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ADAPTIVE RESPONSES OF *Tillandsia Recurvata* (HENO MOTITA) TO CLIMATE CHANGE AND ATMOSPHERIC POLLUTION IN THE REGION OF TULA DE ALLENDE, HIDALGO

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Introduction

Climate change has become one of the greatest environmental and scientific challenges of the 21st century due to its cross-cutting effects on ecosystems, biodiversity, and environmental services on which human life depends (IPCC, 2023). Rising global temperatures, changing precipitation patterns, and intensifying extreme weather events are altering the structure and functioning of plant communities around the world. In regions that historically had a temperate climate, these changes have led to significant ecological imbalances, evidenced by alterations in phenological cycles, reproductive processes, and the spatial distribution of multiple plant species (Allen et al., 2015; Peñuelas et al., 2017).

In Mexico, the impacts of climate change have manifested themselves unevenly, but with particularly notable effects in regions with high industrial concentration, where atmospheric pollutant emissions act synergistically with thermal variations to aggravate environmental degradation processes (INECC, 2020). In the Mezquital Valley, and specifically in the region of Tula de Allende, Hidalgo, a sustained increase in the average annual temperature has been documented, accompanied by a decrease in air quality attributed to emissions from the industrial complex that includes refineries, cement plants, and thermoelectric power plants (SEMARNAT, 2022). These conditions are generating environmental pressures that affect the physiology and ecology of local vegetation, leading to observable adaptive responses in native and opportunistic species.

Among these species, *Tillandsia recurvata* (heno motita) stands out, an epiphytic bromeliad widely distributed in Latin America, recognized for its ability to colonize environments with a high degree of disturbance (Chaves & Rossini, 2019). This species has a remarkable tolerance to extreme conditions, as it obtains most of its water and nutrients directly from the atmosphere through specialized trichomes. However, several recent studies have shown that T. *recurvata* increases its biomass and population density in areas with high levels of atmospheric pollution, suggesting that certain pollutants—particularly nitrogen compounds and particulate matter—may be acting as supplemental sources of nutrients (Cervantes-Sánchez et al., 2019; López-Hernández et al., 2021).

The uncontrolled proliferation of this bromeliad has important ecological implications. By establishing itself on the branches and trunks of living trees, T. *recurvata* initially acts as a harmless epiphyte, but as its biomass increases, it generates an excessive load that reduces the host's photosynthetic capacity, accelerates tissue desiccation, and, in severe cases, leads to the death of the tree (Martínez-Sánchez et al., 2022). In addition, some authors have reported possible allelopathic effects exerted by secondary metabolites released by the bromeliad, which could inhibit the growth of shoots and leaves of the host (Rebollo-Vargas et al., 2020). This negative interaction favors the progressive loss of forest cover, compromising the ecological function of urban and peri-urban ecosystems.

In addition to their proliferation, an unusual reproductive phenomenon has been observed: **viviparity**, understood as the germination of seeds within the fruit before their dispersal. This process, although uncommon in bromeliads, has been reported as a possible adaptive response to environmental stress, especially in contexts of high temperature and low water availability (Cascante-Marín et al., 2018). In the case of T. *recurvata,* viviparity could represent a survival strategy that ensures the continuity of the species in the face of adverse environmental conditions, reducing the risk of mortality of seeds exposed to a contaminated and dry environment.

In the Tula de Allende region, current microclimatic conditions—high temperatures, low humidity, and high concentrations of pollutants such as SO_2, NO_x, and fine particulate matter (PM_{10} and $PM_{2.5}$)—provide an ideal scenario for these adaptations to manifest more frequently (INECC, 2020; SEMARNAT, 2022). The combination of climatic factors and pollutants has favored the establishment and massive expansion of T. *recurvata,* which has gone from being an indicator species of air pollution to becoming an active agent of ecological degradation. Its proliferation is not only a symptom of environmental deterioration, but also an ecological problem that threatens the natural regeneration of forest and urban ecosystems in the ecological restoration area of the Endhó Dam.

This study aims to analyze the effects of climate change and air pollution on the proliferation and expression of viviparity in *Tillandsia recurvata* in the Tula de Allende region of Hidalgo. The study aims to provide empirical evidence on the adaptive mechanisms of the species in the face of extreme environmental conditions, as well as on the ecological implications of its proliferation in the loss of local forest cover. Understanding the relationship between climate change, pollution, and the adaptive biology of T. *recurvata* will strengthen ecological restoration strategies and enable the design of environmental policies aimed at mitigating the effects of this phenomenon on highly vulnerable ecosystems.

General objective

To analyze the relationship between factors associated with climate change and atmospheric pollution and the proliferation and expression of viviparity in *Tillandsia recurvata* within the ecological restoration area of the Endhó Dam, Hidalgo, in order to identify the physiological and adaptive mechanisms that favor its survival and expansion in environments with high pollution loads and thermal stress.

Methodology

This study was developed using a **quantitative** approach supported by **qualitative** tools, and is therefore considered to be **mixed** in nature. The quantitative component is based on the systematic collection of environmental and biological data—such as climatic parameters, concentrations of atmospheric pollutants, and frequencies of reproductive structures with viviparity—which allow objective correlations to be established between environmental conditions and the phenological responses of *Tillandsia recurvata.* The qualitative component is based on direct observation of the organisms and ecological interpretation of adaptive responses, which together enable a comprehensive understanding of the phenomenon from an ecological and physiological perspective.

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In accordance with the objectives set forth, the research is classified as **descriptive and exploratory**. It is descriptive because it characterizes the current environmental and biological conditions of the *Tillandsia recurvata* species within the study area, detailing its reproductive status and associated pollution factors. It is exploratory because the phenomenon of viviparity in this epiphytic species has not been widely documented in the region of Tula de Allende, Hidalgo, or in similar contexts affected by industrial emissions and extreme climate variations. Therefore, the study seeks to generate initial information that lays the foundation for future explanatory research on the physiological mechanisms that induce this type of reproduction under conditions of environmental stress.

The study was conducted on the **campus of the Technological University of Tula-Tepeji (UTTT),** located within the **Ecological Restoration Zone of the Endhó Dam,** an area that represents a transitional microenvironment between semi-arid ecosystems and industrialized areas. During the June-July-August quarter, **random samples** were taken in **ten different areas** of the campus, considering variations in vegetation cover, sun exposure, and proximity to sources of pollution. Fragments of *Tillandsia recurvata* attached to different host trees were collected from each area, forming a **representative composite sample.** NOM-011-SEMARNAT-1996 was used to collect the hay motes in sterile plastic bags so that the structures would not be altered. In the laboratory, the reproductive structures were observed under **a stereoscopic microscope,** identifying the presence of **viviparity** by detecting embryos or developing seedlings inside the fruit.

In the laboratory, the following procedure was followed:

1. The samples were placed on trays and these on the laboratory table and labeled with the place of collection.
2. Phenomenological observations were recorded from the collected seeds, with an emphasis on reproductive structures and special attention to the identification of fruits with signs of viviparity, using the photographic criteria reported by Pérez-Noyola et al. (2020) as a reference. The structures were photographed for comparative analysis.
3. The fruits were observed directly and with the aid of an optical microscope with 4X and 10X objectives.
4. Green, ripe (as a new line of research will test viviparity in vitro), and viviparous fruits were collected and placed in separate sterile Petri dishes.
5. Notes and photographs were taken of the observations and findings.

At the same time, in coordination with the **Secretariat of Environment and Natural Resources of the State of Hidalgo (SEMARNATH)**, records of **temperature, relative humidity, solar radiation, and concentrations of atmospheric pollutants (SO_2, NO_x, PM_{10}, $PM_{2.5}$, and ozone)** were collected for the sampling period. The data were analyzed using descriptive and correlational statistics to establish preliminary trends between environmental factors and the occurrence of viviparity.

Results

Study area

The ecological restoration area of the Endhó Dam is located in the southern region of the state of Hidalgo, Mexico, and covers an area of approximately 540 km^2 distributed among the municipalities of Tula de Allende, Tepeji del Río de Ocampo, Tlaxcoapan, Tepetitlán, Tezontepec de Aldama, Atotonilco de Tula, Atitalaquia, and Tlahuelilpan. This area is part of the upper Tula River basin, a hydrological system that receives wastewater from the Valley of Mexico and whose environmental dynamics have been greatly modified by industrial, agricultural, and urban activities (CONAGUA, 2022).

Figure 1 shows the geographical boundaries of this area (red line), which includes both industrial and urban areas—particularly in the municipalities of Tula de Allende, Atitalaquia, and Atotonilco de Tula—as well as agricultural and semi-desert sectors distributed throughout Tezontepec, Tlaxcoapan, and Tepetitlán. At the center of the system is the Endhó Dam, a body of water that functions as a regulating reservoir and a point of accumulation of atmospheric and aquatic pollutants, generating a microclimate characterized by high temperatures, low relative humidity, and the constant presence of industrial aerosols (INECC, 2020; SEMARNAT, 2023).

The predominant relief is slightly undulating, with altitudes ranging from 1,900 to 2,300 meters above sea level, and its potential vegetation corresponds to xerophytic scrub and induced grassland (Rzedowski, 2006). Currently, large areas of degradation and loss of natural vegetation cover are observed due to deforestation and urban and industrial expansion (García & Vázquez, 2021). The influence of the Miguel Hidalgo Refinery, the Tula Thermoelectric Power Plant, and various cement and lime factories contributes to high concentrations of pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NO_X), ozone (O_3), carbon monoxide (CO), and suspended particulate matter (PM_{10} and $PM_{2.5}$) (INECC, 2020; Sosa et al., 2022).

According to the Köppen climate classification modified by García (2004), the predominant climate in the region is semi-arid temperate (BS1kw), with an average annual temperature of 18 °C and rainfall ranging from 500 to 700 mm per year, concentrated mainly between June and September. Low humidity and high solar radiation, combined with increased industrial emissions, create a favorable environment for the proliferation of epiphytic species resistant to environmental stress, such as *Tillandsia recurvata* (Zepeda et al., 2023).

For this reason, the Ministry of the Environment and Natural Resources (SEMARNAT) has classified this area as a priority site for ecological restoration, with an emphasis on soil recovery, revegetation with native species—such as *Prosopis laevigata* and *Acacia* farnesiana—and the control of opportunistic species. Among these, T. *recurvata* represents an ecological challenge, as its proliferation is closely associated with air pollution and microclimatic alterations resulting from local climate change (Gómez-Meléndez et al., 2021; SEMARNAT, 2023).

Figure 1. Ecological restoration area of the Endhó Dam, which includes the municipalities of Tula de Allende, Tepeji del Río de Ocampo, Tlaxcoapan, Tepetitlán, Tezon-

tepec de Aldama, Atotonilco de Tula, Atitalaquia, and Tlahuelilpan (own elaboration based on satellite images, 2025).

FIGURE 1. Ecological restoration zone of the Endhó Dam.

Source: Own, based on the Decree

Figure 2 shows the location of the **Technological University of Tula-Tepeji (UTTT),** which is within the boundaries of the **Endhó Dam Ecological Restoration Zone.** This location highlights its strategic importance for academic activities and environmental projects aimed at monitoring and restoring the natural environment affected by pollution and environmental degradation in the region.

In Figure 1, we can see that the atmospheric measurements obtained in the municipality of Tula de Allende during 2025 show a marked seasonal variation in pollutant concentrations. The records for ozone (O_3), sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter (PM_{10} and $PM_{2.5}$) showed significant increases between **June, July, and August,** reaching their maximum values during the period of highest solar radiation and ambient temperature. In particular, ozone exceeded **100**

FIGURE 2. Location of the Technological University of Tula-Tepeji.

Source: Own, based on the Decree.

ppb, sulfur dioxide remained above **150 ppb,** while PM_{10} and $PM_{2.5}$ particles exceeded **300 and 100 ppb,** respectively. These concentrations reflect conditions of **high atmospheric pollution and environmental oxidative stress,** characteristic of the Tula industrial corridor.

Concurrently, in *Tillandsia recurvata* samples collected during these same months on the campus of the Technological University of Tula-Tepeji—located in the ecological restoration area of the Endhó **Dam—the presence of reproductive structures with viviparity** was **identified**, a phenomenon consistent with adaptive responses to extreme environmental conditions. The temporal coincidence between **pollution peaks and the appearance of viviparous individuals** suggests a **direct correlation between exposure to atmospheric pollutants and the alteration of the** species' **reproductive processes**.

Added to this are the extreme climatic conditions that have affected the region in recent years, notably heat waves and prolonged droughts that intensified in April and May 2025, when temperatures above 40°C were recorded (CONAGUA, 2025).

Figure 1 shows the monthly variations in the main atmospheric pollutants recorded in the ecological restoration area of the Endhó Dam, corresponding to nitrogen dioxide (NO_2), sulfur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$), carbon monoxide (CO), and tropospheric ozone (O_3).

Nitrogen dioxide (NO_2) concentrations were high in January (~35 ppb), gradually decreased between June and August (~5–10 ppb), and then increased again towards September (~30 ppb). This behavior suggests that emissions from vehicular traffic and industrial activities predominate during the early months of the year, while the lower concentrations recorded between June and August are related to greater atmospheric dispersion and precipitation washout processes. The increase in September could be attributed to the reactivation of industrial activity or to unfavorable weather conditions for the dispersion of pollutants.

In the case of sulfur dioxide (SO_2), concentrations showed background values between 120 and 150 ppb, with a notable increase towards the middle months of the year (~300 ppb) and further spikes in August and September (~180 ppb). These variations reflect the direct influence of emissions from the refinery and associated industrial processes, suggesting the occurrence of plant shutdowns or start-ups, as well as possible changes in the type of fuel used.

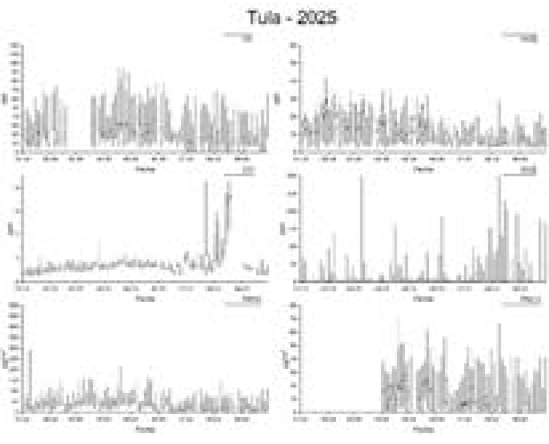
Particulate matter concentrations (PM_{10} and $PM_{2.5}$) showed the most marked pattern of monthly variation. PM_{10} reached high levels in January (60–70 µg/m³), decreasing between June and August (15–25 µg/m³), with a new increase towards September (60 µg/m³). $PM_{2.5}$ showed similar behavior, although with a second intermediate increase attributable to combustion processes and secondary aerosol formation (sulfates and nitrates). The lower values during the middle months of the year can be explained by wet deposition and atmospheric washing.

Carbon monoxide (CO) showed a trend parallel to that of NO_2 and PM, with maximum concentrations in January (1.0 mg/m³), minimum concentrations in the period from June to August (0.2–0.3 mg/m³), and a subsequent increase in September (0.9 mg/m³). This evolution confirms its origin in vehicular and industrial combustion processes.

Finally, tropospheric ozone (O_3) showed an inverse behavior with respect to primary pollutants, reaching its maximum values between April and August (65–70 ppb). This increase is associated with higher solar radiation, which favors photochemical reactions between NO_x and VOC precursors, while its subsequent decrease reflects a decline in incident radiation and an increase in cloud cover.

The oxidative stress generated by high concentrations of ozone, sulfur dioxide, and particulate matter can induce **damage to meristematic tissues and hormonal dysfunction** in epiphytic plants, triggering alternative reproduction mechanisms such as viviparity. This type of response is interpreted as a **survival strategy** that ensures the continuity of the species under conditions of chronic pollution and environmental degradation.

In summary, the results obtained in Tula during the June–August period show a **synchrony between the intensification of atmospheric pollution and the expression of viviparity in** *Tillandsia recurvata*, which **reinforces the hypothesis that atmospheric pollutants act as triggers of physiological stress** capable of modifying the natural reproductive pattern of the species. This finding constitutes a **first experimental indication** in the initial phase of the project and will serve as a reference for the following sampling stages in the eight municipalities that make up the ecological restoration area of the Endhó Dam.



GRAPH 1. Concentrations of O_3, SO_2, SO_2, CO, PM_{10}, and $PM_{2.5}$ during 2025 in the municipality of Tula de Allende, Hidalgo.

Note: Prepared by the authors with data provided by SEMARNATH, 2025.

Figure 3 shows reproductive structures observed in a specimen of *Tillandsia recurvata* collected in the municipality of Tula, Hidalgo. The image shows the coexistence of different reproductive phases in the same plant: (A) flowers in anthesis, (B) developing or fresh fruits, and (C) ripe and dry fruits, some of which show evidence of true viviparity. This finding confirms the reproductive asynchrony of the species, in which floral structures and fruits in different stages of ripeness can be found simultaneously, suggesting an adaptive response to variable environmental conditions, such as the high concentrations of atmospheric pollutants and high temperatures reported for the region (Pérez-Noyola et al., 2020).

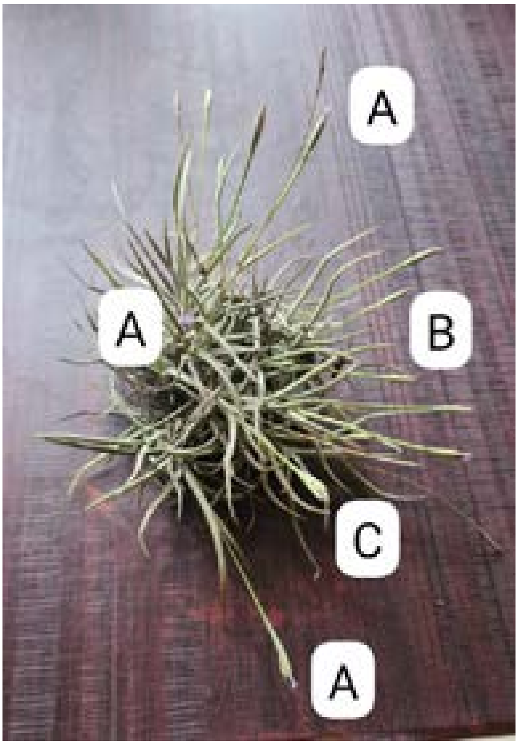


FIGURE 3. Reproductive structures observed in a specimen of Tillandsia recurvata.

Source: Own.

FIGURE 4. Fruit of *Tillandsia* recurvata in an advanced stage of ripeness collected in the municipality of Tula, Hidalgo.

Source: Own.

Figure 4. Fruit of *Tillandsia recurvata* in an advanced stage of ripeness collected in the municipality of Tula, Hidalgo. A bivalve capsule approximately 4.5 cm long can be seen, which begins to open from the apex, revealing the dehiscence process characteristic of the species. The morphology of the fruit corresponds to an elongated linear capsule with thin valves and a leathery texture. This type of structure allows the release of seeds equipped with feathery trichomes that facilitate their anemochorous dispersal; however, in some capsules, the presence of developing seedlings has been recorded, indicative of true viviparity under specific environmental conditions (Pérez-Noyola et al., 2020).

Figure 5 shows a *Tillandsia recurvata* fruit in the process of dehiscence, collected in the Endhó Dam basin, municipality of Tula, Hidalgo. The bivalve capsule, approximately 4.5 cm long, is partially open, showing the release of seeds with whitish feathery trichomes, characteristic of the species. These structures facilitate anemochorous dispersal, allowing the seeds to adhere to available surfaces, such as branches or artificial structures. Observation of this phenological stage allows us to infer an advanced stage of reproductive maturity, and in specific cases, under environmental conditions of high temperature and pollutant concentration, it can lead to the expression of true viviparity (Pérez-Noyola et al., 2020).

FIGURE 5. *Tillandsia* recurvata in the process of dehiscence, collected in the Endhó Dam basin.

Source: Own.

Figure 6 shows a reproductive structure of *Tillandsia recurvata* (Bromeliaceae) in an advanced stage of viviparity, a rare characteristic within the genus. A floral axis is observed that preserves the base of the floral tube and the external bracts partially dry and open, while at its distal end, seedlings developed directly from the ovary emerge.

The seedlings have white, filamentous primary roots, arranged radially and with a hairy appearance, suggesting the onset of an early autotrophic phase. This type of propagation shows evidence of true viviparity, in which seeds germinate before being released, probably induced by environmental stress, such as high concentrations of atmospheric pollutants (NO_2, SO_2, and $PM_{2.5}$) and high temperatures, conditions that, according to Pérez-Noyola et al. (2020), can alter seed maturation and stimulate germination in situ.

The tissue of the pedicel and the base of the ovary show a pale, translucent coloration, indicative of partial dehydration, while the outer surface retains trichomes characteristic of the *Tillandsia* genus, responsible for absorbing environmental moisture.

Taken together, the figure documents clear morphological evidence of the adaptive response of *T. recurvata* to conditions of intense abiotic stress, where viviparity acts as a survival strategy in environments with pollution and high solar radiation, such as those observed in the Endhó Dam basin (Pérez-Noyola et al., 2020).

FIGURE 6. *Tillandsia* recurvata (Bromeliaceae) in advanced viviparity phase

Source: Own

Discussion

The observations recorded in the photographs reveal atypical reproductive behavior in *Tillandsia recurvata* within the ecological restoration area of the Endhó Dam. In photograph 3, the coexistence of flowers, fresh fruits, dry fruits, and fruits with true viviparity on the same plant suggests a simultaneous reproductive strategy that maximizes the dispersal and survival of the species under adverse environmental conditions. This phenomenon can be interpreted as an adaptive response to environmental stress factors, particularly air pollution and microclimatic variability in the region, which influence the phenology and reproductive physiology of epiphytic bromeliads (Benzing, 2000; Díaz & Moreno, 2019).

The presence of fruits with true viviparity (see Figure 6), observed mainly during the months of June, July, and August, coincides with an increase in temperature and relative humidity, conditions that favor early germination of seeds within the fruit. This behavior indicates a phenological change possibly induced by prolonged exposure to pollutants and oxidative stress, factors that can alter the hormonal mechanisms responsible for seed maturation and dispersal (Pérez-Hernández et al., 2020).

In photograph 4, the fruits show different degrees of maturity, supporting the hypothesis of reproductive asynchrony in local populations. Finally, photograph 5, which shows one closed fruit and another open fruit releasing seeds, reinforces the evidence that the reproductive cycle of T. *recurvata* in the region does not occur synchronously, but continuously, which could give it competitive advantages over other plant species in degraded environments. This behavior has been documented in other semi-arid areas of Mexico where T. *recurvata* behaves as an opportunistic species in altered ecosystems (Espejo-Serna et al., 2017).

These findings suggest that the viviparity observed is not an isolated event, but rather a biological indicator of significant environmental changes that warrant further analysis of the adaptive mechanisms of this species in response to stress conditions induced by atmospheric pollution in the Endhó Dam basin.

Conclusions

· The presence of viviparity in *Tillandsia recurvata* constitutes an adaptive response induced by extreme environmental stress conditions, particularly high temperatures, intense solar radiation, and high concentrations of atmospheric pollutants such as SO_2, NO_x, and fine particulate matter.

· The coexistence of flowers, fresh fruits, dry fruits, and viviparous fruits on the same plant demonstrates an asynchronous phenological pattern that allows for continuous reproduction and population persistence of the species under fluctuating environmental conditions.

· The temporal correlation between pollution peaks (June-August 2025) and the appearance of viviparous structures suggests a direct link between air quality deterioration and the modification of the species' natural reproductive processes.

· The viviparity observed could be considered a sensitive bioindicator of the combined impact of climate change and air pollution on the epiphytic ecosystems of the Tula–Tepeji industrial corridor.

· The results of this initial phase provide scientific evidence supporting the need to continue monitoring in the eight municipalities that make up the Endhó Dam ecological restoration area, in order to incorporate these findings into regional ecological restoration and management strategies.

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Acknowledgments

Video provides an effective way to help you prove your point. When you click Online Video, you can paste the embed code for the video you want to add. You can also type in a keyword to search online for the video that best suits your document.

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