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MATHEMATICAL MODELS TO PREDICT EVAPOTRANSPIRATION OF SELECTED PLANT SPECIES FOR PHYTOREMEDIATION

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Abstract: Phytoremediation is effective and sustainable for treating agricultural wastewater. Constructed wetlands use phytoremediation plant species to absorb and break down water pollutants and remediate wastewater. The growth rate and evaporation of suitable plant species are not widely reported to permit their use in constructed wetlands. This study aimed to measure the growth rate and predict the evapotranspiration rate of *Typha latifolia, Phragmites mauritianus* and *Chrysopogon zizaniodes* using the rhizobox technique. Nine rhizoboxes were constructed to establish seedlings of *T. latifolia, P. mauritianus* and *C. zizaniodes*. Evapotranspiration, root depth and leaf area were measured daily for 67 days. Multiple linear regression models (MLRMs) were derived for each plant species, where the evapotranspiration rate (ET) was expressed as a function of the following variables: leaf area (LA), root depth (RD), sunshine hours (SH), relative humidity (RH), wind run (WR), and temperature (T). T. latifolia consumed 16.70 L of water, which is approximately the total volume of water used by *P. mauritianus* (6.40 L) and 0 (10.51 L). The daily leaf area increases were 2.8±1.4, 11.3±7.4 and 29.2±15.0 cm2.day-1 for *P. mauritianus, C. zizanioides*, and *T. latifolia*, respectively. The daily root growth was 1.2±0.5, 1.0±0.3 and 0.6±0.2 cm.day-1 *for T. latifolia, C. zizanioides*, and *P. mauritianus*, respectively. The MLRM differed among species, and the R2 values were greater than 0.89. The regression equations obtained were as follows: *T. latifolia*, ET= 78+5.46*RD–0.0191*LA + 0.153*WR-2.42*RH + 2.45*T+3.74*SH; *P. mauritianus*, ET= 172+1.31*RD+0.552*LA + 0.170*WR–1.65*RH – 3.40*T+2.11*SH; and *C. zizanioides*, ET = 140+3.61*RD+0.0320*LA + 0.195*WR–1.91*RH – 0.78*T+2.83*SH. A comprehensive understanding of the determinants of evapotranspiration, vegetation growth rates and regression models is fundamental for design optimisation, successful operation and maintenance of constructed wetlands.

Keywords: Rhizobox, constructed wetlands, evapotranspiration, *Typha* spp., *Phragmites* spp.

Introduction

Agricultural wastewater management is a significant concern at both industrial and farm levels. Industries show great interest in conserving water resources by recycling wastewater, especially in agricultural sectors with high water demand (Fatima et al, 2024). Implementing wastewater treatment technologies that facilitate water reuse and energy conservation is crucial for enhancing the

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sustainability of various sectors (Leandro et al, 2019). The practice of reusing wastewater in agriculture is important to offset water shortages (Zhang & Shen, 2017), provide plants with essential nutrients, and reduce the need for fertilisers (Akpor et al, 2015). However, utilising treated effluents in farming necessitates management decisions, including compliance with regulations and guidelines for integration into crop production (Chand et al, 2022).

Phytoremediation has emerged as an effective and sustainable method for treating agricultural wastewater, offering a natural and cost-effective solution for water treatment. The process of phytoremediation involves the use of plants to remove, stabilise, or degrade contaminants in water bodies, making it an environmentally friendly remediation technology (Agrahari and Kumar, 2024). Phytoremediation encompasses various processes, such as phytoaccumulation, phytodegradation, phytostabilisation, and rhizofiltration, which collectively help to purify wastewater (Mamat et al, 2022). The utilisation of aquatic plants in phytoremediation effectively removes pollutants like heavy metals from contaminated water bodies (Ali et al, 2020). In the Republic of Mauritius, a notable successfully constructed wetland was set up at La Plantation d'Albion Club Med, whereby they designed a system to treat the wastewater emancipating from the hotel resort and reusing the recycled water for irrigation purposes.

Constructed wetlands are engineered systems that utilise green hydrophytes in shallow, earthen impoundments to treat various sources of water pollution (Ahmed et al, 2021). These wetlands mimic natural wetland processes and have been recognised as effective technologies for reducing pollution loads and improving water quality (Ahmed et al, 2021). Constructed wetlands act as biofilters, similar to estuaries, effectively removing pollutants from wastewater (Vishwakarma, 2022). Vegetation, substrates, soils, microorganisms, and water collectively contribute to the complex processes involved in removing contaminants and improving water quality in constructed wetlands (Soundaranayaki, 2017).

For the establishment of a constructed wetland, knowledge of the evapotranspiration and growth rate of the vegetation is essential (Chazarenc et al, 2010). Evapotranspiration, which encompasses both evaporation and plant transpiration, plays a critical role in altering the water balance within constructed wetland systems (Towler et al, 2004). Ojoawo et al (2015) reported that evapotranspiration significantly affects the water budget of constructed wetlands. The importance of measuring evapotranspiration in constructed wetlands has been highlighted in various studies. Accurate estimations of evapotranspiration are crucial for determining design flow estimates and evaluating the efficiency of constructed wetlands, especially with regard to water quality improvement (Arliyani et al, 2021).

P. mauritianus and *T. latifolia* are two commonly exploited plants in constructed wetlands (Kulshreshtha et al, 2022). However, *C. zizanioides* has also demonstrated promising phytoremediation efficacy, according to Truong (2000). Owing to its unique morphological characteristics, such as a massive deep root system, and its tolerance to a wide range of adverse agro-climatic conditions, including elevated levels of heavy metals, *C. zizanioides* has been evaluated in phytoremediation studies (Abaga et al, 2021; Masinire et al, 2021; Nakbanpote et al, 2024). Although several studies have been conducted on these plants worldwide, their adaptability and growth rates under local conditions are unknown. Due to the differences in climatic and environmental conditions, data from studies abroad might not be relevant to the local context. Thus, this study focused on determining the evapotranspiration and growth rate of *T. latifolia*, *P. mauritianus* and *C. zizanioides*. The main objectives of this study were to determine the most vigorous plant in terms of root and leaf growth among the three species, measure the rate of evapotranspiration of the three plants, and develop mathematical models to predict the evapotranspiration of each of the three species.

Materials and Methods

Description of the study site

The field experiment was carried out at the University of Mauritius Farm, Réduit, 20.23°S and 57.49° E, with an elevation of 307 m above sea level (Worldwide Elevation Map Finder, 2024). The trial lasted over 75 days, during which the experimental site received a mean monthly rainfall of 76.2±5.7mm. The mean temperature was 28.2±1.70C, and the mean relative humidity was 81.8±6.2%.

Construction of Rhizobox

For this experiment, a new design of rhizobox was developed to meet the deep-rooting characteristics of the studied plant species. The rhizobox used was wood on one side wood and glass on the other (Figure 1).

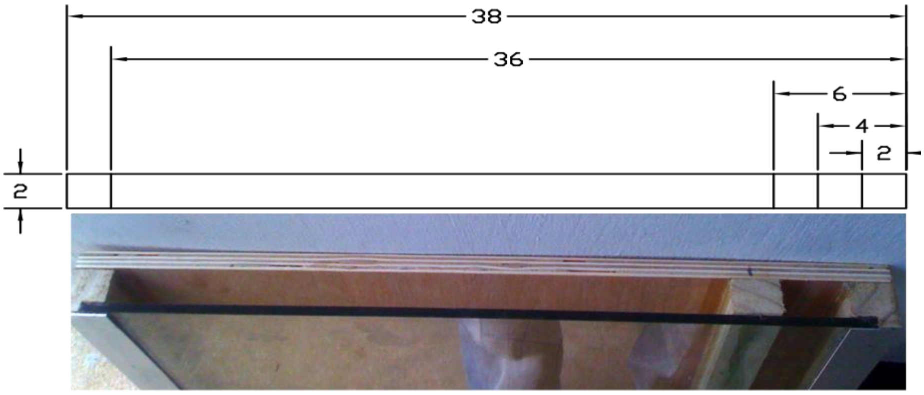


Figure 1: Schematic drawings of the front view (upper photo plate) and top view (bottom photo plate) of the rhizobox used with measurements in cm

The wooden structures were assembled using screws and wood glue. The structures were then coated with polyester resin on all sides to make them waterproof. The glass pane was fixed to the frame with silicon glue to make the structure watertight. The glass pane was affixed to the wooden frame using an aluminium support. The rhizobox consisted of two chambers, namely the root chamber and the water chamber. The root chamber was 30cm long, 2cm wide and 100cm high. The water chamber was 2cm long, 2cm wide and 100cm high. A 98cm long wooden separator leaving an opening of 2cm between the chambers at the bottom was included to allow water movement from the water chamber to the root chamber.

Plant Selection

All the nine plants used were approximately of the same size and stage of growth to enable comparative analysis. Therefore, seedlings of approximately the same size were used. The *P. mauritianus* (common reed) and *C. zizanioides* (vetiver) were procured from a plant nursery, and the *T. latifolia* (cattail) was obtained from the estuarine wetland at Terre Rouge.

Figure 2: Seedlings of *C. zizanioides*, *T. latifolia* and *P. mauritianus*, respectively, before planting

Establishment of the Rhizobox

The 6-8cm bottom layer of both chambers was filled with chippings so as to prevent soil from escaping the root chamber into the water chamber. The root chamber was then filled up to 92cm with an agricultural loamy soil (30% clay, 35% silt and 45% sand). The soil was classified as a Low Humic Latosol or L2 of the Réduit family as per the soil map of Mauritius (Parish and Feillafé, 1965). The total available water (TAW) and readily available water (RAW) contents of the soil are 33.8 mm and 21.9 mm, respectively, for a rooting depth of 45 cm (Chan and Li Pi Shan, 1975).

One plantlet was placed in the middle of each rhizobox and covered with 6cm of soil to hold the plant firmly. The glass side was covered with white tarpaulin to provide the dark conditions needed by the roots, and it was attached with Velcro tape for easy removal and covering. For one week, the plants were watered normally directly into the root chamber to give an adaptation period for the seedlings into the new medium and allow the formation of new roots. The rhizoboxes were leaned glass-side against a metal frame at a zenith angle of 30° facing the north, thus allowing geotropic growth of roots facing glass for easy measurement. Water was then filled in the water chamber until the level in both chambers was above the soil level, which is the mark to which water would be adjusted daily. Finally, the top of the rhizobox was covered with tarpaulin to prevent rainfall from entering and to minimise evaporation from soil and water chambers.

Figure 2: Rhizoboxes showing A. glass pane uncovered; B. front wooden side; C. glass side covered with tarpaulin; and D. side view held by a metal frame

Evapotranspiration Measurement

The rhizobox were filled up, slowly to the mark, with tap water daily to keep the plants in a ponded condition. The volume of water added was noted as the water used by the plant per day. A general water balance equation (Allen et al, 1998) was used:

$I = Q + E + \Delta S$

Where,

I is irrigation or water added daily

Q is runoff ($Q = 0$ since there is no runoff)

E is evapotranspiration

ΔS is the change in storage ($\Delta S = 0$, as the same amount of water is contained within the root chamber all the time)

Therefore $I = E$, that is, the volume of water added = plant evapotranspiration.

Leaf Area Measurement

A Laser Leaf Area Meter (CL-203) was used to record leaf area daily. Then, each leaf was passed through the Laser Leaf Area Meter individually, after which all the individual leaf areas of the particular plant were summed up to obtain the leaf area of the plant. Dried leaves and leaves in the bud stage were not measured.

Root length measurement

A ruler and a measuring tape were used to measure the daily growth of the roots through the transparent glass. The measurement was taken at the start of the root up to the furthest root tip visible.

Experimental design and statistical analysis

In this study, three different plant species were used in triplicates, whereby one plant was established in each of the nine rhizoboxes. The experiment was conducted using a Completely Randomised Design (CRD). Regression analysis was conducted using the multiple linear regression (MLR) model to assess the relationship between the predictor (response) variables and the dependent variable. The R-squared value was calculated to estimate the goodness of fit of the MLR model. An Analysis of Variance (ANOVA) was also conducted to evaluate the statistical significance of the regression coefficients and generate their corresponding p-values.

Results and Discussion

Root depth and growth rate

All three species showed increases in root depth, with *T. latifolia* showing the highest and *P. mauritianus* with the lowest root growth. The roots of *T. mauritianus* were the first to reach the bottom of the rhizobox, while the root depth of *C. zizanioides* and *P. mauritianus* was 78 and 44 cm, respectively, on day 67. The mean root growth rate was 1.2 ±0.5 cm.day-1, 1.0 ±0.3 cm.day-1 and 0.6 ±0.2 cm.day-1 for *T. latifolia*, *C. zizanioides* and *P. mauritianus* respectively (Figure 3).

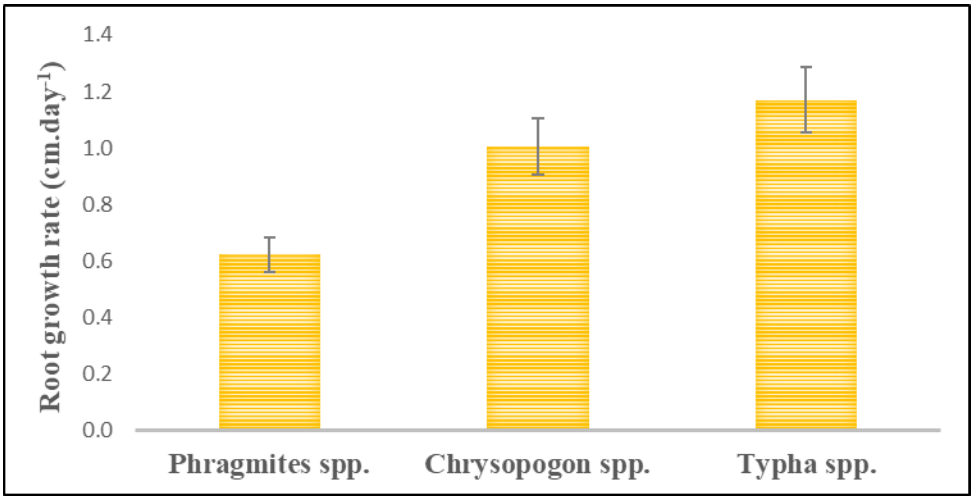


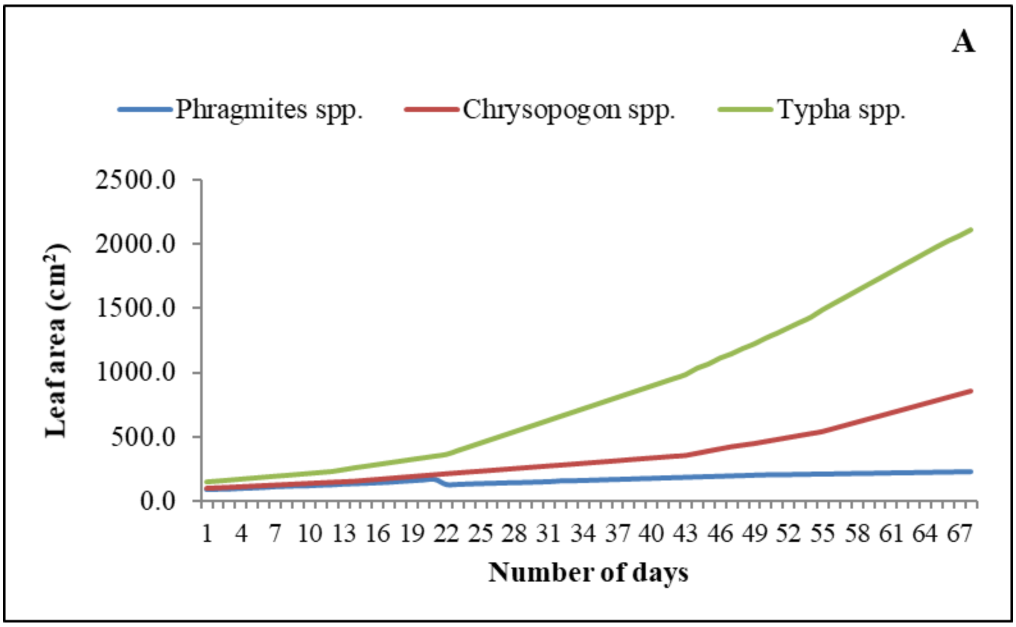
Figure 3: Mean root growth rate per day of *P. mauritianus*, *C. zizanioides spp.* and *T. latifolia*. Vertical error bars indicate the standard deviation of the means (n=67).

Roots of *T. latifolia* grew longer and faster than those *P. mauritianus*, which showed a mitigated growth in waterlogged conditions. Conversely, when the soil is drained and aerated, *P. mauritianus* showed vigorous root growth, with an average daily increase in root length of 2.7 cm (Asaeda and Karunaratne, 2000), suggesting that *P. mauritianus* are better suited for horizontal subsurface flow systems, while cattails thrive in free water surface systems. *C. zizanioides* showed good root growth potential in all types of constructed wetland systems, including floating raft systems in which the roots grow directly in water (Truong, 2000).

In the current study, the roots were waterlogged in the rhizobox to mimic wetlands, and thus, water was not a limiting factor for evapotranspiration. For plants growing in flooded soil, a major stress may be the lack of oxygen to support aerobic root respiration. A common strategy exhibited by wetland plants is internal aeration, accomplished through the development of aerenchyma or airspace tissue. Wetland plants utilise aerenchyma to transport oxygen to their roots, where some of it leaks out into the soil, a phenomenon known as radial oxygen loss (Wolf et al, 2007). Armstrong, Brandle, and Jackson (1994) added that the best wetland species are those that most successfully move oxygen internally from the shoots to the root tips.

Leaf Area

Leaf area increase was small in *P. mauritianus* (89 cm2 to 231 cm2 in 67 days) compared to *T. latifolia* (153 cm2 to 2108 cm2 in 67 days). *T. latifolia* showed the greatest increase in leaf area among the three species. The mean leaf area increase per day was 2.8 ±1.4, 11.3 ±7.4 and 29.2 ±15.0 cm.day-1 for *P. mauritianus*, *C. zizanioides* and *T. latifolia*, respectively.



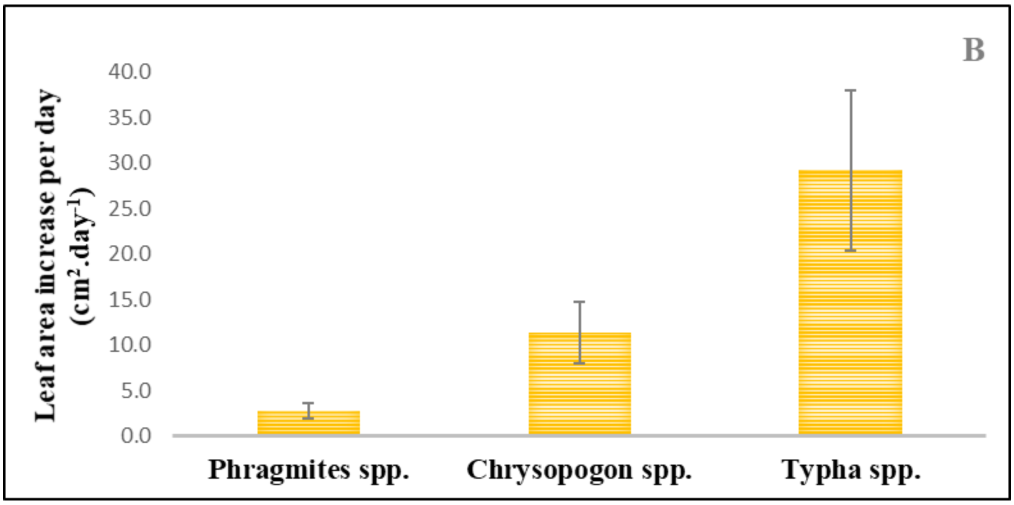


Figure 2: A. Leaf area of *P. mauritianus*, *C. zizanioides* and *T. latifolia* over time; B. Mean leaf area increase per day of *P. mauritianus*, *C. zizanioides* and *T. latifolia*. Vertical error bars indicate the standard deviation of the means (n=67).

The significant difference in leaf area growth rates among these species could be linked to their distinct morpho-anatomical traits and functions. *T. latifolia* showed the most considerable increase in leaf area, which depicts robust growth and high productivity. *T. latifolia* demonstrates a remarkable tolerance to varying nutrient levels, maintaining high productivity even at low nutrient additions, suggesting its adaptability and efficiency in nutrient uptake and utilisation (Haldan et al, 2022). This species has a large leaf area increase and rapid growth rate, which can be associated with its high phytoremediation efficacy. It utilises nutrients for growth while contributing to water purification, making T. latifolia a competitive species in wetland systems.

In contrast, *P. mauritianus*, with a relatively modest increase in leaf area, might exhibit slower growth rates. Asaeda and Karunaratne (2000) demonstrated that *P. mauritianus* performed very poorly in waterlogged conditions, as they recorded poor leaf growth. These findings align with the observations of the present study of very low mean daily leaf area increase of *P. mauritianus* over the study period.

It was also observed that the average leaf growth rate of *C. zizanioides* did not match the vigorous growth recorded by Truong (2000) in waterlogged conditions, where the plants' growth was more than double that of the present study. However, in Truong's (2000) study, the plants were grown in effluent with high nitrogen and phosphorus contents, which may account for the differences. Understanding the differences in species growth can be crucial for ecological management, especially in wetlands where plant species are selected for specific goals (Hadad et al, 2006), such as wastewater treatment or habitat provision.

Crop Evapotranspiration

Evapotranspiration (ET) values of *P. mauritianus*, *C. zizanioides* and *T. latifolia* are depicted in Table 1. The highest evapotranspiration value noted was for T. latifolia, and the lowest for *P. mauritianus*.

Table 1: Mean±SEM values of ET, root length, and leaf area of *P. mauritianus, C. zizanioides*, and *T. latifolia* when the root length of all three species exceeded 40 cm. Within any row, mean±SEM values followed by the same superscripted letter are not significantly different (n>9).

	P. mauritianus	***C. zizanioides***	***T. latifolia***	**p-value**
ET ($mm.day^{-1}$)	23.3±1.2^{a}	35.6±1.2^{b}	49.8±2.0^{c}	P<0.001
Root length (cm)	42.1±0.4^{a}	57.5±1.7^{b}	64.3±2.0^{c}	P<0.001
Leaf area (cm^2)	224.1±1.3^{a}	508.9±28.9^{b}	1154.0±74.0^{b}	P<0.001

Water loss through transpiration helps the plant to dissipate heat that has accumulated as a result of metabolism and radiant energy absorption (Pereira et al, 2006). Hence, a higher ET indicates a higher plant metabolic activity that may imply a higher phytoremedial activity in relation to selecting plant species. The evapotranspiration rate can also help to determine the water yield from a constructed wetland (Knight et al, 2000). In this study, the highest value of evapotranspiration was recorded in T. latifolia and the lowest in *P. mauritianus*. *T. latifolia* had a total water consumption which was more than double that of *P. mauritianus*. Conversely, Oullet-Plamondon et al (2004) measured a higher ET in *P. mauritianus* than in *T. latifolia* in a constructed wetland. However, it is noted that the Phragmites spp. thrived in a horizontal subsurface flow system in the latter study.

In the current research, the rhizobox mimicked a free water surface system, in which Alvarez and Becares (2006) promoted the use of T. latifolia due to its excellent growth rate and performance under such a system. Since *P. mauritianus* has a small leaf area in the present study, the leaf area became a limiting factor for the determination of ET. Thus, a small increase in leaf area showed a significant increase in ET, explaining the higher effect of leaf area on the rate of ET of *P. mauritianus*.

Multiple Linear Regression Models

The three species have their specific Multiple Linear Regression (MLR) equations. The MLR models from which evapotranspiration of *P. mauritianus*, *C. zizanioides*, and *T. latifolia* can be calculated are shown in Table 2, along with the ANOVA p-values and the R-squared values. From the ANOVA at 5% level of significance, there is sufficient evidence ($p<0.05$) that the regression models are highly significant. All three regression models showed very high R2 values (greater than 0.89), meaning that the variability in leaf area, root depth, sunshine hour, relative humidity, wind run, and temperature explained greater than 89% of the variance in evapotranspiration rate. This is regarded as a very good accuracy of the models.

Table 2: The Multiple Linear Regression (MLR) equations from which the ET of *P. mauritianus*, *C. zizanioides*, and *T. latifolia* can be calculated

Mathematical equations		**ANOVA p-values**	**R^2 values**
Evapotranspiration of *P. mauritianus* =	172 + 1.31 (root depth) + 0.552 (leaf area) + 0.170 (wind run) - 1.65 (relative humidity) - 3.40 (temperature) + 2.11 (sunshine hours)	$p<0.05$	0.891
Evapotranspiration of *C. zizanioides* =	140 + 3.61 (root depth) + 0.0320 (leaf area) + 0.195 (wind run) - 1.91 (relative humidity) - 0.78 (temperature) + 2.83 (sunshine hours)	$p<0.05$	0.940
Evapotranspiration of *T. latifolia* =	78 + 5.46 (root depth) - 0.0191 (leaf area) + 0.153 (wind run) - 2.42 (relative humidity) + 2.45 (temperature) + 3.74 (sunshine hours)	$p<0.05$	0.914

MLR Models for the three species

The primary variable affecting the ET of *P. mauritianus* is relative humidity, closely followed by wind speed. This finding aligns with Zhou and Zhou (2009), who demonstrated that ET rates for P. australis were significantly influenced by relative humidity and wind speed, highlighting the critical importance of these factors in ET processes. Additionally, ET for *P. mauritianus* is influenced by root length, leaf area, and sunshine hours, underscoring the multifactorial nature of ET. The ANOVA results indicated that temperature did not significantly affect ET ($p>0.05$). This finding contrasts with earlier studies, such as those by Han et al (2018), which showed a strong dependency of ET on temperature in similar species. However, Zhou and Zhou's (2009) study was conducted in Northeast China, where extreme temperatures were prevalent. Their findings are thus less applicable to the subtropical Mauritian climate.

Monteith's theory points out that ET rates typically increase with rising temperatures. However, the presence of a negative coefficient in the regression equation in this study suggests otherwise. This discrepancy can be attributed to the narrow temperature range observed during the study period. Consequently, the findings indicate that under the specific climatic conditions of Mauritius, temperature may not play as pivotal a role in ET as previously thought. The ET for *P. mauritianus* can be accurately estimated using the derived MLR equation by inputting the corresponding values for the variables identified in this study.

The variable that affected the ET of *C. zizanioides* the most was the root depth, closely followed by relative humidity. Root depth, coupled with relative humidity, are key factors influencing ET, as deeper roots access deeper water sources, which is crucial under varying humidity conditions. Research has also pointed to the hydro-mechanical behaviour of soils affected by root biomass, suggesting that root density and architecture can alter ET rates (Mahannopkul and Jotisankasa, 2019). Wind run and sunshine hours were also high determining factors in the rate of ET. The ANOVA showed that temperature and leaf area have no significant effect on ET ($p > 0.05$). Truong's (2000) findings agree with the involvement of root depth in determining ET but not with temperature and leaf area.

The extent to which the variables affected the ET rate of *T. latifolia* was more or less the same as that of *C. zizanioides*. Root length was the most influential variable on ET, and temperature was the least.

Conclusion

From this study, it can be concluded that *T. latifolia* was the most vigorous plant in terms of root depth, leaf area and water consumption among the three species, while *P. mauritianus* was the least vigorous. *T. latifolia* had the highest ET rates, and *P. mauritianus* had the lowest. *Typha spp*. excelled in waterlogged conditions, confirming its suitability in a free-water surface-constructed wetland. It was confirmed that *P. mauritianus* do not tolerate ponded conditions in the early stages of growth. *C. zizanioides* showed its versatility in ponded situations by virtue of its reasonable growth and evapotranspiration rates. Mathematical models that predict ET were generated for each species. All three equations showed high levels of accuracy in predicting ET. Following this study, the research gap on the lack of species information to permit the design of constructed wetlands has been narrowed. The MLR model developed for *T. latifolia* can be readily used to predict the ET of this species, and it can aid in establishing a free-water surface artificial wetland. A good understanding of the determinants of evapotranspiration, vegetation growth rates and regression models is fundamental to design optimisation, successful operation and maintenance of constructed wetlands.

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Declaration of Interest Statement

The author declares that he has no conflict of interest.

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