3)
Trichoptera	Hydroptilidae	0	2	0	0	2 (0.05)	0	0	0	0	0 (0.0)
Ephemeroptera	Ephemeridae	25	12	75	24	136 (3.3)	11	2	5	9	27 (0.7)
II. Other macroinvertebrates											
Decapoda	Cambaridae	19	112	55	2	188 (4.5)	2	51	19	0	72 (1.9)
Diplostraca	Daphniidae	250	120	180	55	605 (14.6)	0	35	88	0	123 (3.2)
III. Fishes											
Perciformes	Cichlidae	6	17	25	0	48 (1.2)	0	2	0	0	2 (0.1)
Cyprinodontiformes	Poeciliidae	35	210	89	0	334 (8.0)	0	90	35	0	125 (3.2)

Table 2. Taxonomic composition, total abundance (N), and relative frequency (%) of aquatic fauna collected across standardized micro-habitats in Kafr Saad and Abu Rawash during 2024. *: N represents the absolute abundance (total number of individuals), while values in parentheses indicate the relative percentage of each family calculated against the total number of organisms within the respective study area (Kafr Saad or Abu Rawash).

Fig. 2. Aquatic fauna habitats surveyed in Kafr Saad (**a**–**f**) and Abu Rawash areas (**g**–**l**). Photographs in Fig. 2 were taken by the authors (Mohamed Baz).

most diverse and abundant order, followed by Hemiptera and Coleoptera, whereas Odonata, Ephemeroptera, Trichoptera, Diplostraca, and Decapoda occurred at comparatively lower frequencies (Table 2). Fish assemblages were mainly represented by Cyprinodontiformes (Poeciliidae) and, to a lesser extent, Perciformes (Cichlidae).

Marked spatial differences in community composition were observed between the two study areas. Kafr Saad was characterized by a higher occurrence of relatively pollution sensitive taxa, whereas Abu Rawash showed greater dominance of pollution sensitive families, particularly within Diptera (Table 2; Figs. 3 and 4a–f). Seasonal variation in abundance and taxonomic composition was evident across all habitats, with notable shifts between spring–summer and autumn–winter seasons (Fig. 5). At the family level, Culicidae was the most widespread and abundant taxon in both areas, accounting for the highest relative abundance across habitats (Table 2; Fig. 5). Families such as Stratiomyidae, Syrphidae, and Ephydridae were more prevalent in Abu Rawash, while Chironomidae, Coenagrionidae, Daphniidae, and Poeciliidae occurred at higher frequencies in Kafr Saad (Table 2; Figs. 3 and 4).

Two-way ANOVA revealed that season exerted a highly significant effect on aquatic faunal densities ($F = 20.92$, $P < 0.001$), whereas no significant differences were detected among sampling sites ($P = 0.795$). The

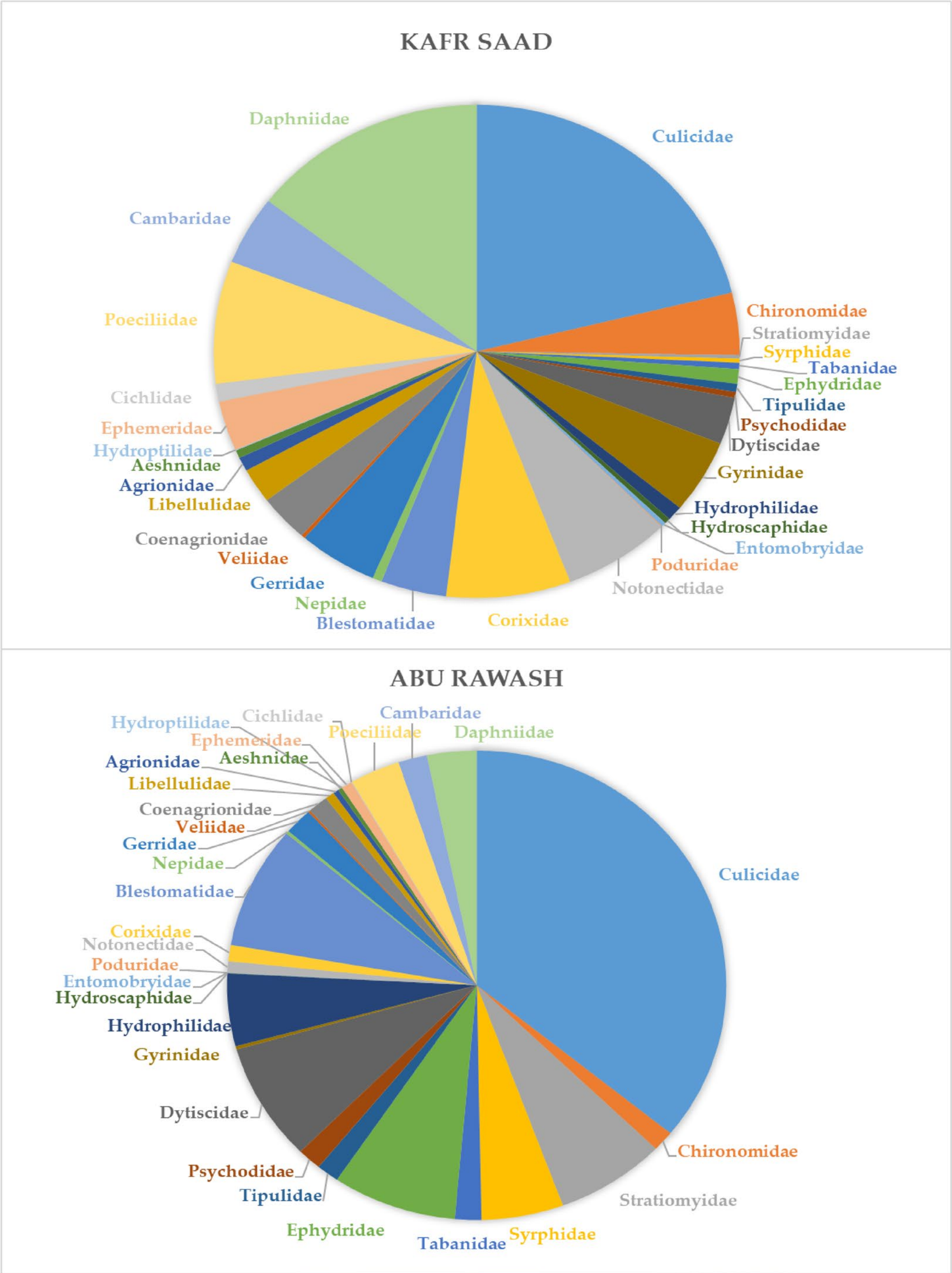

Fig. 3. Families' richness of the aquatic fauna orders during the study period in Kafr Saad and Abu Rawash areas.

interaction between site and season was also non-significant ($P > 0.05$), indicating a consistent seasonal pattern across all study areas. While individual water parameters did not show significant independent effects ($P > 0.05$), aquatic vegetation exhibited a marginal effect on faunal densities ($P = 0.058$).

Diversity patterns of aquatic communities across habitats and sites

A marked spatial variation in aquatic fauna diversity was observed across the studied habitats. Data showed that a clear spatial variation in aquatic community diversity was observed between Kafr Saad and Abu Rawash. Species richness, Shannon–Wiener, and evenness indices were consistently higher in Kafr Saad, particularly within irrigation canals and ditches (H′ = 2.57–2.71) (Fig. 6b,c,e). In contrast, Abu Rawash exhibited lower richness and evenness values, accompanied by higher dominance (Simpson index), indicating a simplified community

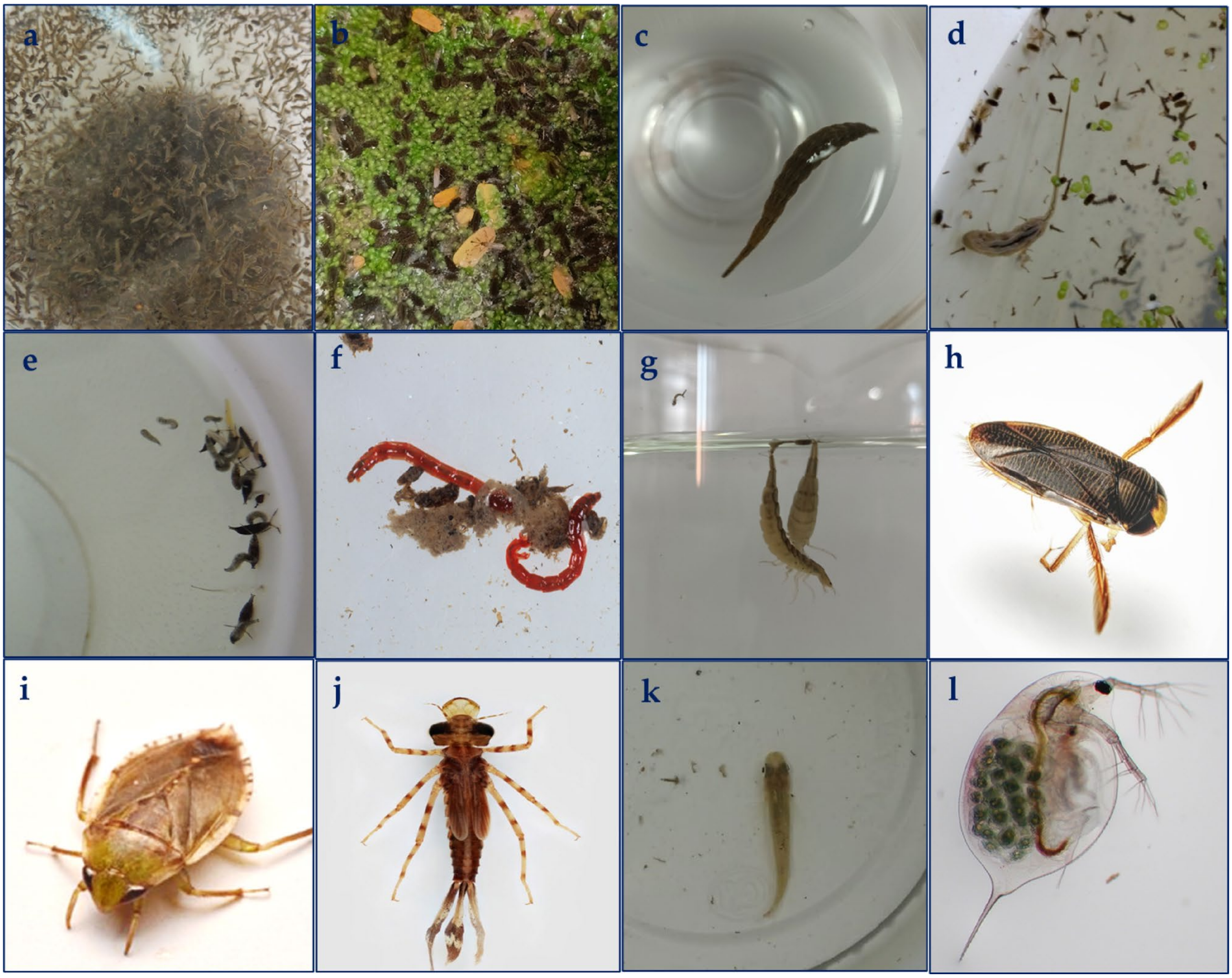

Fig. 4. Dominant types of aquatic fauna collected from Kafr Saad and Abu Rawash areas. (**f**, **h**, **i**, **j**, and **l** are taken from https://upload.wikimedia.org).

structure in several habitats (Fig. 6d,f). Radar charts further illustrated broader taxonomic expansion in Kafr Saad compared to the more constricted diversity profiles observed in Abu Rawash (Fig. 3).

Two-way ANOVA confirmed that diversity patterns were significantly influenced by seasonal variation ($P < 0.001$), while spatial differences between areas were less pronounced (Table 2). Correlation analyses showed positive relationships between diversity indices and selected physicochemical parameters, including water temperature and nitrate concentration (Table 3).

Influence of physicochemical variables on aquatic fauna

Physicochemical characteristics differed significantly between sites and seasons (Table 3). Kafr Saad generally exhibited lower salinity, electrical conductivity, turbidity, and ammonia levels compared to Abu Rawash, which showed elevated values across most habitats.

Correlation and regression analyses demonstrated that water temperature, nitrate concentration, electrical conductivity, and turbidity were significant predictors of aquatic faunal abundance (Table 4). Temperature and nitrate concentration showed strong positive correlations with faunal density, whereas pH and ammonia exhibited negative relationships. Spider diagrams (Fig. 7) illustrated distinct physicochemical signatures, where Kafr Saad exhibited higher variability across multiple parameters, resulting in a broader profile, whereas Abu Rawash showed more stabilized and lower concentrations, leading to a more constrained profile. Seasonal peaks in faunal abundance coincided with higher water temperatures during the warm season (Table 2; Fig. 5).

Multivariate associations between environmental factors and aquatic communities

Canonical Correspondence Analysis (CCA) revealed strong associations between aquatic community composition and environmental gradients (Fig. 8). The first two ordination axes explained the majority of constrained variation, clearly separating sampling sites according to season, water temperature, nitrate concentration, and electrical conductivity. Sampling sites were primarily grouped by season, indicating a pronounced seasonal influence on community structure. In Kafr Saad, several aquatic invertebrate families were

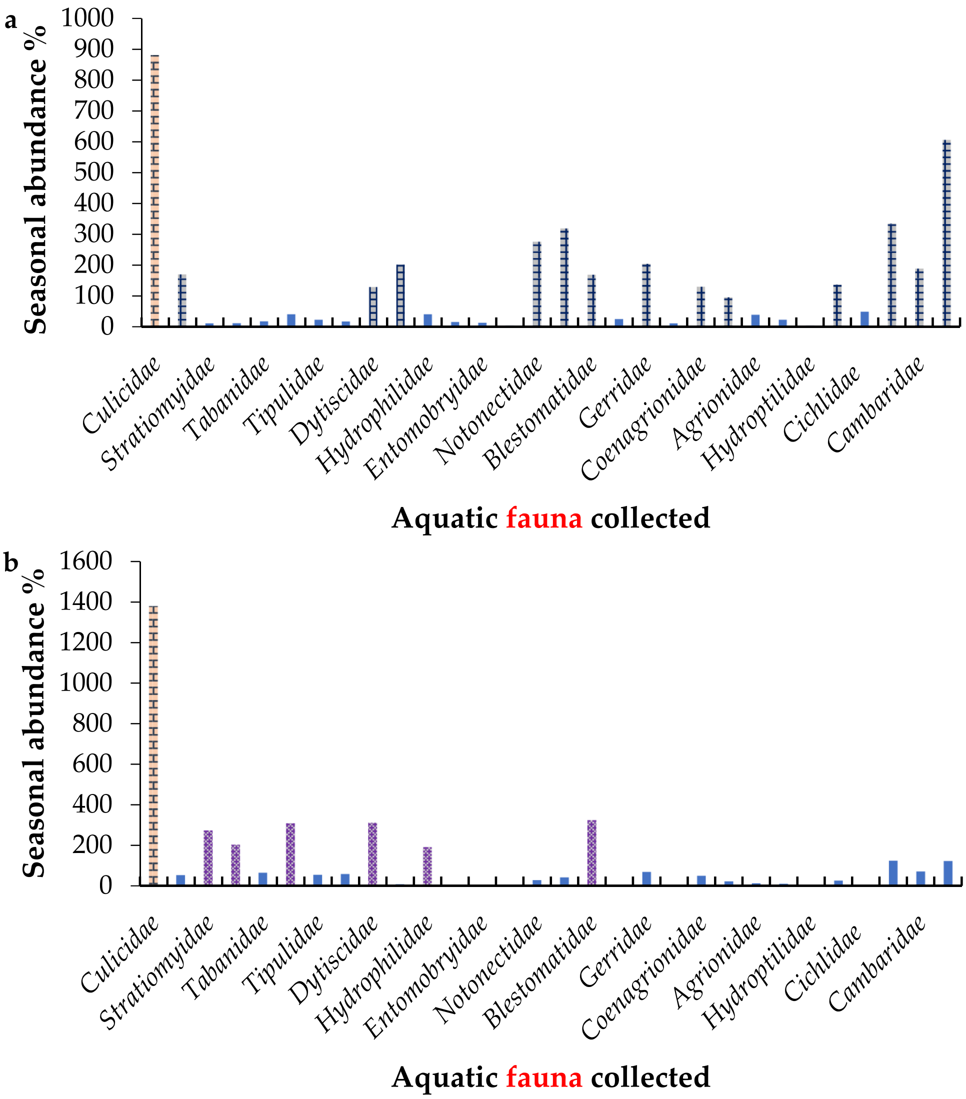

Fig. 5. Comparative seasonal abundance (%) of aquatic fauna collected from Kafr Saad (**a**) and Abu Rawash (**b**) during the two seasons (spring–summer and autumn–winter 2024).

closely associated with vegetated habitats across ditches, canals, and pools (Fig. 8a). In contrast, communities in Abu Rawash exhibited stronger associations with specific habitat types and physicochemical conditions, reflecting spatial heterogeneity in water quality (Fig. 8b).

Overall, the CCA results demonstrate that seasonal variability and key physicochemical parameters jointly structure the distribution and assemblage patterns of aquatic macroinvertebrates and fishes across the studied freshwater habitats.

Discussion

The present study revealed a distinct aquatic community structure in the freshwater habitats of Kafr Saad and Abu Rawash, characterized by a significant numerical dominance of macroinvertebrates (over 90%) compared to fish taxa. The fauna was represented by three major groups: aquatic insects, other macroinvertebrates, and opportunistic fish species, primarily from the Poeciliidae and Cichlidae families. These results demonstrate how water quality and specific habitat features directly shape the composition of freshwater ecosystems.[47]. Specifically,, data revealed clear differences in the aquatic taxa (macroinvertebrates and fish) between the Kafr Saad and Abu Rawash areas, highlighting how water quality and environmental pressures affect biotic communities. The greater variety of species, the number of different types, and the presence of species that cannot tolerate pollution in Kafr Saad suggest that the environmental conditions there are better than those in Abu Rawash. These findings align with recent assessments of Egyptian freshwater habitats, which demonstrated that anthropogenic pressures significantly shift community composition from sensitive to tolerant taxa (Halmy, 2019).

Differences in the aquatic community composition (comprising both macroinvertebrates and fish) were closely associated with key physicochemical factors, including water temperature, dissolved oxygen, nutrient concentrations, electrical conductivity, substrate type, and salinity-related parameters. Similar spatial

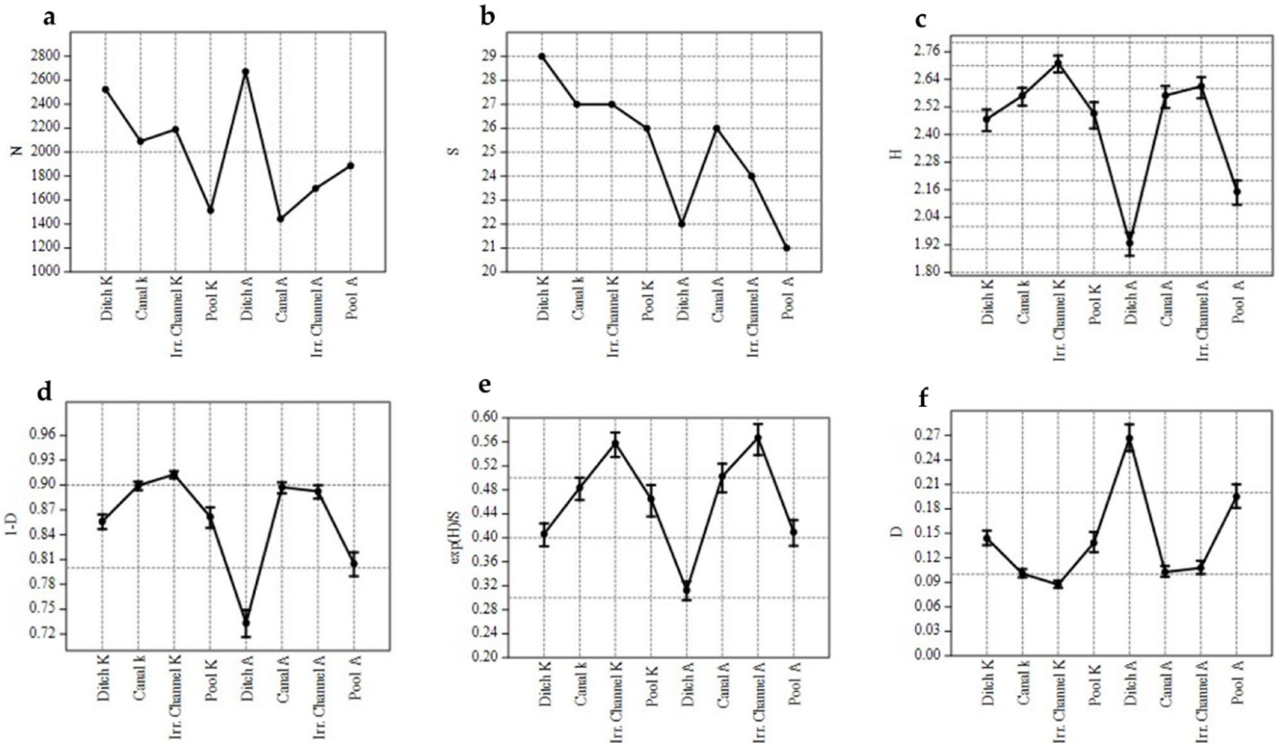

Fig. 6. Diversity indices and taxonomic richness of aquatic communities in the study areas: (**a**) Abundance, (**b**) Richness, (**c**) Shannon–Weiner index, (**d**) Simpson index, (**e**) Evenness, and (**f**) Dominance.

heterogeneity was reported in recent studies on the Nile Delta, where dissolved oxygen and nutrient loading were identified as the primary determinants of macroinvertebrate distribution (Hegab et al., 2025). Habitats characterized by better water quality and greater structural complexity, particularly irrigation canals and channels in Kafr Saad, supported higher species richness and more balanced community structure. On the other hand, areas with more nutrients and organic matter had simpler groups of species mainly made up of those that can survive pollution.

Diptera represented the most dominant and widely distributed order across all habitats, reflecting the high ecological plasticity of this group and its capacity to exploit a broad range of environmental conditions[48,49]. This dominance is a common feature in disturbed freshwater ecosystems globally, as seen in recent studies where dipterans effectively colonized habitats with high organic loading (Dijkstra Akinpelu et al., 2024). However, marked differences were evident in the relative abundance of dipteran families between the two study areas. Pollution-tolerant families such as Ephydridae, Syrphidae, and Psychodidae were more prevalent in Abu Rawash, particularly in ponds and ditches characterized by elevated organic matter. This pattern is consistent with their documented association with organically enriched and polluted aquatic environments[19,50]. The dominance of Ephydridae, Syrphidae, and Psychodidae in Abu Rawash sites is attributed to their specialized respiratory mechanisms (e.g., telescopic siphons), which provide a competitive advantage in hypoxic conditions resulting from high organic pollution[51].

In contrast, Kafr Saad had more pollution-sensitive and moderately sensitive groups, including Hemiptera (Notonectidae, Gerridae, and Corixidae), Ephemeroptera. The classification of these taxa as pollution-sensitive is based on their physiological requirement for high dissolved oxygen (DO) and their low tolerance for organic enrichment, as established in the Hilsenhoff Biotic Index (HBI) and ASPT scoring systems. Our findings underscore a clear ecological partitioning of aquatic taxa driven by localized habitat quality. While the high organic enrichment and dense macrophyte cover in drains and pools favored the proliferation of tolerant Dipteran assemblages, a contrasting pattern was observed in canals and irrigation channels. These lotic environments, characterized by higher dissolved oxygen (DO) concentrations and reduced anthropogenic pollution, served as refugia for sensitive taxa that require cleaner water conditions. This shift in community structure highlights the role of vegetation as both a bio-filter and a structural niche, where the interplay between nutrient availability and oxygen levels dictates the micro-spatial distribution of fauna. Such qualitative distinctions in taxonomic composition, despite the overall quantitative similarity between Kafr Saad and Abu Rawash, confirm that habitat-specific stressors are the primary drivers of biodiversity patterns in these Nile Valley ecosystems.

Fish assemblages further corroborated the observed disparities in environmental quality between the two regions. The higher abundance of fish species, such as *Tilapia zillii* and *Gambusia affinis*, in Kafr Saad suggests that the physicochemical conditions to fish populations. While these species exhibit notable environmental plasticity, their significantly higher density in Kafr Saad is attributed to the presence of dense aquatic macrophytes and favorable water quality (e.g., lower ammonia and higher DO), which support their breeding and foraging

	Temperature (°C)		pH		Ammonia (mg/L)		Nitrate mg/L)		Salinity (ppt)		Dissolved oxygen (ppm)		Electrical conductivity (µS/cm)		Turbidity (NTU)	
	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash	Kafr Saad	Abo Rawash
Ditch	25.00 ± 4.00^{aA}	29.00 ± 4.00^{aA}	7.70 ± 0.10^{bA}	7.00 ± 0.2^{bB}	1.60 ± 0.20^{aB}	3.05 ± 0.15^{aA}	35.00 ± 3.50^{aB}	40.85 ± 2.35^{aA}	116.50 ± 11.50^{aB}	490.00 ± 40.00^{aA}	8.15 ± 0.45^{aB}	5.55 ± 0.95^{cA}	267.00 ± 48.00^{aA}	372.50 ± 57.50^{aA}	15.10 ± 2.60^{aB}	77.30 ± 16.20^{aA}
Canal	22.00 ± 4.00^{aA}	26.50 ± 3.50^{aA}	8.80 ± 0.40^{aA}	7.90 ± 0.30^{aB}	1.00 ± 0.10^{cB}	$2.30d \pm 0.10^{cA}$	26.30 ± 2.30^{bB}	30.55 ± 0.95^{bA}	72.80 ± 6.00^{aB}	350.00 ± 10.00^{bA}	8.70 ± 0.70^{aB}	7.20 ± 0.20^{aA}	206.00 ± 4.00^{aB}	290.00 ± 20.00^{bA}	14.00 ± 0.50^{aB}	61.50 ± 14.00^{aA}
Ir. Channel	21.50 ± 5.50^{aA}	26.50 ± 5.50^{aA}	8.35 ± 0.25^{aA}	7.40 ± 0.20^{abB}	1.05 ± 0.05^{cB}	2.25 ± 0.05^{cA}	21.60 ± 0.30^{cB}	31.50 ± 1.50^{bA}	72.60 ± 2.60^{aB}	315.00 ± 10.00^{bA}	8.50 ± 0.70^{aB}	7.00 ± 0.20^{abA}	204.90 ± 15.10^{aB}	292.80 ± 12.20^{bA}	15.75 ± 0.95^{aB}	61.60 ± 16.40^{aA}
Pool	24.00 ± 7.00^{aA}	29.00 ± 7.00^{aA}	7.60 ± 0.10^{bA}	6.95 ± 0.15^{bB}	1.30 ± 0.10^{bB}	2.65 ± 0.15^{bA}	30.50 ± 2.30^{abB}	35.10 ± 1.70^{bA}	83.40 ± 2.20^{aB}	340.00 ± 35.00^{bA}	7.65 ± 0.15^{aB}	5.95 ± 0.35^{bcA}	246.30 ± 31.70^{aB}	345.00 ± 30.00^{abA}	15.30 ± 0.50^{aB}	69.70 ± 18.50^{aA}
Mean	23.13 ± 2.07^{A}	27.75 ± 2.02^{A}	8.11 ± 0.21^{A}	7.31 ± 0.17^{B}	1.24 ± 0.10^{B}	2.56 ± 0.13^{A}	23.60 ± 4.81^{B}	34.50 ± 1.66^{A}	86.33 ± 7.25^{B}	373.75 ± 27.83^{A}	8.25 ± 0.26^{B}	6.43 ± 0.33^{A}	231.05 ± 15.11^{B}	325.08 ± 18.59^{A}	15.04 ± 0.59^{B}	67.53 ± 6.66^{A}
	Site		Site		Site		Site		Site		Site		Site		Site	
F-value	1.561	0.172	23.540	9.264	234.083	13.833	55.124	36.687	412.441	12.243	23.069	2.475	17.026	2.442	40.897	0.222
P-value	0.246	0.612	0.001	0.006	0.000	0.002	0.000	0.000	0.000	0.002	0.001	0.136	0.003	0.139	0.000	0.878
LSD	12.06	8.14	0.54	0.36	0.28	0.19	4.79	3.23	46.15	31.15	1.24	0.84	74.31	50.15	26.77	18.06

Table 3. Mean values (± SD) of physicochemical water quality parameters recorded in Kafr Saad and Abu Rawash during the study period (2024). a, b & c: There is no significant difference ($P > 0.05$) between any two means, within the same column have the same superscript letter. A, B & C: There is no significant difference ($P > 0.05$) between any two means for each parameter, within the same row have the same superscript letter; DO, Dissolved oxygen; E.C.: Electrical conductivity; Turb.: Turbidity; 1: Kevin et al. (2016). * Average value of parameters. a, b, c; no significant difference ($P > 0.05$) between any two means with the same superscript letter within the same column. DO, Dissolved oxygen; E.C.: Electrical conductivity; Turb.: Turbidity

Predictor	Correlation	Simple regression			Multiple regression values				
Variable	r	β	*P*	R^2	β	*P*	F value	*P*	R^2
Temperature	0.912**	154.246	0.001	0.913	111.530	0.024	166.459	0.004	0.889
pH	-0.914**	-810.50	0.001	0.792	150.578	0.377			
Ammonia	-0.904**	-922.50	0.678	0.678	122.539	0.455			
Nitrate	0.811**	134.232	0.001	0.987	123.231	0.004			
Salinity	0.950**	5.206	0.231	0.942	0.724	0.374			
Dissolved oxygen	0.136	90.542	0.748	0.012	28.594	0.417			
Electrical conductivity	0.960**	4.216	0.001	0.932	0.874	0.006			
Turbidity	0.971**	5.206	0.001	0.932	0.874	0.013			

Table 4. Simple and multiple correlation and regression models relating water conditions to aquatic fauna densities in breeding habitats in the Kafr Saad and Abu Rawash areas. * Correlation is significant at the 0.05 level (2-tailed);.** Correlation is significant at the 0.01 level (2-tailed).

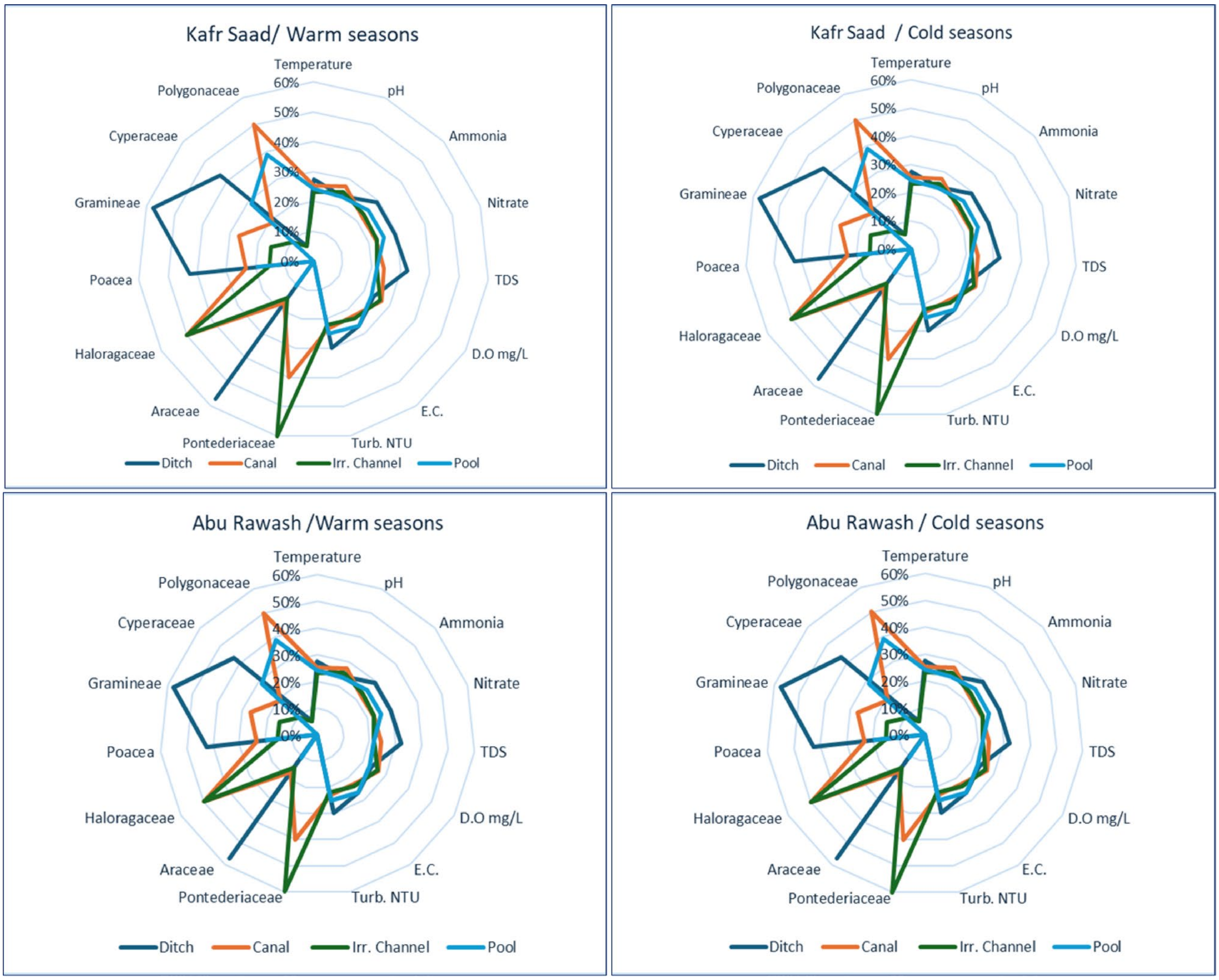

Fig. 7. Spider diagram of water quality and plant habitat correlations in Abu Rawash and Kafr Saad during warm and cold seasons.

activities more effectively than the degraded habitats of Abu Rawash[52]. Furthermore, fish are highly sensitive to fluctuations in water quality; factors such as hypoxia, nutrient enrichment, and chemical pollutants can severely impair their growth, reproduction, and immune systems[53]. Consequently, the reduced abundance or absence of fish in Abu Rawash reflects cumulative environmental stress associated with organic loading and anthropogenic contamination.

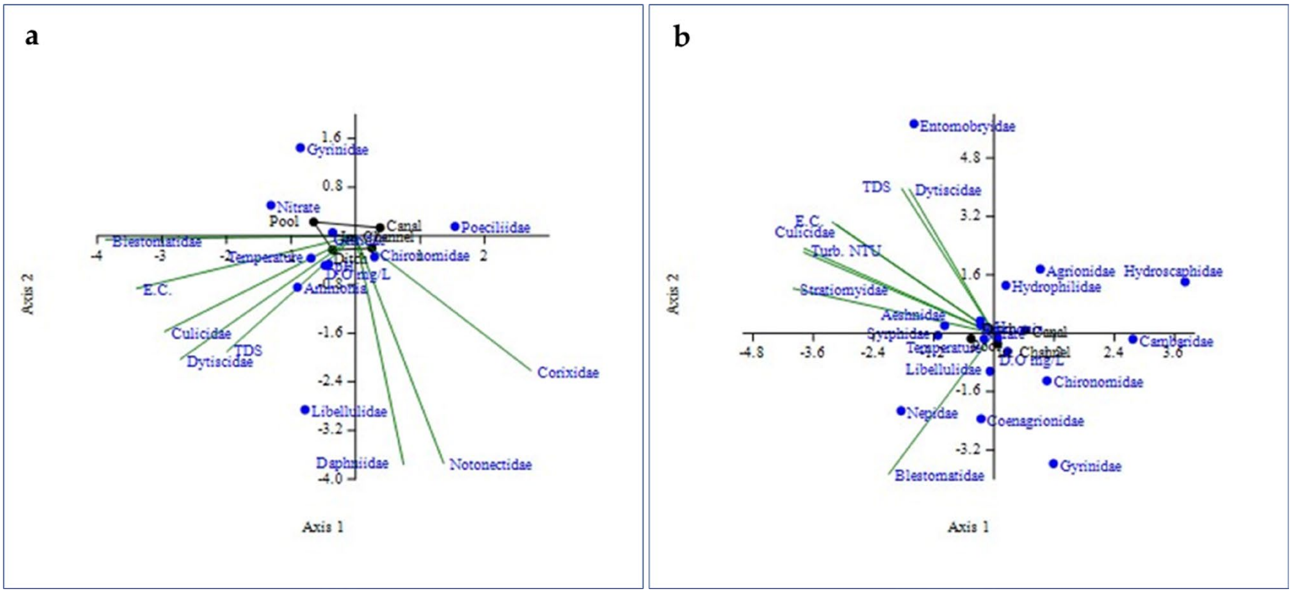

Fig. 8. The CCA ordination biplot illustrates the relationship between aquatic fauna in various habitats (ditch, canal, irregular canal, and pool) and the plant groups associated with sites in Kafr Saad (**a**) and Abu Rawash (**b**) across all seasons.

The reduced abundance or absence of fish in Abu Rawash, especially in the agricultural ditches and irrigation channels, likely reflects cumulative environmental stress associated with nutrient loading and potential contamination. This contamination is primarily driven by the discharge of untreated domestic wastewater and agricultural drainage, leading to excessive levels of ammonia and depleted dissolved oxygen, which create inhospitable conditions for most fish species.

Fish assemblages further reinforced the observed differences in environmental quality between the two areas. Regarding their taxonomic and ecological status, *Tilapia zillii* is identified as a native species indigenous to the Nile system, whereas *Gambusia affinis* is an introduced and acclimatized species widely distributed for biological control. Although both species exhibit high environmental plasticity and tolerance, their significantly higher density in Kafr Saad is attributed to favorable ecological factors, including the presence of dense aquatic macrophytes, which provide essential refugia and spawning grounds, alongside optimal physicochemical parameters such as higher dissolved oxygen and lower ammonia levels. In contrast, the marked reduction or absence of these species in Abu Rawash reflects cumulative environmental stress. This stress is characterized by the synergistic impact of the specific stressors observed in our results, namely persistent hypoxia (low dissolved oxygen), elevated nutrient loading, and potential anthropogenic contamination. These factors, acting in combination, create a hostile environment that surpasses even the high tolerance limits of these resilient species[53].Water temperature emerged as a major driver of seasonal variation in aquatic community structure. Seasonal temperature increases correlate with elevated invertebrate densities and taxonomic diversification, especially in summer, as noted in analogous freshwater ecosystems[54]. Temperature fundamentally regulates biological processes, including metabolic rates, growth, and reproductive cycles of macroinvertebrates[55,56]. Furthermore, the inverse relationship between water temperature and dissolved oxygen solubility significantly influences species composition and their interspecific interactions[55]. These findings align with previous studies in the Nile Delta, which reported that thermal fluctuations dictate the phenology and successional patterns of aquatic insects and associated fauna[54]. Nutrient concentrations, particularly nitrate, also played a key role in structuring aquatic communities. Nitrate from farm runoff and household waste can boost plant growth in water, but if there is too much, it can cause problems like low oxygen levels and a shift to species that can survive pollution. In this study, higher nitrate levels in Abu Rawash were linked to fewer types of insects and more tolerant species, while lower levels in Kafr Saad were connected to more types of insects and the presence of sensitive species.

Aquatic macrophytes contributed significantly to habitat complexity and biodiversity patterns. Habitats with plants offered protection, food, and places to breed, which helped increase the number and variety of small animals living there. The strong association between vegetated habitats and diverse assemblages in Kafr Saad underscores the buffering role of habitat structure against environmental stress.

The type of substrate also affected the types of organisms living on the bottom, with fine and coarse sediments supporting different groups based on how they feed and their life cycles[57,58]. Such habitat-specific preferences contributed to the observed spatial heterogeneity in aquatic community composition.

Multivariate analyses (CCA) confirmed that temperature, nitrate concentration, and electrical conductivity were among the most influential variables driving species distribution patterns across sites and seasons. The clear difference between Kafr Saad and Abu Rawash along these environmental factors shows how both physical and chemical conditions, as well as habitat structure, affect the organization of aquatic communities.

The patterns we saw match earlier research from the Nile Delta and other freshwater areas, which showed that when sensitive species (like mayflies, dragonflies, and true bugs) are replaced by more tolerant species (like mosquitoes, midge larvae, and shore flies), it signals that the environment is getting worse. Researchers have also reported similar relationships in tropical and temperate rivers worldwide[59–61].

Overall, the present study demonstrates that both aquatic insects and fishes serve as effective biological indicators of water quality and environmental stress. The greater variety and presence of sensitive species in Kafr Saad show that the environment is in better shape, while the prevalence of tolerant species and fewer fish in Abu Rawash suggest more ecological stress. These findings point to the necessity of maintaining water quality to sustain diverse and functional aquatic communities and highlight the value of integrating biological indicators with physicochemical measurements for freshwater ecosystem assessment and management.

Conclusion

Freshwater ecosystems fundamentally consist of aquatic insects and fishes, widely recognized as sensitive bioindicators of water quality and environmental disturbance. Clear spatial differences were observed between the two sites, with consistently higher diversity and abundance of aquatic macroinvertebrates and fishes recorded. Kafr Saad had a wider variety of aquatic invertebrate families, such as Culicidae, Chironomidae, Dytiscidae, Gyrinidae, Notonectidae, Corixidae, Coenagrionidae, Cambaridae, and Daphniidae. It also had more fish families, such as Cichlidae and Poeciliidae. The presence of only two fish families throughout the study period highlights the severe environmental constraints within the investigated Nile Valley segments. The prevalence of Cichlidae (e.g., *Oreochromis niloticus*) and Poeciliidae (e.g., *Gambusia affinis*) is typical for habitats characterized by high organic pollution and fluctuating dissolved oxygen levels. These taxa are known for their high tolerance to physiological stress, unlike other native Nile fish that require higher water quality standards, which were absent due to the observed pollution levels (Saad et al., 2023; Ismaiel et al., 2025). In contrast, aquatic communities in Abu Rawash showed reduced diversity and greater dominance of pollution-tolerant taxa, indicating less favorable environmental conditions. Differences in physicochemical water quality closely linked these patterns. Kafr Saad had a nearly neutral pH, lower levels of ammonia and nitrate, higher amounts of dissolved oxygen, and less cloudiness, while Abu Rawash showed signs of environmental stress. Statistical analyses validated that water temperature, nutrient concentrations, and electrical conductivity were principal factors influencing aquatic community structure. Overall, the results demonstrate that spatial variation in physicochemical conditions plays a key role in structuring aquatic insect and fish assemblages in Nile Valley freshwater systems. The combined use of aquatic insects and fishes as bioindicators provides a reliable approach for assessing ecosystem health. This study offers valuable baseline data that can support biomonitoring programs, guide water quality management, and contribute to the conservation of freshwater biodiversity in Egypt.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Conceptualization, MMB, SAR, AMS, YAE, ABD and MEG; methodology, MMB, SAR, WMH, YAE, MEG and ABD; validation, MMB, HSG, MHA, YAE, FAH, ABD and MEG; formal analysis, MMB, SAR, AMS, WMH and MEG; investigation, MMB, SAR, FAH, WMH, YAE , HSG, MHA, MEG and ABD; resources, MMB; data curation, MMB, SAR, AMS, FAH, ABD and MEG; writing—original draft preparation, MMB, SAR, YAE, WMH, HSG, MHA, ABD and MEG; writing—review and editing, MMB, SAR, HSG, MHA, YAE, WMH, ABD and MEG; supervision, MMB, HSG, MHA, MEG and ABD; All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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