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Modelling growth, yield, and future climate suitability for underutilized tropical tuber crops-'aroids': a review

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ABSTRACT

Elephant-foot yam and taro are important tropical tuber crops that are often overlooked and underutilized in the context of climate change and food security. This study aims to explore existing modelling studies focused on growth, yield, and future climate suitability of these crops. Several crop models have been tested internationally to simulate the growth and yield of aroids, including SUBSTOR-Aroids, AquaCrop, and WOFOST. In India, the QUEFTS model has been used to estimate crop yield for aroids based on site-specific nutrient management. Additionally, the EcoCrop model has been employed to predict the future climate suitability of aroids. However, it is important to note that there are limited studies available for aroids compared to other tropical tuber crops. This highlights the need to prioritize research on these underutilized aroids, considering their superior per-hectare production compared to major food grain crops. The review emphasizes the necessity for further modelling studies on aroids to identify or develop better model structures that can be applied across various agro-climatic conditions.

Key words: Elephant-foot yam, Taro, Aroids, Climate change, Food security, Crop models, Climate suitability

Aroids consists of tropical root and tuber crops, which are elephantfoot yam (*Amorphophallus paeoniifolius*(Dennst.) Nicolson) and taro (*Colocasia esculenta* var. antiquorum(L.) Schott) (Sunitha et al., 2023; Sunitha et al., 2021; Sunitha *et al*., 2013). Aroids encompass tropical root and tuber crops, including elephant-foot yam (*Amorphophallus paeoniifolius*) and taro (*Colocasia esculenta* var. *antiquorum*). Despite being staple foods in African countries, aroids have received relatively little attention in research (Bora and Handique, 2023; Raju and Byju, 2019; Ravi *et al*., 2011). However, they exhibit superior dry matter production per hectare compared to major food grain crops and are rich in carbohydrates and essential minerals, making them valuable as supplementary food to combat malnutrition in developing nations (Pushpalatha and Byju, 2020; Bradbury and Holloway, 1988; Nedunchezhiyan *et al*., 2022).

Elephant-foot yam is primarily grown in the Philippines, India, Malaysia, Indonesia, China, and Sri Lanka (Kamalkumaran*et al*., 2020; Sunitha *et al*., 2020), while taro is extensively cultivated in Nigeria, Cameroon, China (mainland), Ghana, and Papua New Guinea (FAO STAT, 2021). These crops are adaptable to a wide range of soil and climatic conditions, with an ideal pH of 5.5 - 6.5 and well-distributed rainfall ranging from 1000 - 3000 mm for elephant-foot yam and 1500 - 2000 mm for taro (Sunitha *et al*., 2020; https://www.cabi.org).

To comprehend crop growth stages and final yield under various environmental conditions and predict crop growth and yield changes due to climate change, modelling studies are essential. While crop models are available for major tropical root and tuber crops such as cassava, sweet potato, and yam (Raymundo *et al*., 2014; Moreno-Cadena *et al*., 2021), there are limited modelling studies for taro, and no specific crop growth modelling studies have been reported for elephant-foot yam, despite its significance as one of the major aroids.

The literature analysis reveals a knowledge gap in modelling studies for aroids, particularly elephant-foot yam and taro, compared to other tropical root and tuber crops (Pushpalatha *et al*., 2021a; Pushpalatha *et al*., 2021b; Pushpalatha *et al*., 2021c). As underutilized crops, elephant-foot yam and taro require more research attention worldwide. Interestingly, there is only one published article focusing on yield management through site-specific nutrient management for elephant-foot yam, and

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four published articles on taro, including studies on nutrient management.

Given the importance of aroids in terms of food security, it is crucial for researchers to focus on these crops. This study aims to analyze existing modelling studies and models for elephant-foot yam and taro, specifically in relation to their growth and yield. Additionally, it will discuss the prediction of future climate suitability for these crops. By addressing the knowledge gap and emphasizing the significance of aroids, this study aims to provide insights to researchers to address malnutrition and the food-demand gap in developing countries.

MODELS TESTED FOR CROP GROWTH, YIELD AND CLIMATE SUITABILITY

SUBSTOR-Aroids model

The SUBSTOR-Aroids model, developed by Singh *et al.* (1998), is specifically designed to simulate the growth and development of taro under various conditions, including unlimited, water-limited, and water and nitrogen-limited conditions. It also incorporates sub-models for upland and low-land conditions. The model considers temperature as a major factor influencing crop phenological development, expressed in terms of daily thermal time or growing degree-days (GDD), as estimated by Santhosh Mithra *et al.* (2012).

In SUBSTOR-Aroids, crop phenological development is directly proportional to temperature when the minimum temperature (Tmin) is greater than the base temperature (Tbase), and the daily maximum temperature (Tmax) is less than 33 °C. However, when Tmin is less than Tbase or Tmax exceeds 33 °C, the model estimates the daily thermal time using weighted 3-hourly temperature data. Crop maturity is influenced by both crop variety and temperature. Root formation and growth are also dependent on soil moisture conditions.

Photoperiod plays a significant role in determining the number of cormels in SUBSTOR-Aroids, as reported by Singh *et al.* (1992). Leaf area is considered crucial for biomass production through photosynthesis. The model estimates leaf appearance as a function of GDD and genotype, using the Gompertz function to simulate leaf area expansion. The number of leaves is determined based on daily thermal time. The specific leaf weight ratio for taro ranges from 38 to 42 g m-2. Potential biomass accumulation is a non-linear function of intercepted photosynthetically active radiation, which is an exponential function of the leaf area index. The optimum temperature for biomass accumulation in taro is found to be 28 °C. The model incorporates a water-stress reduction factor based on Ritchie (1985) and determines nitrogen deficiency using the concept described by Godwin and Jones (1991).

According to Singh *et al.* (1998), the phyllochron interval or the GDD required for a single leaf tip to appear in the crop varies depending on the variety, typically ranging from 122 to 180 °C. Assimilate allocation to roots, leaves, petiole, and corm is determined by the model. During the early growth stage, around 90-100% of assimilates are allocated to roots, leaves, and petiole, while this value drops to 20% during the late season due to accumulation as corm. Leaf growth is reduced under stress conditions, and water limitation leads to increased assimilate allocation to the roots. The model considers assimilate partitioning to be dependent on crop variety, growth stage, and water and nitrogen conditions of the soil. Senescence is influenced by crop growth stage, shading, soil conditions, and environmental factors.

The SUBSTOR-Aroids model demonstrated good performance with an agreement value of 0.95 based on a dataset from 1988 to 1992 in the USA (Singh *et al.*, 1998). However, there is limited available data on this model, and further testing is required. Subsequently, the SUBSTOR model was incorporated as an Aroid module in the Cropping System Model (CSM) of the revised Decision Support System for Agrotechnology Transfer (DSSAT-CSM) community (Jones *et al.*, 2003). The model's complexity and input requirements have limited its applications in developing countries.

FAO-AquaCrop model

The AquaCrop model, developed by FAO (Steduto *et al.*, 2009), is a water-driven model that is widely used to estimate crop yield, gross irrigation requirements, and water productivity. In AquaCrop, yield estimation is based on biomass accumulation and harvest index (HI), which is the ratio of harvested yield to total biomass (Steduto *et al.*, 2009; Hsiao *et al.*, 2009). The model assumes a linear relationship between biomass growth rate and transpiration. The daily soil-water balance in AquaCrop is determined by considering various factors such as infiltration, runoff, deep percolation, crop uptake, evaporation, transpiration, and capillary rise.

Evaporation is estimated based on the percentage of canopy cover (Raes *et al.*, 2009). The model requires input parameters related to the crop, soil, and monthly meteorological data. AquaCrop is known for its ability to work with minimum input data, which makes it suitable for underutilized crops like taro compared to other models in the DSSAT community. AquaCrop was first applied to taro by Mabhaudhi *et al.* (2014) in South Africa. They used field data from 2010-2011 and 2011-2012 to calibrate and validate the model. The results showed a good fit with R2 values of 0.92 and 0.844 for calibration and validation, respectively, and low root mean square error (RMSE) values of 2.38% and 1.85%.

However, further studies using AquaCrop on a wider scale and in different major growing regions of taro are needed to derive more general conclusions about its applicability for this crop. In summary, AquaCrop is a water-driven model that estimates crop yield, gross irrigation requirements, and water productivity. It has been used successfully for taro in South Africa, but more research is needed to validate its wider applicability in different taro-growing regions.

WOFOST model

The World Food Studies (WOFOST) model, developed by Boogaard *et al.* (1998), is a crop simulation model that calculates the potential crop yield, water-limited yield, and nutrient-limited yield on a daily basis from emergence to maturity, taking into account crop variety and environmental conditions.

In WOFOST, daily biomass accumulation is determined based on gross photosynthesis, growth, and maintenance respiration. The daily gross assimilation is the integration of the assimilation rate over the leaf layers throughout the day. A portion of the assimilate is allocated to maintenance respiration and growth respiration, while the remaining assimilate is partitioned among different plant organs.

Leaf area is calculated as a function of temperature and is derived from specific leaf area and the crop's development stage. Canopy growth stages are represented using a Gaussian interpretation. Temperature, solar radiation, and atmospheric CO2 are the major factors influencing crop growth and phenological development in WOFOST.

The soil-water balance in WOFOST is simulated using the tipping bucket approach (Boogaard *et al.*, 1998), and potential transpiration is estimated based on the approaches by Penman (1948, 1956) and Choisnel *et al.* (1992). Evaporation is estimated using the methods developed by Jarvis (1981) and Feddes *et al.* (1978).

Important crop parameters required for model calibration in WOFOST include variety-specific values of thermal times for different growth stages (such as emergence, tuber initiation, and maturity), assimilate conversion coefficients, maximum rooting depth, daily root development rate, and partitioning fractions. Thermal time, expressed as growing degree-days (GDD), for different growth stages is calculated using the daily mean temperature and base

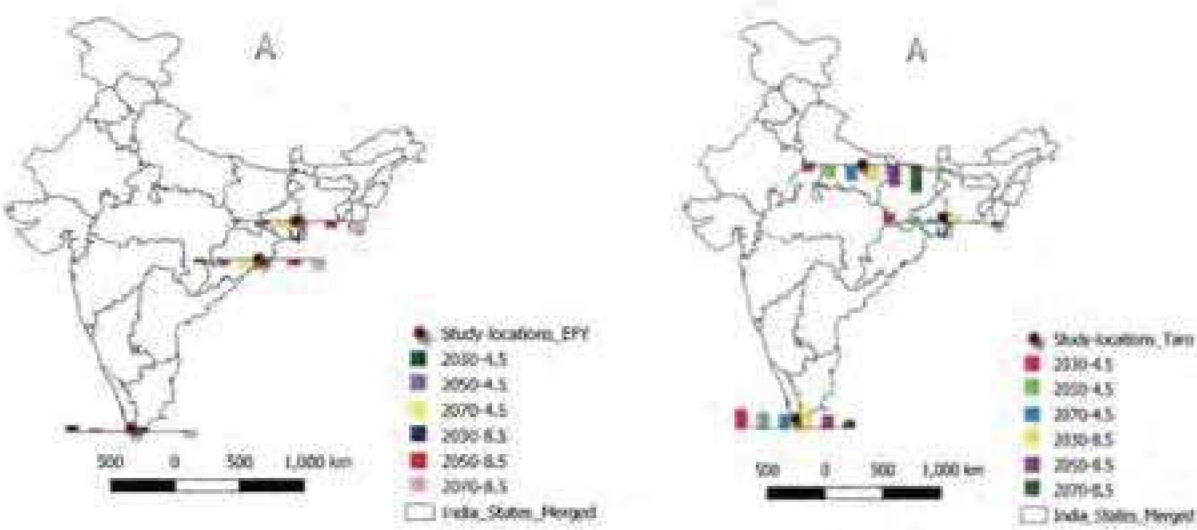

Fig. 1. Yield changes (%) in elephant-foot yam (EFY) and taro for 2030, 2050, and 2070 (*Source*: Pushpalatha *et al.*, 2022)

temperatures specific to each crop variety (Santhosh Mithra *et al*., 2012).

In summary, the WOFOST model is a comprehensive crop simulation model that estimates crop yield, water-limited yield, and nutrient-limited yield based on crop variety and environmental conditions. It incorporates factors such as temperature, solar radiation, atmospheric CO2, and soil-water balance to simulate crop growth and development from emergence to maturity. Calibration of the model requires variety-specific parameters and thermal times for different growth stages.

This model is used in India to simulate the yield of elephantfoot yam and taro with a model error of -0.51 and -0.86%, respectively. The future yield predictions for these crops using WOFOST indicated a percentage change of -10 to 6, -12 to 4, and -16 to 19, -28 to 18 for the future scenarios (Figure 1) for the two representative concentration pathways 4.5 & 8.5 (Pushpalatha *et al*., 2022). These results highlights the importance of these two crops in the future in ensuring food security, especially in rural tribal areas.

QUEFTS model- crop yield based on nutrient management

The QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model, developed by Janssen *et al*. (1990), is a tool for site-specific nutrient management of nitrogen (N), phosphorus (P), and potassium (K) in tropical soils. The model estimates crop yield based on the availability of these nutrients, assuming no other constraints such as water stress or other agronomic practices.

QUEFTS establishes the relationship between chemical soil tests, potential NPK supply from soils and fertilizers, actual NPK uptake by crops, and crop yield. It provides a practical approach for optimizing nutrient management to achieve higher yields in a site-specific manner. This model is particularly useful for understanding nutrient requirements and optimizing fertilizer application in tropical crops.

For elephantfoot yam, Byju *et al*. (2016) calibrated the QUEFTS model and reported a linear increase in corm yield with N, P, and K uptakes of 3.97, 0.71, and 7.05 kg N, P, and K per 1000 kg of corm. Similarly, Raju and Byju (2019) calibrated the QUEFTS model for taro and found a linear relationship between cormel yield and nutrient uptake at rates of 12.97, 2.97, and 17.47 kg N, P, and K per ton of cormel. These studies provide valuable insights into the nutrient requirements and their impact on yield for elephantfoot yam and taro.

However, it is important to note that these calibrations and relationships need to be validated across different major elephantfoot yam and taro growing regions worldwide. Validation studies will help to ensure the accuracy and applicability of the QUEFTS model in different agro-climatic conditions and soil types, enabling effective site-specific nutrient management for these crops.

EcoCrop tested to quantify climate suitability

The EcoCrop model, developed by Hijmans *et al*. (2001), is based on the FAO-EcoCrop database ((FAO, 2000) and focuses on the ecological requirements of crops. It considers optimal ranges of minimum and maximum temperatures, precipitation, and climatic limits where crop production is not possible. The model defines two ecological ranges for each crop, consisting of minimum and maximum absolute temperatures and rainfall. It also includes an optimum range of minimum and maximum temperatures and rainfall. The EcoCrop model calculates separate indices for precipitation and temperatures and then combines them to determine the suitability index for a specific crop. The suitability index ranges from 0 to 1, where a value of 1 indicates excellent suitability for crop growth. The model provides an indication of climate suitability for a crop based on these indices. In the case of elephantfoot yam, Byju *et al*. (2016) used the EcoCrop model to predict climate suitability in India. They assessed the future climate suitability and provided state-wise suitability values for major growing regions in India. The study reported a suitability change ranging from 0.8% to 9.6% across different regions. However, it is worth noting that researchers consider the EcoCrop model to be less sophisticated and less reliable compared to empirical niche models (Taba-Morales *et al*., 2020). Empirical niche models, which are based on observed crop occurrences and environmental variables, tend to provide more accurate and reliable predictions of climate suitability compared to purely ecological models like EcoCrop. As of now, there are no available studies using the EcoCrop model for taro.

CONCLUSION

This study focuses on the existing modelling studies for the growth, yield, and future climate suitability of two tropical tuber crops, elephantfoot yam and taro. It highlights the limited information available on crop models for these aroids and the need for further research in this area. The reviewed crop models include SUBSTOR-Aroids, AquaCrop, WOFOST, and QUEFTS, which have been tested for growth and yield estimation. The EcoCrop model has been used to assess the climate suitability of elephantfoot yam. However, it is observed that there is a lack of studies specifically focused on aroids compared to other tropical tuber crops.

The review emphasizes the importance of studying aroids in the context of food security and climate change. Despite the limited available data, the existing studies suggest that aroids, including elephantfoot yam and taro, have the potential to be recommended as future crops due to their superior dry matter production per hectare compared to major foodgrain crops.

Furthermore, the review recommends conducting more modelling studies on aroids to develop better model structures that can be applied across different agro-climatic conditions. This would help in enhancing our understanding of aroids and their potential as underutilized crops, contributing to food security and sustainability.

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