

Original Research Paper

Effect of Temperature and Precipitation on Global Mangrove *Rhizophora* Species Distribution

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Abstract: Climate change influences the distribution of mangroves towards tropical or temperate regions of the world. We hypothesized that *Rhizophora* species organized along complex spatial and temporal temperature and precipitation gradient. To determine the affinity of different mangroves with climatic parameters, the response of eight *Rhizophora* species to seven climatic parameters (i.e., annual mean temperature, annual precipitation, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range and temperature of driest month and precipitation of warmest month) was analyzed with Arc GIS and Maxent software. For temperature and precipitation there was significant difference ($p < 0.001$) among species location. Only *R. selala* ($p < 0.001$) differed most from the rest taxa in temperature. The jackknife test in Maxent revealed that minimum temperature of coldest month (regularized training gain ~ 0.71), temperature annual range, (regularized training gain ~ 0.66) and annual mean temperature (regularized training gain ~ 0.36) were the most important environmental parameters that determine the occurrence of *R. mangle*, being the most dominant species. This outcome was further validated by an accuracy of 91%. This implies that temperature was a better predictive parameter than precipitation in the distribution of *R. mangle*.

Keywords: Arc GIS, Bioclim, Climate Change, Maxent, Mangroves, *Rhizophora* Species

Introduction

Mangroves occupy more than 150,000 km², occur in over 123 countries and contain more than 73 species and/or hybrids (Bunt, 1992; Spalding, 1997; Spalding *et al.*, 2010). Mangroves are divided into the Indo-West Pacific (IWP) and the Atlantic East Pacific (AEP) groups (Duke, 1990; Macnae, 1968). They originated from a warm environment (Plaziat *et al.*, 2001) and their distribution is influenced by meteorological events (Alongi, 2008) such as temperature (Duke, 1992) and precipitation (Saenger and Snedaker, 1993). These climatic parameters influence their habitat specificity (Feller *et al.*, 2010). Although, tolerance to warm conditions dictates their distribution, they sometimes drift to temperate regions where inhospitable weather threatens their existence (Hogarth, 1999). Global warming causes mangroves to spread beyond their latitudinal limit (Ellison, 2000; Field, 1995). For example, New Zealand, southern Australia, southern

Brazil and South Africa are countries that have temperate weather, but have mangroves. Tropical conditions are the best for mangroves, but excessive heat increase the rate of evaporation leading to increase in salinity (Gilman *et al.*, 2008). This situation triggers the succession of salt tolerant mangrove species (e.g. *Avicennia germinans*) over low salt-tolerant species (e.g. *Rhizophora*) (Lugo, 1980). Increase in temperature affects hydrology, evapo-transpiration and water runoff (Dai *et al.*, 2009; Solomon, 2007). Temperature greater than 35°C affects root structure, seedling establishment and photosynthesis in mangroves (Chakraborty, 2013). Continuous rise in temperature can lead to modification, increase in diversity and migration of species into sub-tropical salt marsh areas (Perry and Mendelsohn, 2009) and Arctic pole (Cavanaugh *et al.*, 2014).

Precipitation regulates nutrient up-take and affects productivity (Snedaker, 1995) and survival (Tomlinson, 1998) of mangroves. Moderately warm and wet

equatorial areas with high rainfall have rich supply of mangrove population (Record *et al.*, 2013). However, increase in sea level (Lyu *et al.*, 2014) generates excess water, which drowns mangroves (Gilman *et al.*, 2008).

Similarly, extreme events like global cooling and warming (IPCC, 2014; Scherer and Diffenbaugh, 2014) lead to range shifts and the extinction of organisms (Hewitt, 2004a; Yokoyama *et al.*, 2001). Mangrove propagules are dispersed by tidal currents, but land barriers prevent their movements (Duke, 1990) leading to a discontinuous distribution. This discontinuity causes intra-specific, morphologic and genetic variation in *Rhizophora* species (Dodd *et al.*, 1998).

Rhizophora species were used for this study because they have global dominance as compared to other mangrove species (Rabinowitz, 1978). They are found in latitude 28°N and 28°S in the AEP. They are halophilic and viviparous in nature, which give them the advantage of faster growth and wider distribution outside their geographic range. *Rhizophora mangle* is the most widespread of all *Rhizophora* species. They are also one of the species that have extended beyond the tropics into the temperate region (Afzal-Rafii *et al.*, 1999). The present study examines the key climatic parameters determining the global distribution pattern of *Rhizophora* species. The objective of this study is to determine the climatic and environmental variables that have higher distribution of *R. mangle* species around the globe.

Materials and Methods

Study Species

The eight *Rhizophora* species studied are *R. apiculata*, *R. mangle*, *R. mucronata*, *R. racemosa*, *R. stylosa*, *R. harrisonii*, *R. × lamarckii* and *R. × selala*. Three of these are hybrids i.e. *R. × harrisonii*, *R. × lamarckii* and *R. × selala*. *Rhizophora* species have similar distribution pattern but vary morphologically. The AEP taxa are *R. mangle* and *R. racemosa* while the IWP taxa are *R. mucronata*, *R. stylosa* and *R. apiculata* (Duke, 1992). Mangroves share sympatric and reproductive similarities and undergo hybridization and niche specialization (Cerón-Sousa *et al.*, 2010). For example, *R. × lamarckii*, is an intermediate between *R. apiculata* and *R. stylosa* while *R. stylosa* and *R. mucronata* are morphologically similar (Duke, 1990).

Data Collection and Analysis

Present-only data of mangrove *Rhizophora* species from 41 countries were retrieved from Global Biodiversity and Information Facility (GBIF; <http://www.gbif>) and Tropicos of the Missouri Botanical Garden (www.tropicos.org). Similarly, climatic factors (i.e. environmental data) which were major predictors of

species were downloaded from BIOCLIM (<http://www.bioclim.org>), a bioclimatic analysis and prediction system which uses surrogate terms derived from mean monthly climatic estimates, to approximate energy and water balance at a given location (Nix, 1986). BIOCLIM is a monthly temperature and rainfall values from the past to the current conditions between 1950 and 2000 prepared to generate more biologically meaningful variables (Hijmans *et al.*, 2005). The climatic parameters downloaded (Table 1) are all associated with mangrove distribution patterns (Alongi, 2008; Duke *et al.*, 1998; Gilman *et al.*, 2007).

Data Processing and GIS Software

ArcGIS 9.1 (ESRI, 2006) was used to create shape files for the presence data in a species distribution map (Fig. 1). Countries shape file was exported into Arc GIS with the “Add XY Data” command. The file was converted to raster with the “Hawths Analysis Tool” in extensions. The temperature and precipitation data (Table 2) were then extracted from the shape file already created and the average and standard error calculated and analyzed in R environment, version 2.9.0 (R Core Development Team, 2008).

Maxent (Maximum Entropy Method)

Binary probability distribution in Maxent software version 3.1.0 (Phillips *et al.*, 2006) was used to determine the most important environmental data. Maxent uses background data based on maximum entropy, which is the cumulative probability of species occurrence (Phillips *et al.*, 2004). It uses the principle of environmental niche modeling, where the niche model was divided into a sample and an environment part, which are jointly used to predict species occurrence. Maxent is similar to the Gibbs probability distribution ($q\lambda$) equation and both maximize the product of the probabilities of the sample locations (Phillips *et al.*, 2004; 2006).

Maxent uses the jackknife test to assess environmental variables that are important to species ecological niche and distribution (Phillips *et al.*, 2004). Jackknife test gives the quality of the models and checks the suitability of the environment for each species. The probability of occurrence of species in Maxent is divided into two in-built suitability ranges of 0-49 (unsuitable) and 50-100 (good). Maxent also uses the Receiver Operating Characteristics (ROC) curve to calculate the Area Under the Curve (AUC). The AUC measures the speed with which the model encompasses the testing points and varies between 0 and 1, where 0 is the least and 1 the maximum obtainable point. Thus, the higher the training gains, the better the model and the lower the training gain the poorer the model.

Table 1. Environmental data and training gains used in modeling *R. mangle*. It shows that minimum temperature of coldest month is the most important climatic parameter influencing *R. mangle* distribution. The seven environmental variables are in-built in Maxent software and represented by BIOS1-7. In the course of the analysis the most significant variable was scored and detected graphically (Fig. 2)

S/No	Parameters	Description of environmental variables	Training gains
1	BIO 1	Annual Mean Temperature (C° * 10)	0.38
2	BIO 5	Maximum Temperature of warmest month (C° * 10)	0.07
3	BIO 6	Minimum Temperature of coldest month (C° * 10)	0.71
4	BIO 7	Temperature annual range (P5-P6) (C° * 10)	0.66
5	BIO 12	Annual Precipitation (mm)	0.00
6	BIO 13	Precipitation of warmest month (mm)	0.11
7	BIO 14	Precipitation of driest month (mm)	0.00

Table 2. Average coordinates of *Rhizophora* species presence-only data and their temperature and precipitation tolerance range retrieved from countries shape file in databases (i.e. GBIF and Tropicos). It shows that that *R. mangle* had the highest training gains

Species	Longitude (x) ±SE	Latitude (y) ±SE	No. in GBIF & Tropicos	Temperature (C°)±SE	Precipitation (mm)±SE
<i>R. × harrisonii</i>	-68.7±3.6	6.9±0.7	49	26.6±1.09	2456.0±1.2
<i>R. apiculata</i>	141.2±1.9	-7.5±0.7	69	26.1±1.0	2576.5±1.0
<i>R. × lamarcki</i>	-9.4±0.08	147.3±0.04	2	26.6±0.2	1423.5±28.9
<i>R. mangle</i>	-86.8±0.5	15.6±0.2	1277	25.5±1.8	1944.0±109.4
<i>R. mucronata</i>	-2.4±1.8	101.3±4.6	103	25.2±1.8	1668.0±87.5
<i>R. racemosa</i>	7.4±0.4	-59.7±3.4	85	25.9±2.6	2602.0±119.7
<i>R. × selala</i>	164.3±0.01	164.1±0.01	12	23.4±0.01	1106.0±0.01
<i>R. stylosa</i>	-14.5±0.7	139.7±1.03	104	25.4±3.4	1498.0±77.9

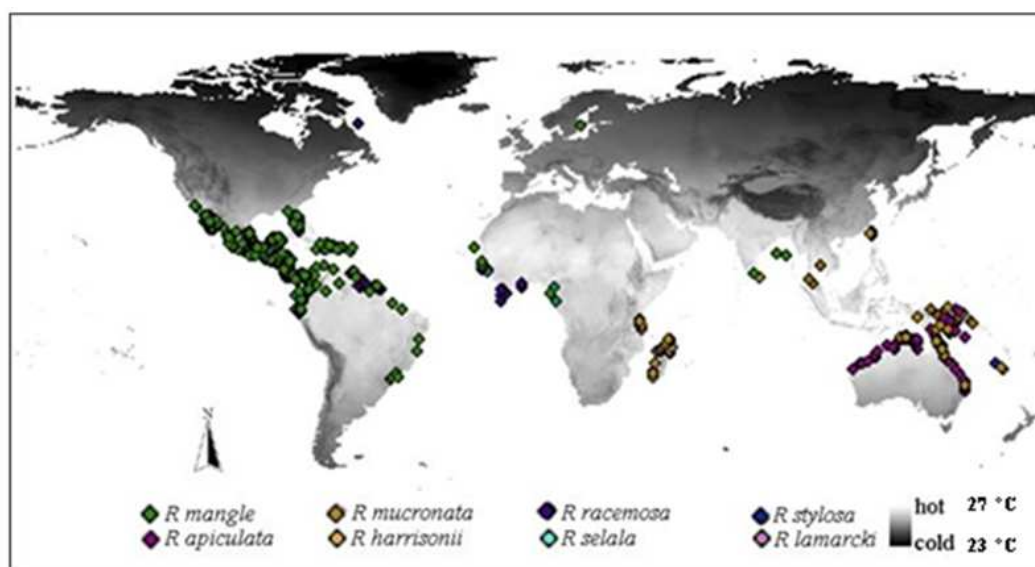


Fig. 1. Global distribution of eight *Rhizophora* species indicates that more species are found in the tropical and equatorial regions in the Atlantic East Pacific region than the Indo-west Pacific regions. *Rhizophora mangle* (green color) is the most dominant *Rhizophora* species around the globe

Two characteristics that stand out in this analysis are the response curves and the variable model contributions. They give the environmental variables that have the most influence on the distribution of *Rhizophora* species and indicate the affinity each species have for the temperature and precipitation variables. In all, seven climatic parameters (i.e., annual mean temperature (BIO 1), Maximum

temperature of warmest month (BIO 5), minimum temperature of coldest month (BIO 6), temperature annual range (BIO 7), annual precipitation (BIO 12), precipitation of warmest month (13) and precipitation of driest month (14)), that are in-built in Maxent were used to graphically present the most significant variable that determine the distribution of the species investigated.

Statistical Analysis and Model Assessment

The ROC and the statistical analysis were performed to validate the data and to test the significance of the variables investigated respectively. The ROC and AUC were not only used to assess the suitability of species occurrence, but were also used as response curve to determine the variables (i.e. temperature and precipitation) that had the highest impact on the distribution of *Rhizophora* species globally. The classifier for the species was plotted as “sensitivity versus 1-specificity”. Sensitivity and specificity are defined as the proportion of correctly predicting presence and absence of species (Wilson *et al.*, 2005). Swets (1988) classified AUC range as follows: 0.90-1.00(excellent); 0.80-0.90 (good); 0.70-0.80 (fair); 0.60-0.70 (poor); and < 0.60 (fail).

Pairwise comparisons using t-tests with pooled standard deviation were conducted for temperature and precipitation. A Tukeys HSD test was also done to determine the specific differences. A one-way ANOVA test was also performed to determine the level of significance among species using the residuals. All tests were done in R statistical environment (R Development Core Team, 2008). Normality, homoscedasticity, Shapiro-Wilk and Bartlett tests were performed to ensure that the data were normal and the variances equal (Logan, 2010).

Results

The result indicates that there was a significant difference in temperature ($F_{7,1,700} = 8.8$, $P < 0.001$) and precipitation ($F_{7,1,700} = 19.2$, $P < 0.0001$) amongst the *Rhizophora* species. To determine specific differences,

results from the pairwise t-test (Holm, 1979) indicated that *R. selala* was the most significantly different taxa ($P < 0.001$). The Tukeys HSD further shows that *R. selala* was the most significantly different species in terms of temperature and precipitation.

The mean temperature tolerance range of species was 23-26°C, while the mean precipitation tolerance range was 1100-2600 mm in the areas sampled. *Rhizophora* species that occur in the wettest areas (i.e., precipitation > 2000 mm) are *R. racemosa*, *R. × apiculata* and *R. × harrisonii*. In the same vein, *Rhizophora* species that occur in the driest areas are *R. × selala*, *R. × Lamarckii* and *R. × stylosa*. This result indicates that the hybrid species have more affinity for low precipitation. *Rhizophora. × harrisonii* and *R. × lamarckii* had more affinity for higher temperature (i.e. 26°C), whereas *R. × selala* had affinity for the lowest temperature (23°C) in this study. Because of the low sample size of other *Rhizophora* species (i.e. < 10 %, Table 1), *R. mangle* (Fig. 1), which had over 70% occurrence and more training stations (Table 2) was analyzed separately.

Therefore, Maxent results indicate that the most important climatic variable in the distribution of *R. mangle* was minimum temperature of coldest month (regularized training gain 0.71). This outcome was based on the jackknife test, which revealed that when this important parameter was removed from the environmental data it reduced the performance of the entire model. Two other important parameters were temperature annual range (regularized training gain 0.66) and annual mean temperature (regularized training gain 0.38) (Table 2).

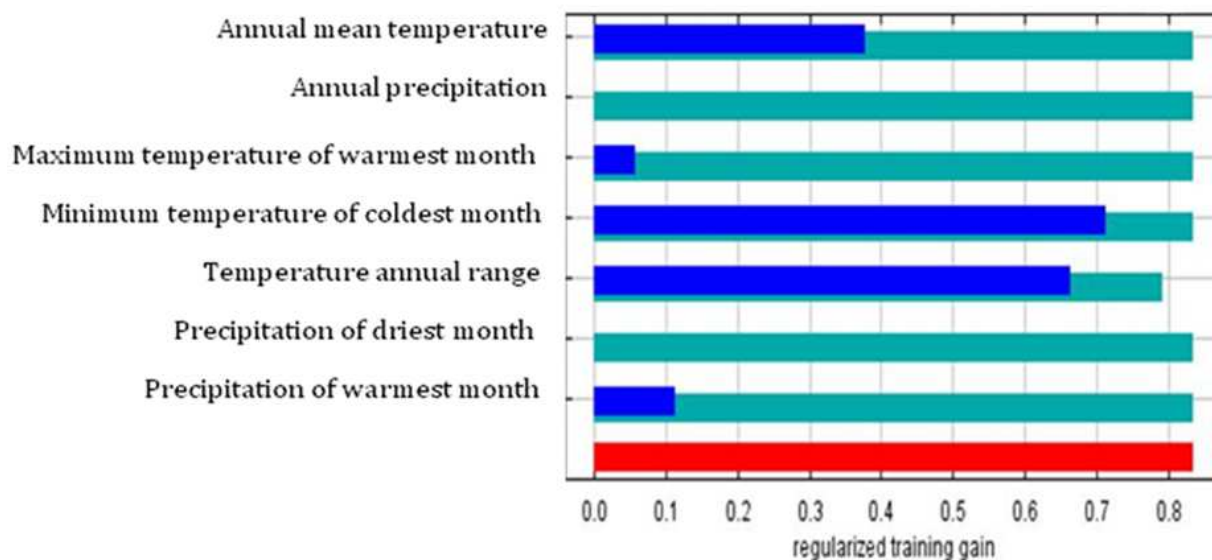


Fig. 2. Jackknife of regularized training gain for *R. mangle* indicates that the most significant climatic parameter is minimum temperature of coldest month. This indicates that cold was a limiting factor for *R. mangle* distribution (The green color on the bar graph indicates that it is without variables, the blue shows it has only variable and the red indicates that it has all variables)

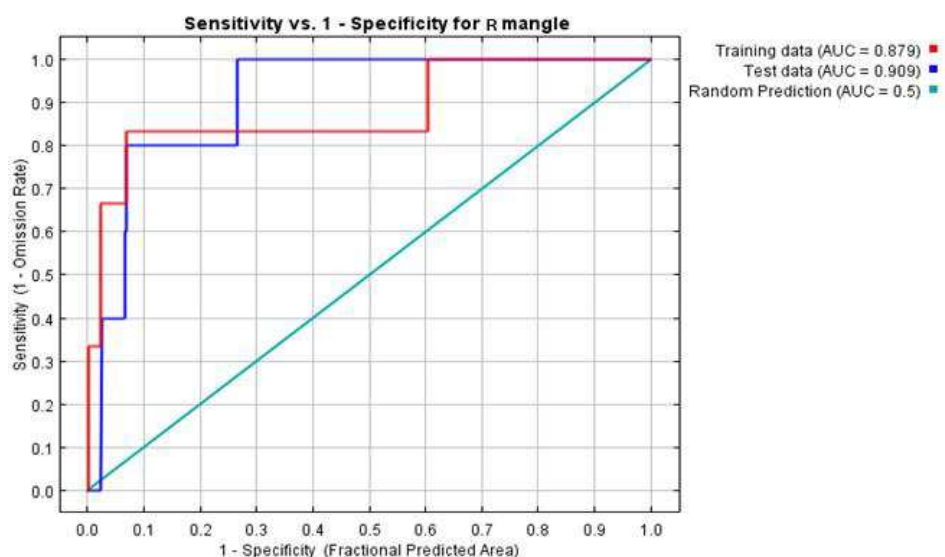


Fig. 3. Receiver operating system (ROC) prediction of *R. mangle* distribution (i.e. AUC = 91% accuracy)

However, values of maximum temperature of warmest month, annual precipitation, precipitation of warmest month and precipitation of driest month were all low (Table 2). This result is further shown in Fig. 2 where the dark blue bars in the legend indicates the contributions of the environmental variables alone while the bluish green bar shows the performance of the model without the environmental variables and the red shows the results when all the variables are put together.

The AUC of the training data (red curve) was 0.88, while AUC for the test data (blue curve) was 0.91 (Fig. 3) in line with the prediction of DeLong *et al.* (1988). Since the percentages of both the training and test data were above 80%, it was assumed that there is a high level of confidence in the prediction of species distribution as influenced by temperature and precipitation.

Discussion

The influence of temperature and precipitation on species distribution (Cavanaugh *et al.*, 2014) indicates that climate change will influence the diversity and global distribution of mangroves (Said, 2003). Therefore the emergence of unprecedented temperature regime is significant towards the survival of organisms and ecosystems (Diffenbaugh and Charland, 2016). This study indicates that temperature and precipitation influence *Rhizophora* species distribution. *Rhizophora* species have low tolerance for temperatures below 0°C and above 38°C (Duke and Allen, 2006). Similarly, precipitation below 40 mm is intolerable to *Rhizophora* species. Nevertheless, precipitations in the warmest and coldest quarters are the highest predictors of mangrove distribution (Record *et al.*, 2013). The most important

predictor of the distribution of *R. mangle* from this study was the minimum temperature of the coldest month. This is in line with other studies that showed that current mangrove distributions are limited by the 16°C isotherm of the coldest month (Ellison, 1994; Gilman *et al.*, 2008). Historically, *Rhizophora* species originated from a hot environment in the Tethys Sea during the Eocene period (Plaziat *et al.*, 2001). This is why they have affinity for hot tropical climates, but global warming is forcing them to adapt to cooler temperature climates around the world, and move away from their latitudinal limits (Feller *et al.*, 2010). Presently mangroves grow outside their geographic ranges in botanic gardens, nurseries and green houses, where favorable temperatures and precipitations are simulated. Although, temperature was a better predictor of *R. mangle* distribution than precipitation in this study, the fact remains that precipitation is also important to the growth and development of mangroves (Saenger and Bellan, 1995) as recorded in our study (i.e. 1000 to 2500 mm). *Rhizophora* species are less halophilic as compared to *Avicennia germinans* that are more halophilic (Lugo, 1980). During drought low precipitation cause increase in salinity levels (Snedaker, 1995), which leads to the migration of *Rhizophora* species to areas of lesser salinity (Lugo, 1980). In contrast, increased precipitation leads to increased run-off, which decreases salinity levels in mangrove environment (Gilman *et al.*, 2008). Thus, during sea level rise *Rhizophora* species may have higher survival than other mangrove species (Pachauri, 2015) given their physiological adaptation and tolerance to flooding (Greenway and Gibbs, 2003; He *et al.*, 2007).

Rhizophora mangle dominance is hinged on their ability to survive diverse climatic and environmental

conditions. Since minimum temperature of coldest month influence their distribution, it implies that cold condition will limit their expansion while warm condition will accelerate their expansion into warmer environments. During future climate change mangroves will undergo positive range shift by migrating (Root *et al.*, 2003) to warmer environments. This means species that cannot shift their ranges (Schloss *et al.*, 2012) because of habitat destruction, geographic isolation and low genetic fitness will go into extinction (Parmesan and Yohe, 2003). For instance, many parts of the world such as Eurasia, North America, tropical South America and tropical North Africa are experiencing $> 1.0^{\circ}\text{C}$ warming over the past half century (IPCC, 2013). In addition, global warming is causing some areas to move into a regime where coolest years are warmer than the hottest years (Diffenbaugh and Scherer, 2011). This has resulted to low inter-annual variability in the tropics and has created new temperature regimes (Anderson, 2011; Diffenbaugh and Scherer, 2011). What all these mean for the mangroves is that there will be an explosion in population growth.

The databases used for this study applied the principle of synonymy or name matching (Holm-Nielsen *et al.*, 1988) to retrieve species information (i.e. name, coordinates and references) from websites. Temperature and precipitation were used because they are the key climatic parameters used in ecological niche modeling for forecasting species distribution (Ellison, 2002; Gilman *et al.*, 2008). Some limitations of georeferencing and data collection were observed (Dahdouh-Guebas, 2011; Record *et al.*, 2013), but were corrected (Yesson *et al.*, 2007) before they were used for analysis. In addition, other parameters that might contribute to species distribution (e.g. soil moisture, radiation, humidity and salinity) will be considered in future work.

Conclusion

Temperature and precipitation enhance the survival of mangroves, but temperature had better predictive power than precipitation in mangrove global distribution. The distribution of *Rhizophora mangle*, the most dominant *Rhizophora* species, is mostly influenced by minimum temperature of coldest month, temperature annual range and annual mean temperature. Out of all the *Rhizophora* species, *R. selala* may likely have more tolerance to future climate change.

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Author's Contributions

Aroloye O. Numbere: Contributed in experimental design, performed data analysis, interpreted the results and did the manuscript writing.

Gerardo R. Camilo: Developed the hypothesis and initiated the conceptual design, supervised the project and was involved in all aspect of the work.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

Conflict of Interest

None of the authors has any conflict of interest to declare.

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