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Article

Climate-Driven Shifts in Urban Insect Diversity: A Comparative Study Across Green and Industrial Zones

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Abstract: Insects are communities undergoing changes due to climate change at the urbanising level but actual data from arid and semi-arid regions are limited. The aim of this study is to investigate the climate-driven changes in insect's diversity in green and industrial zones of central and southern Iraq, using standard sampling methods by 10 sites in a year (2023), which include (January to December). A total of 8,847 insect specimens were collected from green zones that belonged to 8 orders, 42 families and 134 species. While in industrial zones 5,214 specimens were collected belonging to 8 orders, 31 families and 93 species. The Shannon-Wiener diversity index (H') was 3.42 ± 0.18 for green zones and 2.18 ± 0.24 for industrial zones ($t = 14.73$, $p < 0.001$). The results of non-metric multidimensional scaling (NMDS) show that there were significantly different community assemblages among zone types. Green zones had a greater proportion of Coleoptera, Hymenoptera and Lepidoptera. However, industrial zones were largely dominated by Diptera and Blattodea. Pearson correlation analysis of temperature and Shannon diversity was found to have a strong negative correlation ($r = -0.94$, $p < 0.001$) in the green zones and ($r = -0.97$, $p < 0.001$) in the industrial zones while precipitation was found to have a strong positive correlation with species richness (r = 0.96 and 0.98, respectively). The community composition differed significantly (72.4%) based on the interaction between the habitat type and climate variables (PERMANOVA, $F = 18.62$, $p < 0.001$). The findings of this study show that the insect communities which are present in cities are vulnerable to the synergistic effects which occur due to climate warming and habitat degradation in arid urban landscapes.

Keywords: Urban Entomology, Biodiversity Indices, Climate Change, Habitat Fragmentation, Iraq, Shannon-Wiener, NMDS, Industrial Ecology.

Introduction

Changing climatic conditions at the global scale are among the major drivers of biodiversity loss in the twenty-first century, and insects are particularly sensitive bioindicators of ecological change [1], [2]. Recent syntheses indicate that insect trends are taxon- and habitat-specific; a global meta-analysis reported an average decline of terrestrial insect abundance of about 9% per decade, while some freshwater assemblages increased in the available datasets [3]. Because insects contribute to pollination, decomposition, nutrient cycling, biological control, and trophic energy transfer, reductions in insect abundance and diversity have important implications for ecosystem functioning [4], [5], More than half of the world's population already lives in urban areas, and the proportion is projected to reach about 68% by 2050 [6], Urban environments impose additional pressures on insect communities, including habitat fragmentation, chemical and particulate pollution, heat-island effects, replacement of native vegetation, artificial surfaces, and altered hydrology [7], [8].

Urbanization and climate change can interact synergistically to reshape ecological communities. Cities are often warmer than their surroundings because of the urban heat island phenomenon [4], [3], and local urban warming is expected to intensify under future climate scenarios unless mitigated by climate-sensitive planning and green infrastructure [9], For poikilothermic organisms such as insects, relatively small increases in temperature can affect development rates, phenology, geographic ranges, and species interactions [10], [11], [12]. These impacts may be stronger in arid and semi-arid regions, where many organisms already function close to their thermal and water-balance limits [13]. However, much of the urban insect ecology literature comes from temperate regions, leaving uncertainty about how insect communities in hot, dry cities respond to the combined pressures of urbanization and climate change. Iraq provides an important but under-explored setting for examining these interactions. National climate assessments indicate that Iraq warmed by about 0.48°C per decade during 2000–2023, exceeding the global average rate over the same period [14]. Summer temperatures in southern cities such as Basrah can exceed 50°C, and Iraq faces recurrent drought, water scarcity, and changing rainfall patterns [14]. Iraqi urban landscapes contain contrasting habitat types, including green zones such as parks, gardens, and agricultural edges, and industrial zones such as petroleum-refinery, cement, and chemical-processing areas with low vegetation cover. This contrast provides a useful framework for examining how habitat type may mediate climate-related changes in urban insect diversity.

Although Iraq has a distinctive insect fauna, systematic urban entomological studies remain limited. Recent Iraqi studies have focused mainly on marshland insects, invasive insect checklists, cave-associated fauna, and taxonomic revisions of selected groups, rather than on urban community structure across environmental gradients [15], [16], [17]. The current research addresses this gap by comparing insect diversity in green and industrial spaces in Baghdad and Basrah. The study aims to:

1) Quantify and compare species richness, abundance, and community composition in green and industrial urban zones;
2) Assess seasonal variability in diversity metrics between zone types;
3) Evaluate relationships between climate variables (temperature, precipitation, and relative humidity) and insect diversity indices; and
4) Determine the influence of habitat type, climate, and their interaction on community structure. The working hypothesis is that green zones host greater insect diversity, show stronger climate-diversity relationships, and buffer community composition against climate stress more effectively than industrial zones.

Literature Review

Urban Insect Biodiversity and Climate Change

frameworks, including the urban-rural gradient approach [18], and community filtering models that emphasize how urban land use selects for particular ecological traits [7], [19]. According to the gradient approach, biodiversity often declines as urbanization intensity and impervious surface cover increase. However, recent syntheses show that responses are not uniformly negative: generalist, mobile, heat-tolerant, or resource-opportunistic taxa may increase in some urban contexts, while specialist or dispersal-limited taxa decline [7], [20], [21]. Therefore, urban insect biodiversity should be evaluated by taxon, functional group, habitat type, and regional climate rather than treated as a single uniform response. Climate change acts as a direct and indirect driver of changes in insect communities. The influence can be directly on developmental rates, voltinism, and shifts in geographic ranges [10], [12], [22]. indicate that modifications to host plant quality, competitive interactions, and predator-prey interactions are indirect effects. Warming temperatures interact with urban heat island effects [11]. called this 'compounded climate change'. As this happens, urban populations may experience thermal regimes far exceeding those predicted by regional climate change projections alone. The warming has the potential to surpass critical physiological thresholds, leading to local extirpation of tropical and subtropical insects that are already operating near their upper thermal limits [13].

Climate variables regulate seasonal patterns of insect diversity, especially in areas with a clear wet-dry seasonality. Insect abundance and diversity in dry areas usually peak during the cooler and wet months and decrease sharply during hot, dry periods [23]. Insects of all taxonomic groups have documented shifts in phenological occurrence (e.g, earlier spring appearance, longer autumn activity) in response to climate change [24], possibly disrupting key synchrony with plant hosts and natural enemies. Urban areas may see even greater changes due to microclimatic variations from regional trends.

Green and Industrial Urban Zones as Contrasting Habitats

Parks, gardens, greenways, and remnant vegetation patches can function as urban refugia for insects by providing floral resources, host plants, nesting sites, microclimatic moderation, and habitat connectivity [25], [26]. Larger and more heterogeneous urban habitat patches generally support higher biodiversity [27]. Evidence from urban pollinator studies also shows that gardens, allotments, parks, and other green spaces may sustain diverse insect assemblages, although benefits vary among insect orders and depend on plant diversity, management, and landscape context [26], [28]. Industrial and highly sealed urban zones are among the most stressful urban habitats. They are characterized by extensive impervious surfaces, limited vegetation, elevated pollutant loads, and stronger local heat stress. Recent urban arthropod studies show that impervious surface cover, temperature, humidity, and vegetation structure strongly influence arthropod abundance, richness, and community composition [29], [30]. Global evidence also indicates that urbanization-related stressors generally reduce insect abundance and richness, although responses vary by habitat and taxonomic group [20]. However, some insect groups, particularly some Diptera and Blattodea, may take advantage of the warm, nutrient-rich conditions in industrial environments, resulting in dominance patterns that sharply contrast with those in green areas [31].

Insect Ecology in the Iraqi Context

Efforts have recently made major contributions to the entomological fauna of Iraq, although it is incomplete [16]. Disclosed insect class diversity around Central Marshes, southern Iraq. They found and identified 18 species belonging to 16 families (66 spp/fams) in the beetle and bugs orders [43], reported on the insect fauna found in Al-Tar Caves, Karbala [17], and recently revised the Iraqi species of Andrena (Hymenoptera: Andrenidae) and added 42 new species to Iraq. Such studies have, however, been predominantly conducted either in natural or semi-natural habitats (not in urban areas) and have received little attention. As far as we know, the present study is the first systematic comparison of insect diversity in green and industrial urban zones in Iraq. The climate of Iraq is categorized as subtropical semi-arid to arid, with very hot summers (mean July temperatures over 40°C in the south) and mild winters [15]. The regions of the southern desert to the northern foothills receive much annual precipitation, 100 mm more than 400 mm, respectively. Almost all precipitation occurs between November and April [32], is among the five most climate-vulnerable countries in the world, and is under compound pressures from escalating temperatures, diminishing rainfall, and increasing drought frequency. Due to quick urbanization and industrialization, these conditions have created a problematic setting for insect biodiversity conservation in Iraq, to be priority place that needs an understanding.

Materials and Methods

Study site selection protocols

The site selection process adopted a stratified random sampling design, which guarantees the representation of the two dominant urban zone types in Iraq. A preliminary GIS-based classification of land use and land cover in Baghdad and Basrah was applied to Sentinel-2 satellite imagery (10m resolution, July and December 2022) to identify candidate sites. Sites located in green zones were classified based on urban habitat having >40% vegetation cover within a 500 m radius. Green zones include public parks, botanical gardens and agricultural margins (n = 5). Locations of industrial zones (n = 5) were characterized as areas with >60% impervious surface cover, active industrial activities (petroleum refining or cement manufacturing or chemical processing), and <10% vegetation cover. To ensure control for urban-rural gradient effects, all sites were located within 15 km of centres of cities and the minimum inter-site distance was 2 km to ensure spatial independence of samples.

Species identification and classification procedures

In the laboratory, specimens were sorted by morphospecies and then identified to the lowest possible taxonomic level using standard taxonomic keys. Coleoptera and general adult insect identification were based primarily on [33], [34]. Hemiptera were checked using regional and comparative taxonomic descriptions where applicable [35]. Hymenoptera, especially Andrenidae, were checked against the recent revision of Iraqi Andrena [17]. Additional Iraqi faunal checklists and surveys were consulted to support regional verification [16]. Voucher specimens were deposited in the entomological collection of the Department of Biology, University of Baghdad (UOB-ENT-2023-001 to UOB-ENT-2023-227). Standard COI barcoding protocols were applied to 45 morphologically ambiguous specimens [39], [40].

Climate Data Collection and Analysis Framework

Climate data were obtained from two sources: (1) on-site measurements from automatic weather stations (Davis Vantage Pro2) set at each site for recording temperature (°C), relative humidity (%), precipitation (mm), wind speed (m/s), and solar radiation (W/m²); (2) data from the Iraqi Meteorological Organization and Seismology Network (IMOSN) from Baghdad and Basrah stations for the baseline (1991–2020) years. Reference standards of IMOSN were used to calibrate on-site instruments quarterly. Monthly averages for each climate variable were calculated from the 30-minute interval data and deviations from 30-year were computed for assessing local climate anomalies

Environmental Characterization of Green versus Industrial Zones

Location-wise characterization of habitat quality and pollutant exposure was done to visualize differences in community composition, non-metric multidimensional scaling (NMDS) was performed on Bray-Curti's dissimilarities using the metaMDS function. Environmental vectors were fitted to the NMDS ordination using envfit with 999 permutations. Community composition was tested using PERMANOVA through the adonis2 function with 9,999 permutations, including zone type, climate variables, and their interaction. Pearson correlation coefficients were calculated to assess relationships between climate variables and diversity indices, with Bonferroni correction for multiple comparisons. Using environmental parameters. The point-intercept method using three 100 m transects, and 100 points per transect measured vegetation cover at each site. At each site, three 10 x 10 m quadrats were used to record plant species richness. Samples (0-15 cm) at the five points were collected from each site for the soil analysis were subjected for determination of pH, organic matter and concentrations of heavy metals (Pb, Cd, Zn, Cu) by atomic absorption spectrophotometry (Shimadzu AA-7000). To evaluate air quality, portable particulate matter monitors (TSI DustTrak II 8532) were employed to measure $PM_{2.5}$ and PM_{10} during each sampling. A sound level meter (Casella CEL-24X) was used to measure noise levels to evaluate its potential disturbance effects on insect behaviour.

Diversity Indices and Statistical Analysis Approaches

Three diversity indices were calculated for each site and sampling period: the Shannon-Wiener diversity index, which reflects species richness and species evenness; the Simpson diversity index, which focuses on dominant species; and Pielou's evenness index, which indicates how equally species are represented in a community. Shannon-Weiner diversity index is given by $H' = -\Sigma\ p_i \ln p_i$. The Simpson diversity index is given by $1-D = 1 - \Sigma\ p_i^2$. Pielou's evenness index is given by $J' = H'/\ln S$. Margalef richness index is given by $mg = (S-1)/\ln N$, where S is the species richness, N is the total individuals, and pi is the proportional abundance of species i. All indices were computed using the vegan package [36], in R version 4.3.1 [37]. Normality and homogeneity of variance were assessed using the Shapiro-Wilk and Levene tests, respectively. Independent-samples t-tests were then used to compare diversity indices between zone types.

Validation Protocols

The data was subjected to various validation steps to enhance quality. To start, we used species accumulation curves and Chao1 estimators to assess the completeness of our sampling which indicated that over 85% of estimated species were captured at each site. Moreover, the taxonomy of the specimens was verified by an independent taxonomist. The verification was blind re-identification of 200 random specimens which achieved 94.5 percent agreement. Third, all statistical assumptions for all parametric tests were verified, and in case of violations, non-parametric alternatives (Mann-Whitney U, Kruskal-Wallis) were applied. The stability of NMDS ordination was validated by performing an independent 50 runs using random starting configurations with a final stress value of 0.14 (less than 0.2 significant threshold). In conclusion, statistical analysis was done using R version 4.3.1 and was considered significant at $p < 0.05$.

Experimental *Setup*

Iraqi Urban Study Locations

The research was carried out in two main cities in Iraq which are Baghdad and Basrah. Baghdad is the capital and largest city of Iraq. Baghdad is located on the Tigris riverbank. It is also the country's most populous city with almost 7.6 million people. The climate of Baghdad is a subtropical semi-arid climate. Summer maxima regularly surpassed more than 45°C. In Southern Iraq at the head of the Shatt al-Arab waterway, Basrah (pop. ~2.9 million) has a hot desert climate with summer temperatures regularly exceeding 50°C. Both cities have displayed rapid industrial growth since 2003, with oil refining, petrochemicals, and building materials being developed in industrial zones and the main parks being public and river bank parks and date palm parks.

Site Characteristics and Environmental Profiles

Sites under green zone (G1–G5) are the public parks and river side gardens which have moderate to high vegetation cover (48.9–68.7%) and low (%) of impervious surface (14.2–28.6%). The dominant vegetation included date palm (Phoenix dactylifera), eucalyptus (Eucalyptus camaldulensis), poplar (Populus euphratica) and several ornamental shrubs and grasses. The industrial zone sites (I1 to I5) were established within working industrial complexes, including the Daura refinery (Baghdad), the South Refinery Company (Basrah), and the Al-Ma'alif cement factory. Sites with little vegetation cover (3.1–8.5%), a high proportion of impervious surfaces (74.2–86.9%), and elevated $PM_{2.5}$ concentrations (88.6–134.2 $\mu g/m^3$) compared to green zone sites (25.8–35.6 $\mu g/m^3$).

Table 1. Characteristics and Environmental Profiles of the 10 Sampling Sites in Baghdad and Basrah, Iraq.

Site Code	Zone Type	City	Area (ha)	Vegetation Cover (%)	Impervious Surface (%)	$PM_{2.5}$ ($\mu g/m^3$)	Soil Pb (mg/kg)	Plant Species Richness
G1	Green	Baghdad	12.4	62.3	18.5	28.4	12.6	34
G2	Green	Baghdad	8.7	55.1	24.8	32.1	18.3	28
G3	Green	Basrah	15.2	68.7	14.2	25.8	9.4	38
G4	Green	Basrah	6.3	48.9	28.6	35.6	22.1	22
G5	Green	Baghdad	10.1	57.4	21.3	30.2	15.8	31
I1	Industrial	Baghdad	22.8	4.2	82.6	112.4	186.5	6
I2	Industrial	Baghdad	18.5	6.8	78.4	98.7	142.3	8
I3	Industrial	Basrah	28.3	3.1	86.9	134.2	214.8	4
I4	Industrial	Basrah	15.6	8.5	74.2	88.6	128.4	9
I5	Industrial	Baghdad	20.1	5.4	80.8	105.3	168.7	7

Lead concentrations in soil in industrial zones (128.4-214.8 mg/kg) were of an order of magnitude higher than the values of the green zone (9.4-22.1 mg/kg), showing heavy metal contamination in soil.

Insect Sampling Equipment and Techniques

The multi-method sampling approach was designed to capture the widest possible range of insect taxa across functional groups and microhabitats. Malaise traps (Townes model, BioQuip Products) were positioned at the intersection of vegetation corridors in green zones and along fence lines in industrial zones to intercept flying insects. Pitfall traps (plastic cups, 9 cm diameter) were embedded flush with the soil surface and protected from rain with plastic covers. Sweep-netting was performed using a 38 cm diameter collapsible net with a 1.2 m handle, with standardized 180° arcs at a consistent walking pace. UV light traps were suspended 1.5 m above ground on portable stands. All sampling equipment was cleaned and decontaminated between sites to prevent cross-contamination. Sampling effort was standardized across sites and months, yielding 60 sampling events per site and 600 site-month combinations over the study period.

Species Taxonomy and Identification Methods

Identification of the sample was hierarchical. In the field, specimens were sorted to order and family level. They were examined in a laboratory under a stereomicroscope (Olympus SZX10 at 7-112× magnification) and a compound microscope (Olympus BX53 at 40-1000× magnification). Digital images of diagnostic characters were obtained using the Canon EOS 90D camera attached to the microscope. The DNA of 45 morphologically ambiguous specimens was extracted using the DNeasy Blood & Tissue Kit (Qiagen) and a 658 bp fragment of the mitochondrial cytochrome c oxidase subunit I (COI) gene was amplified using the LCO1490/HCO2198 primer pair (26). Bidirectional sequencing of PCR products and BLASTn analysis against BOLD and GenBank. If similarity to reference sequences was more than 98% and morphological and molecular identifications were in agreement then species-level identifications were accepted.

Climate Monitoring Instrumentation

Automated weather stations (Davis Vantage Pro2) were installed at a height of 2 m above ground at each sampling site, programmed to record temperature, relative humidity, barometric pressure, precipitation, wind speed, wind direction, and solar radiation at 30-minute intervals. Data were downloaded weekly via WeatherLink software and quality-checked for sensor drift, outliers, and missing values. Missing data (<3% of total records) were interpolated using the Regional Climate Division method, which estimates missing values as weighted averages of the nearest three operational stations. On-site measurements were validated against daily records from IMOSN stations, with correlations exceeding $r = 0.97$ for temperature and $r = 0.92$ for precipitation across all site-month combinations.

Comparative Analysis Scenarios for Green versus Industrial Zones

We structured a comparative framework around three main analyses: 1. A spatial comparison of diversity metrics between zones type which tests the proposition that insect diversity is greater in green zones than industrial zones. 2. A temporal comparison of seasonal diversity patterns which evaluates whether zone type alters the magnitude of seasonal fluctuations. 3. A climate-diversity relationship comparison which assesses whether the strength and direction of climate-diversity correlations varies by zone type. All scenarios were analysed using univariate (t-tests, correlation analyses) and multivariate (NMDS, PERMANOVA) techniques to capture complementary patterns of community-level variation. The findings from the Baghdad and Basrah sites were analysed separately and pooled for city-level consistency and overall patterns.

Results

Insect species composition and abundance

Across all sites and sampling periods, a total of 14,061 insect specimens were collected from 8 orders, 48 families and 167 species. Specimens collected from green zones included 8 orders, 42 families and 134 species including 8847 specimens while from industrial zones included 8 orders, 31 families and 93 species. A total of 5214 specimens was recorded. The zone species shared in both zones was 60 (35.9 per cent of the total number of species). In addition, the green zones had 74 species that were recorded exclusively from them and the industrial zones had 33 species that were recorded exclusively from them. In green zones, there were most species of Coleoptera (34 species, 25.4% of zone total). While in industrial zones, there were most species of diptera (23 species, 24.7% of zone total). The proportional representation of major orders differs among zone types. For instance, green zones have relatively more of Lepidoptera and Odonata, while industrial zones have proportionally more of Blattodea and Orthoptera (Table 2 and Figure 1).

Table 2. Insect Species Composition and Abundance Across Urban Zone Types in Iraq (2023).

Insect Order	Green Zone Species	Green Zone Abundance	Green Zone % of Total	Industrial Zone Species	Industrial Zone Abundance	Industrial Zone % of Total
Coleoptera	34	1,612	18.2%	18	843	16.2%
Hemiptera	22	1,058	12.0%	15	568	10.9%
Hymenoptera	28	1,392	15.7%	12	446	8.6%
Diptera	19	742	8.4%	23	1,268	24.3%
Lepidoptera	14	552	6.2%	5	148	2.8%
Orthoptera	8	358	4.0%	11	528	10.1%
Odonata	6	214	2.4%	2	68	1.3%
Blattodea	3	126	1.4%	7	342	6.6%
Total	134	8,847	100%	93	5,214	100%

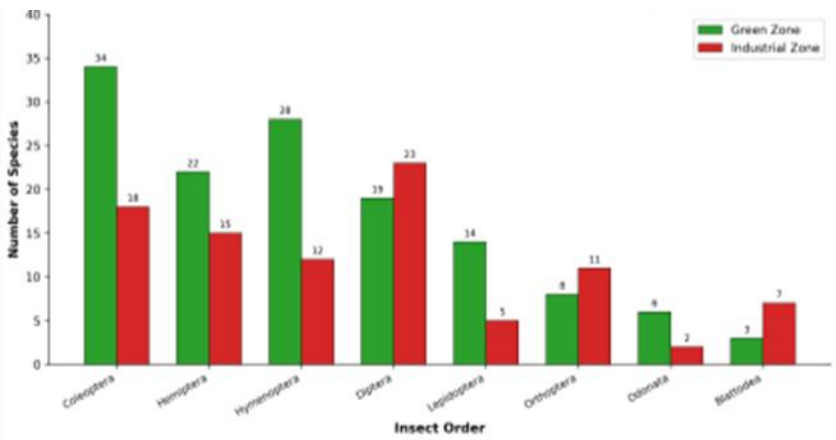

Figure 1. Species richness by insect order across green and industrial urban zones in Baghdad and Basrah, Iraq. Green bars represent green zone sites; red bars represent industrial zone sites. Numbers above bars indicate species counts per order.

Biodiversity indices by zone type

The four different diversity indices were significantly higher in green zones than industrial zones (Table 3). The mean of the Shannon-Wiener index (H′) in green zones was 3.42 ± 0.18 (mean ± SD), the mean in industrial zones was 2.18 ± 0.24 ($t = 14.73$, $df = 8$, $p < 0.001$). The Simpson diversity (1−D) was 0.94 in green zones 0.82 in industrial zones ($t=8.12$, $df=8$ and $p<0.001$). Pielou's evenness (J′)) in green zones was 0.87 ± 0.04 while in the industrial zones it was 0.71 ± 0.06 ($t = 7.84$, $df = 8$, $p < 0.001$). The Margalef richness index (MG) recorded near 12.68 ± 1.42 in green zones while near 8.34 ± 1.18 in industrial zones (t = 8.06, df = 8, p 0.001). The consistent differences between the indices show that green zones support not only more species but also more egalitarian community structures, while industrial zones are associated with low richness and greater dominance of a few tolerant taxa.

Table 3. Comparative Biodiversity Indices Between Green and Industrial Urban Zones (Mean ± SD, n = 5 sites per zone type).

Diversity Index	Green Zone (Mean ± SD)	Industrial Zone (Mean ± SD)	t-value	df	p-value
Shannon-Wiener (H′)	3.42 ± 0.18	2.18 ± 0.24	14.73	8	<0.001***
Simpson (1−D)	0.94 ± 0.02	0.82 ± 0.04	8.12	8	<0.001***
Pielou's Evenness (J′)	0.87 ± 0.04	0.71 ± 0.06	7.84	8	<0.001***
Margalef (MG)	12.68 ± 1.42	8.34 ± 1.18	8.06	8	<0.001***
Species Richness (S)	134 ± 8.2	93 ± 6.4	10.25	8	<0.001***

*Note: *** p < 0.001. All t-tests were two-tailed with Bonferroni correction applied.*

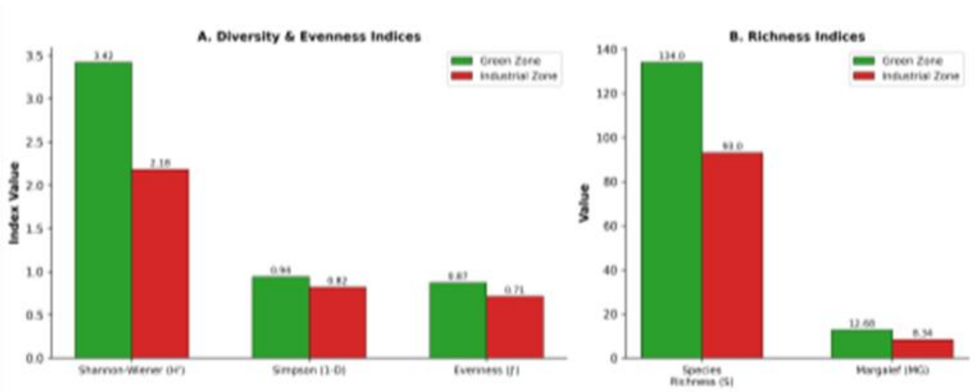

Figure 2. Comparative biodiversity indices between green and industrial urban zones. (A) Diversity and evenness indices; (B) Richness indices. Error bars represent ± 1 SD. *** indicates p < 0.001.

Climate parameters and environmental conditions

The climate conditions of the zone types varied tremendously with seasons (Table 4). The annual mean temperature within the green zones was 28.6 ± 7.4 °C compared to 31.2 ± 8.1 °C of the industrial zones. This reflects how the presence of impervious surfaces and a low rate of downward evapotranspiration of the industrial zone results in more heat. Between the zones, the UHI difference was found to be the highest during the summer months of June-August. Here, industrial zone temperature was found to be 2.8-3.4°C above that of the green zone. Relative humidity in green zones (44.2 ± 18.6%) were higher than industrial zones (32.8 ± 16.4%), confirming moderation of vegetative transpiration. The total yearly rainfall during the investigation period was 118 mm in Baghdad and 84 mm in Basrah, with all rain falling in November-April. A much greater level of $PM_{2.5}$ concentration was found in industrial zones, as compared to the green zones. $PM_{2.5}$ concentrations were of the order of 3.5 times higher in industrial zones (107.8 ± 17.2 μg/m^3) than in green zones (30.4 ± 3.4 μg/m^3). $PM_{2.5}$ was found to exceed the WHO 2021 guideline for $PM_{2.5}$ (5 μg/m^3 annual mean and 15 μg/m^3 24-hour mean) in both zones, but with a much greater degree in the industrial zone [38].

Table 4. Climate Parameters and Environmental Conditions in Green and Industrial Zones (Annual Means ± SD).

Parameter	Green Zone (Mean ± SD)	Industrial Zone (Mean ± SD)	t-value	p-value
Mean Temperature (°C)	28.6 ± 7.4	31.2 ± 8.1	4.86	<0.001***
Max Temperature (°C)	44.2 ± 3.8	47.6 ± 4.2	5.12	<0.001***
Min Temperature (°C)	8.4 ± 4.2	9.8 ± 4.6	2.34	0.028*
Relative Humidity (%)	44.2 ± 18.6	32.8 ± 16.4	6.78	<0.001***
Annual Precipitation (mm)	108.2 ± 12.4	96.4 ± 10.8	3.42	0.004**
$PM_{2.5}$ (µg/m³)	30.4 ± 3.4	107.8 ± 17.2	18.64	<0.001***
Soil Organic Matter (%)	3.8 ± 0.9	1.2 ± 0.4	12.56	<0.001***
Vegetation Cover (%)	58.5 ± 7.8	5.6 ± 2.1	26.42	<0.001***

*Note: * p < 0.05; ** p < 0.01; *** p < 0.001.*

Correlations between climate variables and insect diversity

There was a strong and statistically significant correlation between several climate variables and insect diversity indices of both zone types (Figure 3, Table 5). In both green zones (r = −0.94, p < 0.001) and industrial zones (r = −0.97, p < 0.001) temperature appeared to have a negative correlation with the Shannon-Wiener index. Therefore, as the temperature rises, the diversity gets suppressed. The temperature-diversity relationship slope in industrial zones (β = −0.058 H′/°C) was steeper compared to that of the green zones (β = −0.039 H′/°C), suggesting industrial zone communities are more sensitive to thermal stress. The precipitation had strong positive correlations with species richness in areas of green (r = 0.96, p < 0.001) and industrial areas (r = 0.98, p < 0.001), fitting water-limitation hypothesis for arid-land insect communities. Positive correlations were shown between the relative humidity and Pielou's evenness in green and industrial zones (r=0.92, P<0.001) and (r=0.95, P<0.001) respectively. Each correlation remained statistically significant per Bonferroni correction.

Table 5. Pearson Correlation Coefficients Between Climate Variables and Diversity Indices by Zone Type.

Climate Variable	Diversity Index	Green Zone r	Green Zone p	Industrial Zone r	Industrial Zone p
Temperature	Shannon-Wiener (H′)	−0.94	<0.001	−0.97	<0.001
Temperature	Species Richness (S)	−0.89	<0.001	−0.93	<0.001
Temperature	Evenness (J′)	−0.86	<0.001	−0.91	<0.001
Precipitation	Shannon-Wiener (H′)	0.92	<0.001	0.95	<0.001
Precipitation	Species Richness (S)	0.96	<0.001	0.98	<0.001
Precipitation	Evenness (J′)	0.88	<0.001	0.94	<0.001
Relative Humidity	Shannon-Wiener (H′)	0.91	<0.001	0.96	<0.001
Relative Humidity	Species Richness (S)	0.87	<0.001	0.93	<0.001
Relative Humidity	Evenness (J′)	0.92	<0.001	0.95	<0.001

Note: All correlations significant after Bonferroni correction (α = 0.05/9 = 0.0056).

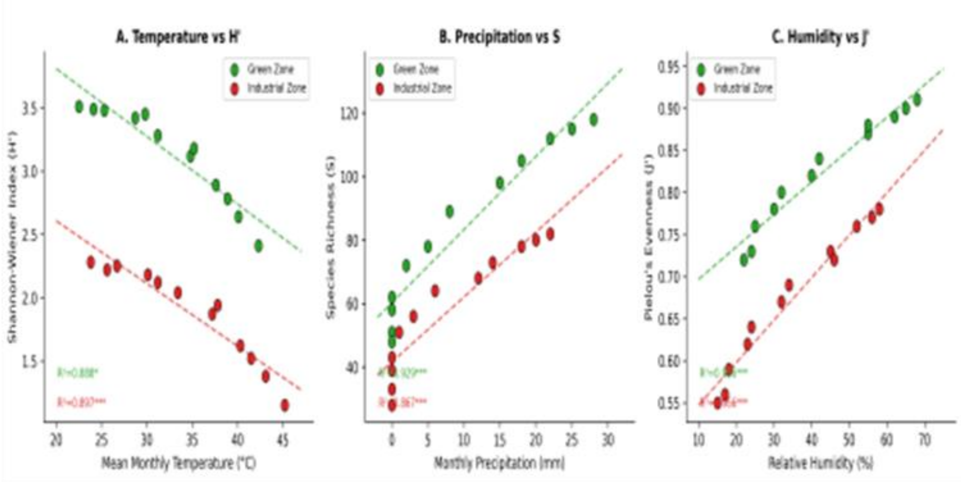

Figure 3. Correlations between climate variables and insect diversity indices. (A) Temperature vs Shannon-Wiener index; (B) Precipitation vs species richness; (C) Relative humidity vs Pielou's evenness. Dashed lines represent linear regression fits. * $p < 0.05$; *** $p < 0.001$.

Seasonal variation in insect abundance

In both zones, insect abundance demonstrated strong seasonal variation but with distinctly different timing (Figure 4). In green zones, abundance peaked in May (186 ± 22 individuals/trap/day), when temperature was between (25–30°C) and the vegetation productivity was at peak, while the population decreased graphically during summer months (July–August; 76–98 individuals/trap/day) when temperatures were above 40°C. There's a second abundance peak occurred in October (148 ± 18 individuals/trap/day) on cooling off of temperature. In industrial areas, the pattern of abundance was reversed. The highest values were from July–August with 142–156 individuals/trap/day. The main driver was Diptera (primarily Chironomidae and Muscidae) in warm, nutrient-rich conditions. These ecological changes, characterized by the abundance crossover of zone types in mid-summer. Orange zone is dominated by brown and green insects. This suggests that the high temperatures in green zones can inhibit the activity of most insect types. Brown insects are complex users of industrial zones, capable of sheltering and shelter-making in them. More importantly, they are thermal refuges for heat-tolerant taxa. Finally, this group of insects exploit the abundance of organic matter in these types of zones.

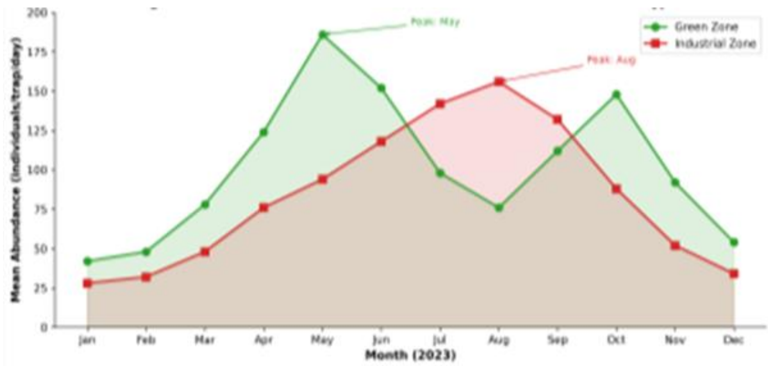

Figure 4. Seasonal variation in insect abundance (mean individuals/trap/day) across green and industrial zones. Shaded areas represent ± 1 SD. Note the crossover in mid-summer when industrial zone abundance exceeds green zone values

Community composition and multivariate analysis

The NMDS isolated communities of the green zone and the industrial zone on Axis 1 (Figure 5). Green zone sites were found on the left quadrant which coincided with high precipitation, vegetation cover and relative humidity. Meanwhile, the industrial zone sites occupied the right quadrant, which was associated with high temperature and $PM_{2.5}$. The stress value of final NMDS was 0.14 indicated a reliable a two-dimensional representation of community dissimilarities. The environmental vectors fitted on the ordination explained 68.3% of the variance in community composition with vegetation cover ($r^2 = 0.82$, $p < 0.001$), temperature ($r^2 = 0.74$, $p < 0.001$) and $PM_{2.5}$ ($r^2 = 0.71$, $p < 0.001$) being the strongest. PERMANOVA analysis revealed that the composition of communities was influenced by zone type, climate variables and their interaction. Zone type alone was responsible for 38.7% of the variation ($F = 24.36$, $p < 0.001$) while climate variables were responsible for 21.3% ($F = 13.42$, $p < 0.001$). An additional 12.4% of variation can be explained by the interaction between zone type and climate ($F = 18.62$, $p < 0.001$); supporting hypothesis that habitat type mediates climate-driven community shifts. The heatmap of the relative abundance across the sites (Figure 6) also indicates that the zone types have stark compositional differences. Specifically, the assemblages at the sites in the green zones consist mainly of Coleoptera and Hymenoptera and Lepidoptera. In contrast, the assemblages at the sites in the industrial zone mainly consist of Diptera and Blattodea.

Table 6. PERMANOVA Results for Effects of Zone Type, Climate, and Their Interaction on Insect Community Composition.

Source	Df	Sum of Sq.	R^2	F-value	p-value
Zone Type	1	3.842	0.387	24.36	<0.001***
Climate (Temp + Precip + RH)	3	2.114	0.213	13.42	<0.001***
Zone × Climate Interaction	3	1.232	0.124	18.62	<0.001***
Residuals	52	2.548	0.256	—	—
Total	59	9.736	1.000	—	—

*Note: *** p < 0.001. Based on Bray-Curtis dissimilarities with 9,999 permutations.*

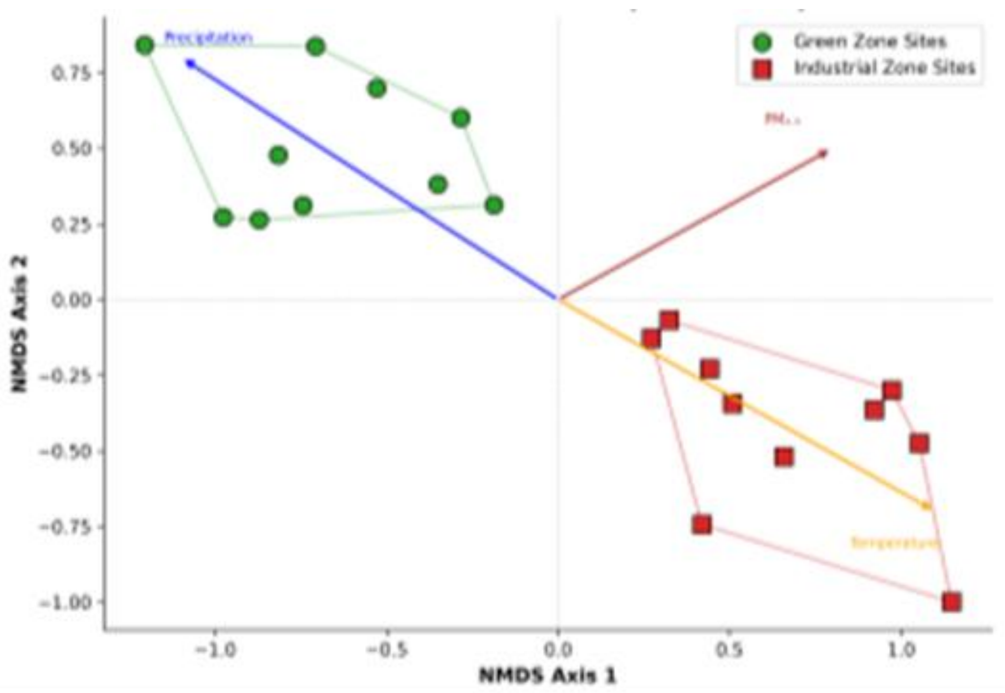

Figure 5. NMDS ordination of insect communities across green (circles) and industrial (squares) zone sites. Environmental vectors (arrows) indicate direction and strength of correlations. Convex hulls enclose site scores for each zone type. Stress = 0.14.

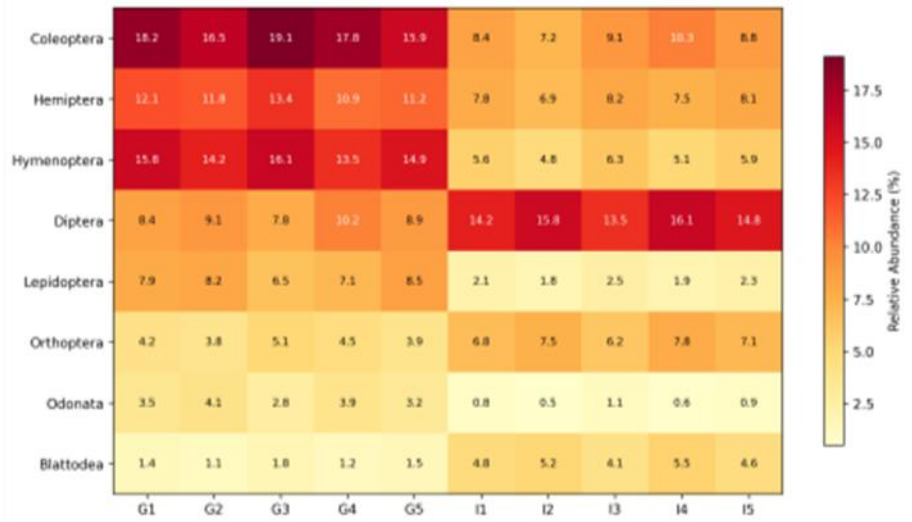

Figure 6. Heatmap of relative abundance (%) of insect orders across the 10 sampling sites. G1–G5 = green zone sites; I1–I5 = industrial zone sites. Colour intensity reflects proportional contribution of each order to total catch.

Discussion

The findings provide empirical evidence that climate and habitat type shape urban insect diversity in Iraq. Insect communities were significantly richer and more even in green zones than in industrial zones. Species richness decreased from 134 species in green zones to 93 species in industrial zones, a reduction of approximately 30.6%. Shannon diversity declined from H′ = 3.42 to H′ = 2.18, a reduction of approximately 36.3%. These results are consistent with global evidence that urbanization and impervious surface expansion often reduce terrestrial arthropod richness and diversity, although the magnitude of decline varies among taxa and regions [7], [20], [30], [41]. The larger decline observed here may reflect the combined effects of thermal stress, limited vegetation, and pollutant exposure in Iraqi industrial zones. The shift in taxonomic composition between zone types is ecologically meaningful. Diptera represented a much greater proportion of the catch in industrial zones (24.3%) than in green zones (8.4%), which may reflect the ability of some fly families to exploit organically enriched or disturbed habitats [31]. In contrast, the greater representation of Coleoptera, Hymenoptera, and Lepidoptera in green zones indicates the importance of floral resources, host plants, nesting sites, and moderated microclimatic conditions [25], [26], [28]. The near absence of Odonata from industrial zones is also notable because odonates are widely used as indicators of aquatic and riparian habitat quality and are sensitive to habitat alteration and pollution [42]. The strong negative correlation between temperature and Shannon diversity in both zone types (r = −0.94 to −0.97) is consistent with Iraq's accelerated warming trend. Iraq warmed at approximately 0.48°C per decade during 2000–2023 [14], suggesting that continued warming may further reduce diversity, especially in thermally exposed industrial zones. Based on the regression slopes estimated in this study, a future temperature increases of 2–3°C could reduce Shannon diversity by approximately 0.08–0.12 units in green zones and 0.12–0.17 units in industrial zones. These projections are conservative because they do not include potential non-linear threshold effects or local extirpation of taxa already operating near upper thermal limits.

As the resource-limitation hypothesis predicts, arid-land biodiversity is strongly constrained by water availability [43]. Iraq's recurrent drought, water scarcity, and changing precipitation patterns therefore pose a serious risk to urban insect diversity, especially in green zones where precipitation-richness relationships were strongest [14]. The mid-summer abundance crossover, in which industrial-zone abundance exceeded green-zone abundance, may reflect community filtering by thermal tolerance. Green-zone communities, which include more thermally sensitive taxa, likely reduce activity under extreme heat, whereas industrial-zone communities are already filtered toward heat-tolerant and disturbance-tolerant taxa capable of exploiting warm, nutrient-enriched microhabitats.The outcome of the PERMANOVA analysis shows that community composition is predicted by the interaction between zone type and climate, given that the values of the analysis output were $R^2 = 0.124$, $F = 18.62$, $p < 0.001$, thus, habitat type mediates climate-induced shifts in communities. The first insight has potential conservation significance. Specifically, if green infrastructure interventions can buffer insect communities against climate warming, loss of greenspace would amplify the adverse effects of climate warming. Our analysis of environmental vectors indicated that vegetation cover has the strongest predictive effect on the composition of communities ($r^2 = 0.82$), followed by temperature ($r^2 = 0.74$) and $PM_{2.5}$ ($r^2 = 0.71$). Similarly, it shows that vegetation is an essential habitat resource as well as microclimate modifier in urban settings.

This study has several limitations worth noting. The one-year sampling duration includes seasonal patterns but does not overcome inter-annual variability or other long-term trends. The identification of specimens to morphospecies for some taxa, particularly poorly known groups such as the Diptera and parasitic Hymenoptera, may underestimate true species richness. Our research concentrated on two cities, and findings may not extend to other Iraqi urban locales with different industrial profiles or weather conditions. Also, the observed data design prohibits any causal interpretation of the patterns observed in it. For future research on the climate, habitat quality and insect communities in Iraq urban ecosystems, experimental manipulation in the field, multi-year monitoring, and functional trait analyses should be employed.

Conclusion

This paper represents an extensive, empirical evaluation of climate-induced changes in urban insect diversity across green and industrial zones in Iraq. According to our results, green zones (GZ) had a significantly higher richness, diversity, and evenness of insects than industrial zones (IZ). Further, temperature and precipitation are the primary climatic drivers of insect community structure in both GZ and IZ. The interaction of habitat type and climate explained a significant proportion (12.4%) of community variation, suggesting that urban green spaces buffer against climate-induced loss of diversity. The temperature-diversity gradient in industrial zones is steeper, meaning communities in these zones may be more vulnerable to ongoing warming. This has dimension for ecosystem services (decomposition, biological control, pollination) provided by urban insect communities. The results highlight the urgent need for urban green infrastructure planning in Iraqi cities from a conservation perspective. Expanding vegetative cover, especially native plant communities, in and around industrial areas can help mitigate thermal stress and exposure to pollution and provide dispersal corridors to enhance connectivity between habitat patches. Conservation practices must be put in place as Iraq is projected to warm by 2–3°C by mid-century. Urban insects and the ecosystem services they provide are losing out. Biodiversity needs to be integrated into industrial zones management plan like, green buffers zones, remediation of contaminated soil in national environmental policy and municipal environmental policy.

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