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MORPHOLOGICAL CHARACTERIZATION AND ADAPTIVE TRAITS OF *ALTERNANTHERA PHILOXEROIDES* (ALLIGATOR WEED) IN DIFFERENT ENVIRONMENTS

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Abstract *The focus of this research is to determine the morphological characterization of the Alligator Weed (Alternanthera philoxeroides) under different environments. The species is an invasive weed plant that has phenotypic plasticity, stress resistance, and ecological amplitude, which makes this plant a menace to ecological systems and crop production. Shooting Typology, which consists of several phenotypic descriptors including plant height, fresh plant weight (FPW), and dry plant weight (DPW), was used as a covariate to establish a relationship with biomass. The use of regression analysis, correlation analysis, and PCA ranked FPW and DPW as significant sources of variability with moderate secondary effects from plant height. Experiments undertaken in three field sites showed that conditions equivalent to Location 1 enhance biomass yield, while other sites displayed stress growth responses. Such a study supplements the source of information on the invasive ability of A. philoxeroides, particularly in relation to biomass production capability and ecological imperialism. It also estimated the usefulness of this weed as a fodder crop, especially in current times where resources are in short supply. The study is useful for developing appropriate management strategies for invasions by these species and the best way by which they can be used in agriculture and ecosystem rehabilitation. Subsequent studies should pay attention to the stability of trait correlations as determined by genetic factors and the physiological makeup of animals, and investigate specific environmental conditions that may exist to update the control strategies.*

Keywords: *Alternanthera philoxeroides; Ecological invasion; Correlation; Regression analysis; Phenotypic plasticity*

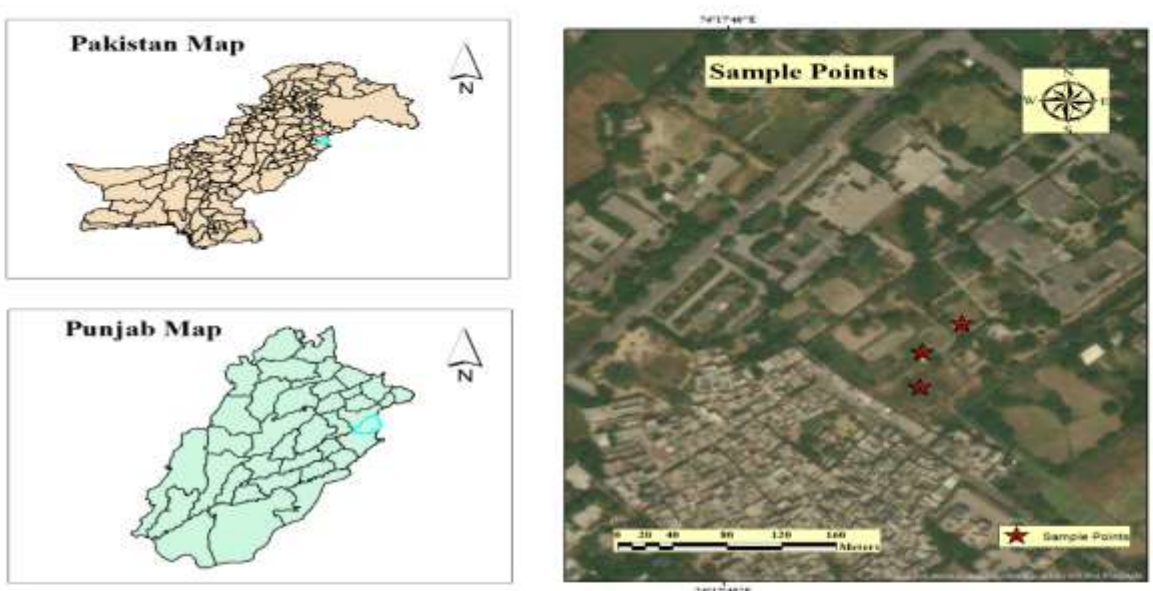
Introduction

Importation of species from one region into another part of the world is one of the greatest challenges facing world environmental conservation nowadays, as seen with the Alligator Weed (*Alternanthera philoxeroides*) (Prabakaran et al., 2019). Given characteristics, invasive species alter the ecological form and function of a system by out-competing and excluding native species. This has negative implications for ecosystem dynamics and environmental security (Christian, 2001). Alligator weed (*Alternanthera philoxeroides*, *Amaranthaceae*, *Caryophyllales*) is native to the temperate areas of South America, still widely distributed and naturalized in a variety of aquatic and dry land habitats in subtropical and temperate regions of the world (Weed, 2002). In mainland China, alligator weed is a listed invasive weed, and it is spreading. Thus, mechanical and biological explanations of alligator weed are troubling because the plant is recalcitrant to control, especially in terrestrial habitats, due to fast regrowth and morphological flexibility (Roy et al., 2023).

It becomes a troublesome weed in many summer season crops in Pakistan, including rice, maize, cotton, and sugarcane, which reduces the yield of the crops by 24-45 % (Farooq et al., 2021). These are reasons such as fast and prostrate growth habit, physio-biological attributes such as its method of reproduction through fragments, phenotypic plasticity, broad ecological amplitude, stress tolerance, absence of natural predators, strong allelopathic capability, and the positive response to global climate change (Shi & Fu, 2017). Several kinds of phytotoxic chemicals have been found in this weed, which have a potent growth depressive impact on crops and weeds (Abbas et al., 2022). Some recommended chemical weed control methods have been proposed by different workers with respect to this weed (Farooq et al., 2021). Nevertheless, low mobility of the herbicide compound in underground or underwater reserve tissues in A. *philoxeroides* reduces its chemical management effectiveness (Howell et al., 2022).

Alternanthera philoxeroides may compete directly with crop fields, fodder, and pastures; therefore, it is pertinent to assess the quality and feed value of this weed before considering its control measures (Hassan et al., 2024). Another method among the agronomical and environmentally friendly, from chemical utilization, is the use of weed plants as fodder crops, with extra advantages like quality fodder for livestock. It also highlighted simple ways of using the weeds to again create forage through which farmers are able to rear more animals cheaply (Cullen et al., 2012). When the demand for fresh forages increases, identifying the potential forage weed can go a long way to meet the nutritional needs of livestock without incurring extra cost to grow fodder (Suthari et al., 2017). The versatility of this weed in growing in aquatic, semi-aquatic, and terrestrial environments can help support fodder during periods of unpredictable rain periods (Tanveer et al., 2018). It was also noted that in the regrowth pattern, *A. philoxeroides* is like that of the pasture species, which apparently is since, following top trimming, the remaining branches developed new buds, and if the buds were trimmed, then the branches below them sprouted more branches (Coetzee et al., 2021). A. *philoxeroides* fodder is quite available in periods of the year when fodder is scanty, like May-June and October–November. It propagates itself by both vegetative parts and seeds, so we use it as fodder, as without its help, it might not be very useful (Driscoll et al., 2024). Some research works done in recent years have focused on the potential of different weed species as a source of fodder and their nutritional potential for animals. Many weed species exhibited nutritive value and digestibility even higher than the common vegetation fodders due to higher protein and leaf-stem ratios (Farooq et al., 2021). Alligator weed usually grows between March and April every calendar year. The aerial part has a vigorous development between May and June, and the plant may reach over one meter high (Sheffield et al., 2022). The flowers are set during July and August, while the seeds are developed between September and November. The plants are dormant during December and February when they are without stems and leaves (Wang et al., 2020). New age research works on alligator weed is based on biological properties (Fang et al., 2024), distribution patterning, management measures, and medicinal uses as an antiviral agent compared to its life history; little is known of its ecological adaptation in varying environments (Qi et al., 2022). The purpose of this research is to examine the morphological description and adaptive mechanisms of *Alternanthera philoxeroides* (Alligator Weed at Different Habitats. For that reason, it is imperative that the morphological differences in combination with the adaptive potential in Pacific cod as a successful invasive species living in extremely different environments are studied both for the furthering of knowledge in the field of ecology and for the optimization of actual management strategies. Focusing on its growth characteristics, main morphological features, and its reaction to various conditions, this study aims to identify the factors that led to its ecological success. The interaction between microhabitat characteristics and behavioral and physiological plasticity in A. *philoxeroides*. Studies on these features will help to explain the invasive capacity of the species and its impact on the localization of native plants. Thus, the results of this study will be valuable for developing efficient long-term management strategies and forecasting the further distribution of A. *philoxeroides* under conditions of climate change and for the successful tackling of invasions of other problematic species, and for enhancing international cooperation to protect the biological diversity.

Figure 1 Sample collecting locations



Materials and Methods

This study was conducted at the field area of the Department of Plant Breeding and Genetics, Faculty of Agricultural Sciences, University of the Punjab, Lahore, to investigate the morphological characteristics and adaptive traits of *Alternanthera philoxeroides*. A single genotype of *A. philoxeroides* was used in this experiment, and the data were collected from three different locations with three replications for the evaluation of the data and to check the performance of the plants at different locations in different environmental conditions.

Plant Material

The genotypes were selected based on their occurrence in different ecological conditions to capture a wide range of morphological and adaptive responses. Each genotype was cultivated in uniform environmental conditions to minimize external variability.

Data Collection

The following parameters were measured in this experiment

Plant Height

The height of each plant was recorded in centimeters with the help of a measuring scale.

Fresh Plant Weight (FPW)

The weight of freshly harvested plants was measured in grams using a digital weighing balance.

Dry Plant Weight (DPW)

After harvesting, the plants were dried in an oven at a 75°C temperature, at a 5% moisture level the dry weight was recorded in grams using a digital weighing balance.

Statistical Analysis

All measurements were performed in triplicate. The data were subjected to statistical analysis to determine the variations in morphological traits among the genotypes. Descriptive statistics, correlation analysis, regression analysis, and biplot analysis were conducted to explore relationships between plant traits and environmental adaptability. Microsoft Excel and RStudio are used to perform all the analysis.

Results

Regression

The regression table gives a description of the links between the dependent variable and the predictors, namely Plant Height and Fresh Plant Weight (FPW). The intercept of the model, of value 0.006, depicts the value of the dependent variable at the time all the predictor variables are equal to zero. But, again, it is not statistically significant as the p-value is 0.977, and the confidence interval (-0.451 to 0.462) contains zero. This implies that the intercept part of the model does not play any important role in the model formulation. The estimated coefficient of 0.008 of the variable Plant Height implies that this variable has a direct effect on the dependent variable, meaning that if the Plant Height increases by one unit, the dependent variable is predicted to increase by 0.008 units. However, this effect does not reach conventional levels of statistical significance; the p-value is.475, CI -0.018 to 0.034. More to that, FPW has a coefficient of 0.021, which suggests a direct relationship between the variable and the dependent variable. Still, this relationship is not a statistically significant one, as can be seen from a high p-value of p value is 0.704. The confidence interval (-0.107; 0.149 includes zero. Looked at overall, then, it becomes clear that neither of the two predictors, namely, Plant Height and FPW delivers a vanishingly small t-value, hence, it can be deduced that these two variables do not contribute to explaining the range of cross-negate for the selected dependent variable. This lack of significance show that the model may be under specified, excluding key independent variables, or that the independent variables themselves relates only feebly with the dependent variable (Table 1).

Table 1. Regression table for Alternanthera philoxeroides

Traits	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.006	0.187	0.03	0.977	-0.451	0.462
PH	0.008	0.01	0.762	0.475	-0.018	0.034
FPW	0.021	0.052	0.399	0.704	-0.107	0.149

Correlation

Scatterplot matrices further give information about plant height and FPW, DPW in relation to Alligator Weed, as well as the distributions of the plant values. A moderate positive correlation (Corr: 0.r = -0.386) is noted between plant height and FPW, depending on the fact that higher plants have more fresh weight, but the correlation coefficient is not very significant. This implies that though height may in one way or another affect fresh weight, besides many factors must be in place to dictate biomass. On the other hand, the correlation between plant height and DPW is weak and negative (Corr: It is found that the covariance of these two variables is (-0.166) which indicates that there is no correlation between these two variables. This tells us that the plants with measured height have equal or equivalent dry weight, hence plant height cannot be extended to dry biomass. The most significant relationship is between FPW and DPW, which shows a strong positive correlation (Corr: 0.846). This suggests the fact that the dry weight of plant is directly proportional to the fresh weight of plant with some constant of proportionality. Such a close relationship emphasizes the role of water content in assessing dry biomass since the quantity of dry weight is obtained when the fresh weight has less water content. Biomass does not vary much with the plant height, while, as for FPW and DPW, they are dependent on each other. FPW can be used far better as the measure for DPW because it is more accurate and powerful, from the comparative standpoint, for estimating biomass in Alligator Weed (Figure 1).

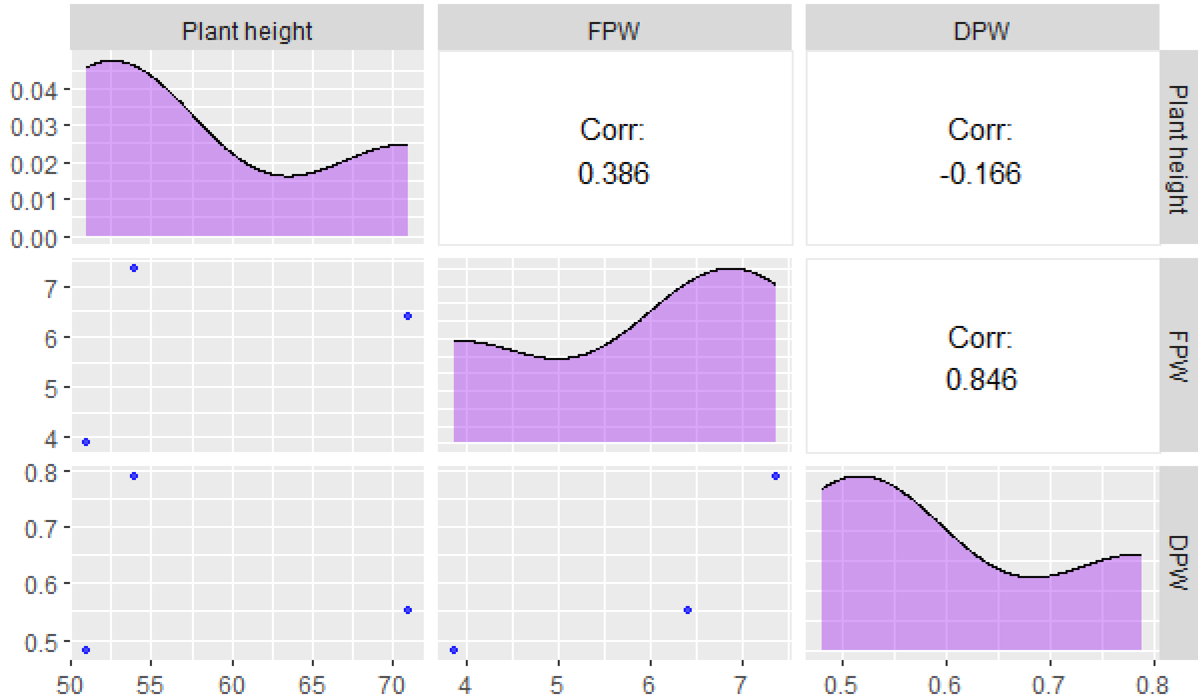


Figure 2. Correlation among different traits of Alligator Weed

Principal component analysis

The first principal component (Dim1) explains a variance of 62.5%, which is the measure that demonstrates the primary variation in the data. The second principal component (Dim2) accounts for 37.5% of the variability; therefore, both PC1 and PC2 account for 100% of the total sample variability. These two components offer a much simpler and more restricted model of the connection between the traits in terms of two dimensions. The yellow dots indicate individual samples, and their locations in the plot show how much they are alike or different from each other, depending on the traits that were examined. The more samples are plotted on the same plane, the more similar their characteristics; and the more they are located in different areas, the more they differ in their characteristics. The arrows denote the traits and point to the extent of their correlation to each of the principal components. The direction and length of the arrows give information regarding the strength and the kind of relation between the traits. Longer arrow corresponds to the higher contribution to the principal components, and parallel-oriented arrows indicate that the correlation between traits exists here. For instance, if arrows for FPW and DPW show much resemblance, it would mean that both these traits affect the principal components equally; in other words, they are positively related (Figure 2). The 'cos2 color scale represents how well each of the traits is explained by the PCA dimensions. All traits are represented well with high cos2 values close to 1, as seen by the yellow shading. This implies that the PCA indeed captures the variance in the data set appropriately. The findings themselves suggest that Dim1 seems to represent the main sources of biomass, which would account for FPW and DPW, whereas Dim2 may be driven by erratic changes associated with other characteristics, including plant height. Finally, the PCA helps to combine all the variables into two principal components, which will help to determine the relationships between the traits more easily. It shows that FPW and DPW may be the major source of variability the high correlation between them; plant height or other traits might play a secondary role only. This analysis gave a clear understanding of how these traits combine and their importance in the dataset (Figure 2).

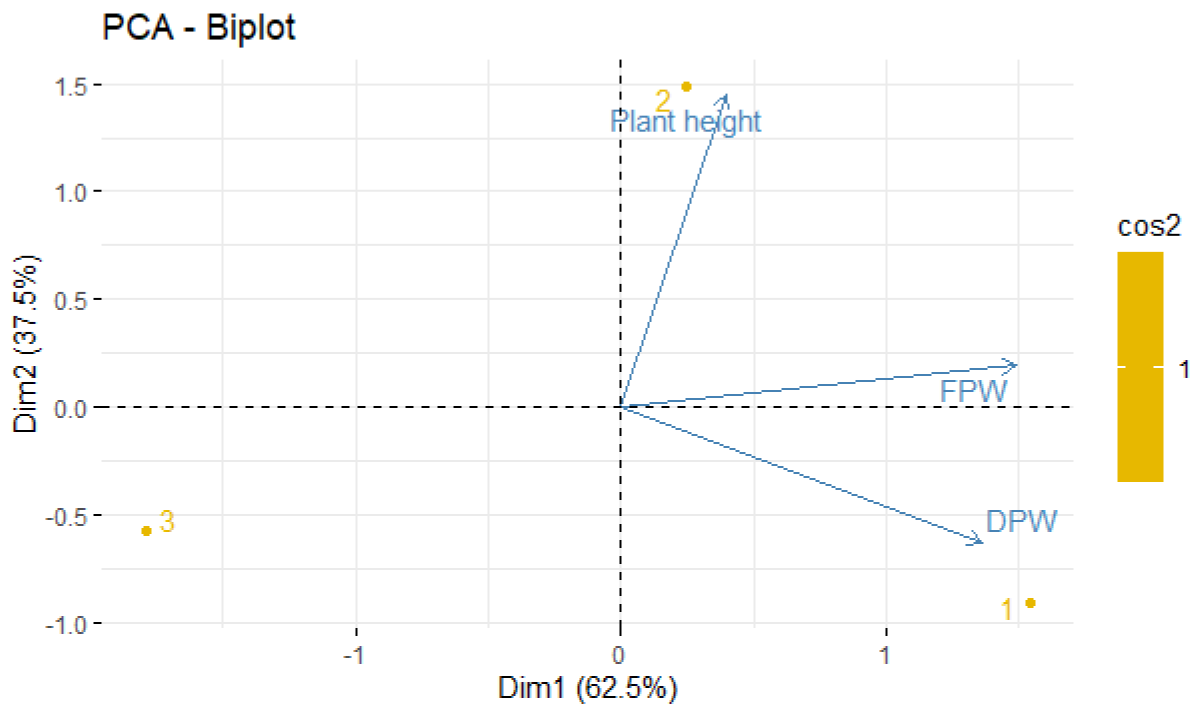


Figure 3 PCA among different traits of Alligator Weed

Discussion

Growth Alligator Weed at three locations offers the necessary and sufficient understanding of the performance of traits under different conditions. Plant samples showed a high positive and significant coefficient of determination between fresh plant weight (FPW) and dry plant weight (DPW), which revealed the significance of fresh growth as an indicator of dry growth. This observation concurs with earlier studies that established that fresh biomass is a measure of the vigor and resource accumulation potential for any plant (Hong-Qun et al., 2023; Hayat et al., 2025ab; Waleed et al., 2025). This also supports the hypothesis that there is covariance between biomass traits, as plants with higher fresh weight contain more water that reduces to a smaller fraction when removed, increasing the dry weight (Liu et al., 2012). While there is evidence of moderate correlation between plant height and FPW, height can therefore not be construed as the sole predictor for productivity in plants. As expected, height sometimes implies access to more light and greater vigor, but biomass data show that height per se does not always equate to obtaining more biomass. This is consistent with what was postulated in the resource allocation theory, whereby plants will invest in a process such as vertical growth or biomass production depending on their environment to some extent, by competition, stress, or nutrient availability (Iqbal et al., 2021; Naeem et al., 2025). Thus, while plant height as a measure of growth performance parameters should be relevant, it should be used cautiously when determining yields (Liu et al., 2022). The PCA extended the results by indicating that FPW and DPW were accountable for most of the variation among the locations, although plant height ranked second. This result underpins biomass traits as a useful tool in framing growth performances of Alligator Weed (Clements & Jones, 2021). Biomass attributes are quite important in view of vigorous production of biomass in invasive plants such as Alligator Weed, where biomass attributes are associated with the invasiveness of a species. The PCA results also confirm the concept that growth is a multivariate process in which various characteristics respond unequally to environmental conditions (Gettys et al., 2014).

Comparing the results of growth performance in different locations, Location 1 was identified as having the highest biomass production, with higher FPW and DPW in comparison with other locations. This suggests that at Location 1 the other factors that may include soil fertility, water availability, or other abiotic factors that may favor biomass accumulation are verse. In contrast to the above findings, Location 2 had higher plant height, although low in biomass characteristics, therefore, indicating that at this site, other environmental conditions may enhance plant height rather than plant biomass. Such a pattern is typical for plants growing in stress conditions where cell expansion is adaptive to gain a competitive advantage in the availability of light or perhaps other resources, all at the potential cost of mass accumulation (Staszek et al., 2021). Location 3 was usually characterized by the lowest performance in all the traits and hence poor growing conditions for Alligator Weed in this site. This could be due to some factors relating to nutrient-limited the ability of plants to grow or produce large biomass within a limited water supply, and some other environmental factors. Poor performance documented at Location 3 emphasizes that the plant performance strongly depends on site conditions, favorable for Alligator Weed growth but not very beneficial for the selected sites (Gettys et al., 2014).

In summary, the findings presented here highlight biomass-related factors, more especially the FPW and DPW as better predictors of Alligator Weed growth than plant height. Thus, these results are important not only to study the patterns and trends in Alligator Weed expansion but also to evaluate its invasive potential and utilization (Wu et al., 2016). From the study, the species has the capacity to generate large biomass depending on the growth condition, as seen at location one, a factor that pronounces it as a biomass resource. However, awareness of the potential for its rapid spread noted in the chapter also makes it a formidable invader capable of sheer domination of certain ecosystems: this aspect implies that its expansion needs to be controlled to prevent impacts on native flora and fauna where it is invasive (Schmid et al., 2023).

Conclusion

The analysis of Alligator Weed's performance across locations and traits reveals significant insights. Plant height showed a moderate positive correlation with fresh plant weight (FPW) but no meaningful relationship with dry plant weight (DPW), while FPW and DPW were strongly positively correlated, indicating that fresh biomass significantly influences dry biomass. Principal Component Analysis (PCA) highlighted FPW and DPW as the primary contributors to variability, with plant height playing a secondary role. Among the locations, Location 2 exhibited the best plant height, but Location 1 consistently outperformed in FPW and DPW, demonstrating superior fresh and dry biomass production, while Location 3 lagged in all traits. Overall, Location 1 was identified as the most favorable site for Alligator Weed growth and productivity, particularly in terms of biomass. Looking ahead, future studies could focus on understanding the environmental or soil factors at Location 1 that support higher biomass production and testing similar conditions in other locations to optimize growth. Additionally, further research could explore genetic or physiological factors contributing to the observed trait correlations and assess their implications for crop management, weed control, or ecological applications.

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Declaration

Acknowledgments
Not applicable

Consent to Participate
Not applicable

Authors contribution
MTT and MM conducted research and wrote the initial draft of manuscript. MTT, MM, and QH collected the literature and wrote the manuscript, and edited the manuscript in original. QH, and MM make final editing in the manuscript. All authors have read and approved the final manuscript. The author have read and approved the final manuscript.

Conflict of Interest
The authors state that there is no conflict of interests with regard to this study. There is no conflict of interest in any financial or personal manner concerning the development of this project, the gathering of data, the interpretation of the data, or the writing and publishing of this paper.

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Data Availability statement
All authenticated data have been included in the manuscript.

Ethics approval and consent to participate
These aspects are not applicable in this paper.

Consent for publication
Not applicable