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Pollinator Decline, Insect Herbivory and Reproductive Failure in Endemic Shrubs Across an Urban Air Pollution Gradient

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Abstract

The collective impact of urban air pollution on endemic plant species in urbanising landscapes relative to other ecological stressors is still poorly comprehended despite its importance as a major ecological stressor. The paper examines the effects of urban air pollution gradients on pollinator activity, the rates of insect herbivory, and the level of reproductive performance of endemic shrubs. Our hypothesis was that as the level of pollution rose, the abundance of pollinators would decline, the level of herbivory pressure would rise, and this would lead to a decline in the level of reproductive success of plants. Field surveys were

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performed within a clearly defined urban air pollution gradient (i.e., low, medium impression of air pollution, and high) and pollinator visitation, herbivory damage, and reproductive measures (fruit and seed set) were measured in an orderly manner. The relationships between air pollution indicators and biological responses and considering site-level variable differences were analysed with the use of Generalised Linear Models and Generalised Linear Mixed Models. These findings indicated that there was a very strong negative relationship among air pollution, pollinator abundance, and high levels of herbivory and significant reductions in reproductive success in the high pollution locations. These results not only indicate the interactive nature of atmospheric pollution into the ecological interaction of multi-trophic systems but also show how endemic shrub species are vulnerable to the atmosphere. The paper presents powerful, model-supported findings of the necessity to have a combined approach to air quality monitoring and biodiversity protection in cities.

Keywords:

Urban air pollution, pollinator decline, insect herbivory, endemic shrubs, reproductive success, GLMM.

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Introduction

The high population density associated with urbanisation has accelerated the rate of air pollution in almost every part of the globe, becoming a serious ecological stressor that is able to modify the atmospheric chemistry, health of plants, and biological relationships in urban and peri-urban environments. Such pollutants as ozone, and the particulate matter have been reported to affect plant physiological processes, disturb the volatile signalings, and alter the workings of the ecosystems and are hazardous to the terrestrial biodiversity (Agathokleous et al., 2022; Agathokleous et al., 2020). However, as an urban vegetation is a sink of atmospheric pollutants, its growth and reproduction are often impaired in the presence of chronic pollution (Das et al., 2025; Prabhakar, 2025). Such environmental forces are especially worrying in the urban environments where ecological processes act in rigid pollution gradients, producing the heterogeneous stress regimes capable of transforming the species relations and stability of the ecological systems.

Pollinators are basic to ensure the reproduction success of plants particularly the endangered plant species which are largely dependent on biotic pollination as a means of population sustenance (Prashanth, 2025). There is growing evidence that air pollution affects pollinator behaviour, sensory perception, and navigation resulting in lower visitation rates and poor-quality pollination services (Fuentes et al., 2016; Madhanraj, 2025; Chowdhury & Chakma, 2025). The urban climate and the structure of the urban landscape are further related with the pollination stress through interaction with pollinator abundance, diversity and efficiency of pollen transfer along urbanization gradients (Biella et al., 2022; Lalit & Chakma, 2023). These disturbances are a severe danger to endemic shrubs, which are especially susceptible to successful downturns in effective pollination due to their geographic particularity of limited geographic distribution and their adaptation to specific ecological setting (Ryalls et al., 2022).

Along with pollination restriction, insect herbivory is another important biotic factor determining the plant fitness and reproductive performance in the polluted environment. The mechanism of defence of plants can be altered by air pollution; this can change the feeding habits of the herbivores, including their level of damage (Duque et al., 2021; Nayak, 2025). High levels of herbivory in combination with low levels of pollination can increase reproductive failure due to displacement of plant resources with flower and seed place (Das et al., 2025; Duque et al., 2021). Nonetheless, a majority of the available research has compared

pollination or herbivory behaviour independently without considering the interactive and probably synergistic impacts of interactions under stress of air pollution in an urban environment (Linden et al., 2023).

Although there has been increased appreciation of the role of pollution-induced ecological disturbance, the studies on the relationship between air pollution, decline in pollinators, insect herbivory, and plant reproductive failure has been only seen to be integrated and appropositively multi-trophic especially in endemic shrub species along urban gradients. The current research is dedicated to the filling of this gap regarding the systematic assessment of the impact of air pollution in urban areas on pollinator activity, the level of herbivory, and reproductive success of endemic shrubs in the urban environment and a clear pollution gradient. Based on a strong Generalised Linear Model and the Generalised Linear Mixed Model framework, the proposed research will quantify both direct and indirect expounds taking into consideration spatial variability (Salabi, 2024**)**. Our hypothesis is that a rise in the level of pollution will cause a decrease in the abundances of pollinators, greater pressure of herbivory, and, thereby, a decrease in the reproductive success of plants. This effort combines several trophic layers into a single analytical system, which offers some new ideas of the pollution-related ecological stress and leads to the evidence-based strategies of maintaining urban biodiversity (Mori & Geweely, 2023; Abdullah, 2025).

Literature Review

The problem of urban air pollution has been well established to contribute significantly to physiological stress among plants over both short-term and long-term exposures to gaseous pollutants and particulate matter, especially in urban and peri urban settings. Ozone and fine particulates are some of the pollutants that disrupt photosynthesis, stomatal processes, and metabolic systems and frequently cause a decrease in growth and impaired reproduction (Agathokleous et al., 2022; Agathokleous et al., 2020). Research has indicated that long-term polluted air can modify the flowering of plants, decrease the pollen viability and deteriorate the entire health of plants thus limiting the capacity to reproduce (Das et al., 2025; Duque et al., 2021). City plants can also trap atmospheric particulates on the fronds of leaf which can further superimpose the physiological stress besides modifying plant-environment relationships (Prabhakar, 2025). The (Table 1) presents a summary of the significant findings on the response of plants to pollution in some of the recent studies.

On top of the immediate effects of air pollution on plants, it also has a profound negative impact on pollinator behaviour and efficiency, thus breaking plant-pollinator mutualism. In both experimental and field-based investigations, atmospheric pollutants have been shown to worsen the quality of floral scent trails, disrupt the olfactory of the pollinators, and increase foraging time, eventually causing lower levels of visitation (Fuentes et al., 2016; Madhanraj, 2025; Chowdhury & Chakma, 2025). Pollinators that are exposed to polluted environments can also have their navigation altered, have a limited learning ability, and species composition which ultimately results in poor pollination services (Dusi, 2025; Chowdhury & Chakma, 2025). The structure of urban landscapes and climate also interrelates with the stress of pollution and determines the diversity of pollinators and the efficiency of pollen transfer along the urbanization gradients (Biella et al., 2022; Lalit & Chakma, 2023). These impacts are especially fatal in endemic plants which were reliant on a few pollinators, and had a low degree of ecological redundancy.

Another pathway of environmental stress that has not been adequately explored in determining plant fitness in polluted environments is insect herbivory. Air pollution has the potential to alter the defence pathways and secondary metabolite synthesis of the plant, which may lead to plant exposure to herbivores, or the change of herbivore site selection (Duque et al., 2021; Nayak, 2025). These stress induced alterations can result in high levels of herbivory pressures, particularly in the urban zones where altered microclimates

and gradients of pollution affect the abundance and activity of the herbivores (Das et al., 2025; Nayak, 2025). Tissue damage that is increasing will not only lessen photosynthetic ability, but can also redirect resources to other stages of growth, such as flowering and seed production, further worsening the adverse impacts of decreased pollination. Nevertheless, the majority of available research has focused on herbivory responses and has not considered pollination under the conditions of pollution stress, restraining an in-depth insight into multi-trophic interactions.

The cause of reproductive failure in the vegetation that experiences the polluted urban environment in most cases is the combination of pollination inhibiting and resource denying elements. A decrease in pollinator visitation, along with an expansion in herbivory and physiological stress may sharply reduce fruit set, seed generation, and fruitful prosperity, especially in those endemic and problematic species with limited adaptive potential (Das et al., 2025; Duque et al., 2021). Although there is a rising body of work of evidence regarding pollution-induced disturbances in various trophic strata, very limited studies have utilised the combined analytical models that can unravel cascading impacts both directly and indirectly in environmental gradients. Generalised Linear Models and Generalised Linear Mixed Models have proved to be effective in the analysis of the ecological data of non-homogeneous urban landscapes and enable authors to model non-normal response variables with consideration of the spatial and site-level variability (Biella et al., 2022; Lalit & Chakma, 2023). GLM and GLMM frameworks are superior to more basic correlation-based designs and have a higher inferential power and ecological interpretation capabilities, rendering them well adapted to the study of the pollution-mediated interaction between plants, pollinators, and herbivores.

Table 1. Summary of key studies on air pollution effects on plant–insect interactions and reproduction

Author	Focus	Key findings	Relevance to present study
Agathokleous et al. (2020, 2022)	Ozone pollution and ecosystems	Ozone disrupts plant physiology, pollinator behavior, and ecosystem interactions	Establishes air pollution as a multi-trophic ecological stressor
Fuentes et al. (2016)	Air pollution and floral scent	Pollutants degrade floral volatiles, increasing pollinator foraging time	Explains mechanisms behind reduced pollinator visitation
Ryalls et al. (2022)	Air pollutants and pollination services	Anthropogenic pollutants significantly reduce insect-mediated pollination	Supports pollinator decline under polluted conditions
Duque et al. (2021)	Ozone effects on plants and biotic interactions	Ozone alters flowering, herbivory, and reproductive outcomes	Links pollution to both herbivory and reproduction
Das et al. (2025)	Urban air pollution and plant reproduction	Air pollution correlates with reduced reproductive efficacy in urban plants	Direct evidence for pollution-driven reproductive failure

Study Area and Experimental Design

The experiment was carried out in an urban environment in which the degree of spatial differences in terms of air pollution was high, which allowed evaluating ecological reactions on a clearly outlined pollution gradient. The three categories of pollution that are low, medium and high were based on the long-term air quality conditions and closeness to large distribution points of major emissions including traffic routes, industrial areas, and centres with large populations. This gradient-based can be used to compare biological responses between contrasting pollution regimes in a systematic way minimising confounding effects of rapid changes in land-use (Wenzel et al., 2020). Information about the places of sampling sites and their comparative level of pollution is displayed in (Figure 1). The atmospheric variables (Traditionally used indicators of air quality) that included fine particulate matter (PM 2.5), nitrogen dioxide (NO 2), sulphur dioxide (SO 2), and a combined

Air Quality Index (AQI) were used to characterise air quality at each location. These are measures of ecological relevance that are commonly used in environmental evaluation measurements in urban areas. The data on pollution were collected at the monitoring stations close to the site and complemented with the site measurements in the cases when they were required to guarantee the proper reflection of the local conditions of exposures. The coproduction of various pollutants gives a total picture of quality of air of the ambient zone and describes the cumulative stress on the vegetation and communities of insects residing in the urban area.

Spatial and temporal replication was employed in the experiment design in order to provide robust inference. The sampling of multiple independent sites personalities under each category of pollution was done to address the problem of spatial heterogeneity whereas observations were recurring throughout the flowering season to ensure the capture of a temporal variation in the behaviour of pollinators, herbivory pressure and reproductive performance. Such a duplicated design minimizes the impact on short-term variations in the environmental properties and confirms the power of identifying the consistent trends in pollution-related trends across the gradient. The criteria for site selection were also well formulated to ensure the ecological comparison between the ends of the gradient. Every site was hosting populations of the target endemic shrub communities and had similar habitat, soil type and management regimes hence isolating air pollution as the contrast variable. Places that had been disturbed recently, actively landscaped, and/or where pesticides were used were avoided to minimise confounding variables on plant-insect interactions. The study design using gradient-based site classification and replicated sampling gives a stringent model of relating urban air pollution and pollinator activity, the intensity of herbivory, and reproductive success in plants.

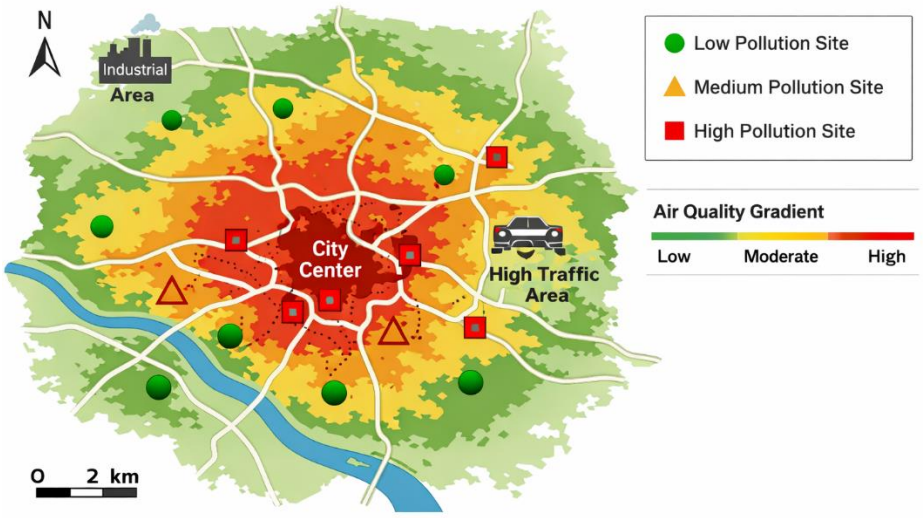

Figure 1. Spatial distribution of sampling sites across the urban air pollution gradient showing low-, medium-, and high-pollution zones

Methodology

The target endemic phenotypes were one or more species of shrub that occur naturally across the targeted urban landscape, and are also known to depend mostly on insect-mediated pollination to engage successfully in reproduction. The selection of species was grounded on their ecological significance, uniformity between the ranges of the pollution gradient, well-defined flowering and fruiting development. The chosen shrubs are conspicuous in bloom, their reproduction can be quantified and the effects of herbivory can be observed, thus it is appropriate in the evaluation of multi-trophic reaction to air pollution in urban areas. Simple ecological characters such as growth form, flowering period and reproductive strategy were recorded in order to be

comparable across the sites of the study. Visual observation protocols were utilized to carry out pollinator survey over the prime period of flowers. The individual focal plants were monitored at every site during a fixed time slot when weather conditions were good to reduce review effects on the study caused by weather conditions such as temperature, winds, or rain. Contingent insects all contacting insects that came into contact with reproductive structures were counted by all and sorted into broad functional groups. The abundance of pollinators was measured in terms of visits made in a given period, and visitation rate was one visit made per flower per time unit. These measures were used to complement each other as they give an estimate of pollination activity and were averaged over repeated observations to minimise bias by time.

Insect herbivory was also evaluated by measuring the foliar damage to sampled plants at a given site. A random sample of continuous expanded leaves in each plant was taken and the percentage of the area removed or damaged was visually estimated using standardised reference charts. The intensity of herbivory was then placed under categorical levels (low, moderate, high) with the percentage damage level identifying the thresholds. This will allow the comparison of herbivory pressure on a consistent basis across sites but help to capture biologically significant spaces in tissue loss. The reproductive success of plants was measured by various reproductive measures in order to represent various levels of reproductive performance. The conversion of flowers into fruits was determined as the ratio of flowers that were able to mature into full-fledged fruits. The number of viable seeds per fruit was used to measure seed set and size (measured by and growth and number of deformities visible) measured fruit viability. All these measures are an indication of the efficiency on pollination as well as resources that is allocated after pollination and this is a measure that offers a combined evaluation of the reproductive performance under different pollution levels.

Table 2. Summary of variables, measurement methods, and GLM/GLMM specifications used in the study

Variable category	Variable	Measurement unit / method	Model role	GLM / GLMM distribution
Air pollution metrics	$PM_{2.5}$, NO_2, SO_2, AQI	μg m^{-3}; ppm; index values from monitoring data	Fixed predictor	Gaussian
Pollinator activity	Pollinator abundance / visitation rate	Number of visits per flower per unit time (visual observation)	Response variable	Poisson / Negative binomial
Insect herbivory	Leaf damage intensity	Percentage of leaf area damaged (visual estimation)	Response variable	Binomial
Plant reproduction	Flower-to-fruit conversion	Proportion of flowers setting fruit	Response variable	Binomial
Plant reproduction	Seed set / fruit viability	Number of viable seeds per fruit; categorical assessment	Response variable	Poisson / Binomial
Environmental covariates	Temperature, humidity, canopy cover	°C; %; visual/photographic estimation	Fixed covariates	Gaussian

Temperature, relative humidity, pH and nitrogen concentration were monitored at the same time when biological sampling was done to eliminate possible confounding factors. Relative humidity and ambient temperature of each site was measured using portable gauges and canopy cover determined visually or by hemispherical photograph. The distance scores such as accessibility to roads, people activities, and observable management policies were also recorded. These covariates were added in order to differentiate the pollution effects against an overall environmental effect. Generalised Linear Models and Generalised Linear Mixed Models were used to conduct statistical analysis in order to determine the correlations between air pollution and variables of biological responses. A Poisson or negative binomial distribution was used to model pollinator counts, binomial based models were used to analyse herbivory proportions, and data appropriate

link functions were used to model reproductive success measures. Indicators of air pollution and biological predictors were considered as fixed effects whereas site identity became a random effect to cater spatial clustering. The information criteria and residual diagnostics were used to select the model and all the assumptions of the model were considered. An overview of response variables, predictors, distributions and model forms is listed in (Table 2). Every analysis was done on the normal statistical package, and the level of significance was measured at a standard level.

Results and Discussion

Obvious geographic difference in the air pollution levels were measured at the study sites chosen, which validated the existence of a clear urban pollution gradient. The concentration of PM 5 pollutants near city centres and major traffic routes were always higher, as well as that of NO 2 and SO 2, and lower pollution loads were observed in more remote and less troubled areas. Medium-pollution locations exhibited in between values where urban conditions are transitional. This gradient gave a strong environmental context to assess biological terms of response and assure that the observed patterns of plants and insect relationships can be effectively understood in context of the level of pollution. The generalised linear mixed model analysis showed that there is a significant and statistically significant decrease in the abundance and visitation rates of the pollinator with increase in the concentration of air pollution. The most optimal pollination activity was observed at the low-pollution sites and declined in a gradual manner to highly polluted sites, and this implies a strong negative relationship between air quality degradation and pollination services. The estimated GLMM coefficients revealed that pollution measures and measures were some of the strongest predictors of pollinator decline after both site-specific variability. The trends can be illustrated graphically in (Figure 2) and show that the effects of urban atmospheric stress are evident in the way the pollinators are reduced progressively in the direction of the pollution gradient and how sensitive the pollinators are to atmospheric stress levels in cities.

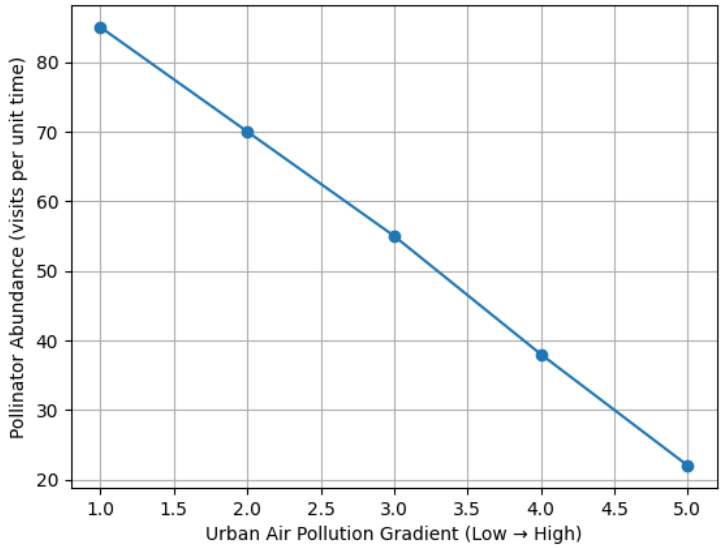

Figure 2. Pollinator abundance across the urban air pollution gradient

This is not the case with insect herbivory, which showed a positive correlation in the level of damage caused by greater exposure to pollution. The leaf area loss was higher and the population of herbivores was more on the plants, which were in high pollutions compared with low-pollution areas. This trend is an indication that physiological stress caused by pollution may compromise the ability of plants to defend themselves or may change the palatability of leaf, thus making them prone to attack by herbivores. The

pressure induced on the herbivores in the polluted condition is observed to increase, which is suggestive of the idea that air pollution never only disturbs mutualistic relationships like pollination but also escalates antagonistic ones, fueling the stress levels in endemic shrubs. Plant reproductive success decreased significantly across the urban pollution gradient, which was the combined effects of low pollination with high herbivory. Conversion rates of flower-to-fruit and seed set were greatly reduced at the highly polluted locations suggesting the presence of strong reproductive deficiency to extreme environmental exposure. Faked results indicated that the abundance of pollinators was positively correlated to reproductive indices, whereas the intensity of herbivory had an adverse impact. The results of the studies indicate that both pollination limitation and tissue damage have a role in dictating reproductive outcomes, and thus the need to take into account several biotic pathways to analyse plant fitness in polluted urban ecosystems.

It was also found that incorporated GLMM results showed that there were strong effects of interaction between the level of pollution, the pollinator activity, and herbivory intensity. There was most severe reproductive performance reduction in sites where pollination had been reduced and high herbivory occurred together, but not at added effect. The resulting combined model, as shown in (Table 3), can be summarised and indicated that air pollution plays a more central role in connecting several trophic disturbances due to its influence on individual factors and the air pollution interaction with them. The spatial heterogeneity is significant in the ecological research of cities because the site-level random effect helped to increase model fit and emphasized the importance of accounting for spatial variation. This data is excellent evidence of ecological and conservation value, which suggests that urban air pollution can disrupt plant-pollinator-herbivore interactions, with non-uniform effects on endemic shrub species. The patterns found are consistent with increasing research on how sensory impairment of pollinators due to pollution and plants being put at a disadvantage in urban settings due to stress interact to deteriorate reproductive success rates. The present research will improve the current knowledge of multi-trophic ecological responses to urbanisation by combining gradient based field data with an effective GLMM that builds on previous research that favours air quality management as an element in urban conservation and planning efforts on biodiversity.

Table 3. Summary of GLM/GLMM results showing effects of air pollution, pollinator activity, and herbivory on plant reproductive success

Response variable	Predictor	Estimate (β)	95% Confidence Interval	p-value
Pollinator abundance	Air pollution index	−0.47	−0.62 to −0.31	< 0.001
Herbivory intensity	Air pollution index	+0.38	+0.21 to +0.55	< 0.001
Flower-to-fruit ratio	Pollinator abundance	+0.52	+0.34 to +0.69	< 0.001
Flower-to-fruit ratio	Herbivory intensity	−0.29	−0.45 to −0.12	0.002
Seed set	Pollinator abundance × Herbivory	−0.41	−0.63 to −0.19	< 0.001

Limitations and Future Research Directions

Although this study did offer valuable information on the role of pollution in mediating interactions between plants and insects there are some limitations which need to be recognised. First, the research was carried out in one flowering period and limits the possibility to take the inter annual fluctuations in the quality of air pollution, population of pollinators, dynamics of herbivory, and plant responsiveness to reproduction. The observed relationships could be affected by seasonal variations in climate, occasional instances of pollution, and annual variation of insect communities. Multi seasonal monitoring over time would thus be useful in determining the temporal consistency of pollution induced ecological trends. The second constraint is associated with the type of the research i.e. observational nature which limits causal inferences. Although the gradient-based design and GLMM framework can be used to draw strong statistical relationships, experimentation on this topic is needed to unambiguously establish causal relationships between air pollution

and pollinator behaviour, intensity of herbivory, and reproductive failure. The influence of pollutants on the experiment either through controlled exposure (pollution manipulation, or exclusion studies) or in uncontrolled exposure contexts may prove useful in untangling of the direct pollutant effects and correlated urban stressors as well as mechanistic verification of the pathways proposed in this work.

Future studies ought to also consider increasing the taxonomy beyond the endemic species of shrub and insect groups of such species discussed herein. The sensitivity of different plant species to air pollution can vary and pollinator and herbivore taxa vary considerably in the physiological tolerance and behavioural acclimatisation to environmental stress. Better representation of plant functional types, pollinator guilds and herbivore assemblages would enhance the generalisation of results and add knowledge on how pollution is reconfiguring multi-trophic urban ecosystem networks. Last, more analytical and technological methods are capable of being integrated that would present the promising prospects of future research. Tight interaction of field ecological research with experimental manipulation, plant volatiles analysis using chemical analysis, and precise monitoring of pollution would provide even better understanding of the mechanisms behind the experiment (Guo et al., 2024). Further, comparison of analyses with more variables of landscape connectivity and urban planning would enhance the extrapolation of ecological results in conservation and management approaches to reduce the effects of air pollution on biodiversity in cities (Ogbonnaya & Mzeha, 2026).

Conclusion

This research paper has shown that air pollution in urban areas has a powerful and complex effect on plant insect interactions, which cause significant losses in pollinator behaviour, insect herbivory, and, in turn, reproductive failure of endemic shrub species across a pollution gradient (Vanderplanck et al., 2021). The analysis enables the provision of statistically valid evidence that air pollution is a focal force of connecting the biotic disturbance of urban ecosystems with considering the spatial heterogeneity by combining field observations of various trophic levels and a strong Generalised Linear Mixed Model framework (Seidenath et al., 2023; Kagarura & Gichoya, 2023). In particular, the results elucidate the utility of the ecological inferences that are sourced with GLMM in unravelling the intricate and often non-linear connexions in urban habitats as well as the susceptibility of endemic vegetation to aggregate pressure relating to both mutualistic and antagonistic associations. Conservatively, the findings highlight the importance to include air quality on urban biodiversity plans since the control of atmospheric pollution is vital to ensure the pollinator services, reproductive success of plants and ecological stability in fast urbanizing landscapes.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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