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Current and future development of *Acrocomia aculeata* focused on biofuel potential and climate change challenges

Tayna Sousa Duque[1], Gabriela Madureira Barroso[1]✉, Cláudia Eduarda Borges[1], Débora Sampaio Mendes[1], Ricardo Siqueira da Silva[1,3], Anderson Barbosa Evaristo[2] & José Barbosa dos Santos[1]

The search for sustainable alternatives to petroleum has driven research on biofuels, with a focus on those derived from organic biomass. This study centres on macaúba (*Acrocomia aculeata*), a promising oilseed for biodiesel production. Advances in cultivation techniques and the mapping of climatically suitable areas are essential to consolidate the use of this species in the energy sector. This work aimed to utilise predictive modelling with the CLIMEX software to assess the current and future climatic suitability of macaúba in the context of climate change. Data on the global distribution of macaúba, growth and stress parameters, as well as climatic variables, were collected. The modelling was conducted based on the A2 SRES scenario for the present, 2050, 2080, and 2100, including the generation of the Weekly Growth Index. Results indicated high suitability in tropical regions, particularly in Brazil and Indonesia. However, future projections highlight significant challenges due to rising temperatures and reduced rainfall. The study provides a critical perspective to guide sustainable policies in the energy sector, underscoring the potential of macaúba as a viable biodiesel source while warning of the challenges posed by climate change.

Keywords Climex, Modeling, Organic biomass, Climate change, Energy sustainability

The growing concern about the environmental impacts resulting from the indiscriminate use of oil has instigated the search for sustainable and innovative alternatives in the energy sector. This non-renewable resource is used as the main source of energy by society in fuels, cosmetics, medicine and plastic manufacturing[1]. Despite being a crucial source for several applications, it has a high potential for emission of greenhouse gases and can trigger harmful events to the environment, such as oil spills and ecosystem degradation[2,3]. With the need for energy transition, biofuels emerge as a promising renewable energy source to mitigate the negative impacts associated with oil[4,5].

Biofuels produced from organic biomass can serve as a partial or complete substitute for petroleum and natural gas fuels in combustion engines and other energy generation systems[4]. Additionally, they are known for their low pollutant emission rates[4,6,7]. Several types of biofuels are obtained from plant species, the most significant being ethanol and, with notable expansion, biodiesel[8,9]. Biodiesel stands out as a sustainable alternative, resulting from the reaction of animal or vegetable fat with alcohol, known as transesterification[8,10]. In addition to being a clean technology, its use reduces dependence on oil and brings economic advantages to several countries[11].

A notable portion of biofuels originates from agricultural products, around 22.4% from canola oil; 15.5% of soybean oil and 10.3% of palm oil produced are used to manufacture biodiesel[12]. Projections indicate an increase in the biofuels market[13]. Therefore, the use of agricultural raw materials impacts the global market and food security[12]. Additionally, competition between the agricultural and energy sectors can exert an indirect influence on land use, with the conversion of natural areas into agricultural land to meet food demand[14]. Therefore, the use of non-agricultural raw materials can mitigate competition between food and fuel.

[1]Department of Agronomy, Federal University of Jequitinhonha and Mucuri Valleys, Diamantina CEP: 39100-000, Minas Gerais, Brazil. [2]Institute of Agricultural Sciences, Federal University of the Jequitinhonha and Mucuri Valleys, Unaí CEP: 39447-790, Minas Gerais, Brazil. [3]Department of Ecological Modelling, Helmholtz Centre for Environmental Research—UFZ, Permoserstr. 15, 04318, Leipzig, Germany. ✉email: gabriela.madureira@ufvjm.edu.br

The macaúba tree, *Acrocomia aculeata* (Jacq.) Lodd. ex Mart. (Arecaceae), native to the Americas, stands out as a promising oleaginous resource for bioenergy, particularly biofuels[15–19]. The species has an estimated oil yield of 6.2 tonnes per hectare, surpassing soybean and comparable to palm oil[15,18,20–22]. Moreover, the use of *A. aculeata* in biofuel production supports the sustainable energy transition and enhances agricultural sustainability. The species can be intercropped with other crops, adapts to diverse soil and climate conditions, and contributes to the rehabilitation of degraded areas[22].

Despite macaúba's exponential potential for biodiesel production, the lack of detailed information about its ecological requirements and performance in various climatic conditions is a gap that deserves attention[23]. The impact of climate on plant growth is indisputable[24]. Projected climate changes, such as rising global average temperatures, could significantly alter the optimal conditions for macaúba cultivation, thereby affecting biodiesel production[25]. In this context, predictive mechanistic modeling with tools like Climex software[26] is essential for assessing the current and future climatic suitability of macaúba, taking into account the species' specific climatic and physiological variables[27].

This study aims to address this knowledge gap by conducting predictive modeling of the climate suitability of *A. aculeata* in both present and future scenarios influenced by climate change. Additionally, it seeks to evaluate the impact of these projections on global biodiesel production. Integrating knowledge about bioenergy, climate change, and biodiesel with a predictive approach will support decisions that promote an efficient and sustainable transition to renewable energy sources.

Materials and methods

Distribution of *Acrocomia aculeata* in the world

Occurrence data for *A. aculeata* were collected from several sources, including the Global Biodiversity Information Facility[28], the European and Mediterranean Plant Protection Organization[29], and the United States Department of Agriculture[30]. Additional data points were identified through a bibliographic review of databases such as Web of Science, Science Direct, Scielo, and Google Scholar. After filtering out incomplete or duplicate records, a total of 381 occurrence points were compiled.

Climex

Species Distribution Models (SDMs) are tools that link species occurrence data with predictor variables[31]. They are valuable for evaluating the effects of climate change on plant distribution and occurrence[32]. These models can be created using software like Climex, which utilizes biological information, climate data, and species occurrence to generate predictions[27]. Within this software, parameters for biological growth and stress are used to determine the Ecoclimatic Index (EI). The EI indicates potentially suitable areas for species establishment, with a scale from 0 to 100, where values of 30 or higher signify high suitability[27,33].

The Growth Index (GI) enables the estimation of a species' potential geographic distribution and suitability under changing climate conditions[27]. Furthermore, the software calculates the Weekly Growth Index (GIw), with values close to 0 indicating unfavorable growth conditions. Conversely, when the GIw exceeds 0, it signifies favorable conditions for the species' development[27].

Parameter adjustments and model validation in climex software

The ecological niche model for *A. aculeata* was developed using the species' biological information and known distribution data. In Climex software, biological parameters were adjusted to enhance climatic suitability at occurrence sites ($EI \geq 30$)[34]. The model was validated by comparing the predicted highly suitable areas with the actual locations of the species in Brazil.

Growth parameters

Acrocomia aculeata is a tropical species that thrives in temperatures between 15 °C and 35 °C, as highlighted in previous[22,35]. Temperature is a crucial factor for the macaúba fruit's characteristics within climatic zoning, with optimal conditions occurring between 20 °C and 25 °C[36]. Furthermore, ongoing experiments with ten macaúba progenies in the Unaí region, Minas Gerais, Brazil, revealed that the species' growth is optimized at average and maximum temperatures of 24 °C and 31 °C, respectively.

Previous studies have explored the optimal climatic conditions for germinating *A. aculeata* seeds[37,38]. Seed germination thrives within a temperature range of 25 °C to 35 °C[15,37], with temperatures around 35 °C breaking dormancy in the soil seed bank, providing a promising approach for species propagation[39]. Ecophysiological investigations reveal that *A. aculeata* exhibits robust photosynthetic resilience to rising temperatures, maintaining high levels of net photosynthesis even at temperatures approaching 34 °C[40]. Nevertheless, environmental factors such as temperature fluctuations during fruit development can influence the oil concentration in the mesocarp[41], a critical factor for biodiesel production.

Considering climatic zoning, global distribution and conditions for growth and seed germination, the ideal temperature parameters for the establishment of *A. aculeata* (DV1 and DV2) were set at 25ºC and 35ºC (Fig. 1; Table 1).

The lower temperature limit (DV0) for macaúba seeds was established at 12 °C due to observed reductions in embryo germination between 12 °C and 15ºC[38]. Furthermore, the species' limited occurrence in temperate regions, such as Urbana, Illinois, USA, where the average annual temperature is 11.8ºC, highlights *A. aculeata*'s sensitivity to colder climates[28]. The upper temperature limit was defined at 40ºC, as temperatures at or above this threshold result in decreased seed viability under both dry and humid storage conditions[39] (Table 1).

Acrocomia aculeata thrives best with annual precipitation ranging from 1100 mm to 2000 mm[22,42], conditions typical for tropical species. Additionally, precipitation levels significantly affect both fruit production[43] and the fatty acid composition of the species' oil[44].

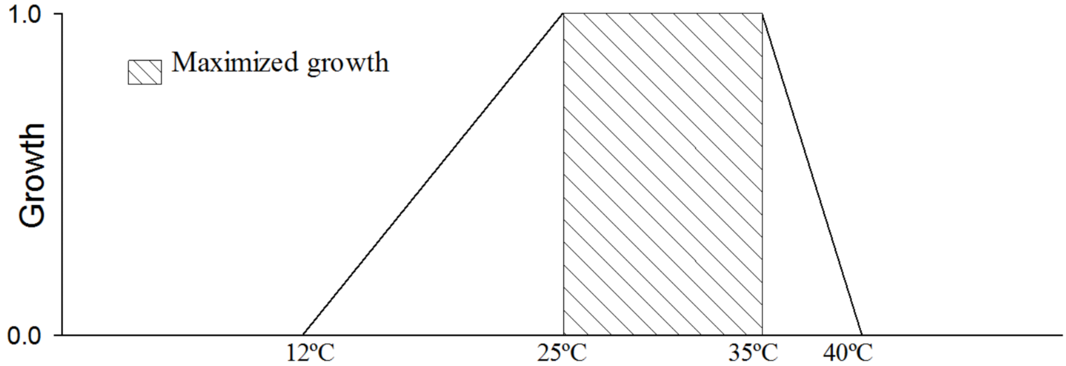

Fig. 1. Temperature as a function of population growth. Parameters used to define suitable temperature ranges for *Acrocomia aculeata* population growth. DV0 = 12ºC: Lower temperature limit, DV1 = 25ºC: Lower ideal temperature, DV2 = 35ºC: Upper ideal temperature and DV3 = 40ºC: Upper temperature limit.

Parameters	Code	Unit	Value	References
Lower temperature limit	DV0	ºC	12	[38]
Lower ideal temperature	DV1	ºC	25	[37]
Upper ideal temperature	DV2	ºC	35	
Upper temperature limit	DV3	ºC	40	[39]
Lower soil moisture limit	SM0	--	0.25	----
Lower ideal soil moisture	SM1	--	0.7	[27]
Upper ideal soil moisture	SM2	--	1.5	
Upper soil moisture limit	SM3	--	2.5	
Cold stress temperature threshold	TTCS	ºC	12	[38]
Cold stress accumulation rate	THCS	$week^{-1}$	-0.0001	----
Heat stress temperature threshold	TTHS	ºC	40	[39]
Heat stress accumulation rate	THHS	$week^{-1}$	0.01	----
Drought stress threshold	SMDS	--	0.25	----
Drought stress accumulation rate	HDS	$week^{-1}$	0.0001	

Table 1. Adjusted parameter values (VA) for modeling *Acrocomia aculeata* using climex.

At Climex, humidity parameters are crucial and tailored to regional climatic conditions. The lower humidity limit (SM0) is set at 0.25, taking into account the species' ability to thrive in drier environments, supported by anatomical characteristics such as a higher cuticle and stomatal density on the abaxial surface of the leaves[44]. The upper and optimal limits for soil moisture (SM1, SM2, and SM3) are established at 0.7, 1.5, and 2.5, respectively, aligning with prescribed guidelines for tropical regions[27] (Table 1).

Stress parameters

The temperature limit for cold stress (TTCS) is set at 12ºC based on DV0, which restricts the potential distribution of *A. aculeata* in temperate regions where the species has not been observed. The rate of cold stress accumulation (THCS) is established at -0.0001 $week^{-1}$ (Table 1). Additionally, the temperature threshold for heat stress (TTHS) is defined at 40ºC, with a corresponding heat stress accumulation rate (THHS) of 0.01 $week^{-1}$ (Table 1).

Annual precipitation directly influences the production of macaúba fruits and oil[41,43] and also limits the species' distribution in desert regions[41]. Consequently, in ecological niche modeling, the threshold for drought stress (SMDS) and the rate of drought stress accumulation (HDS) were established at 0.25 and 0.0001 $week^{-1}$, respectively (Table 1).

Meteorological data

The modeling of *A. aculeata* utilized Climond 10' grid climatic data files, encompassing meteorological variables like average minimum and maximum temperatures, precipitation, and monthly relative humidity. Data from 1981 to 2010, centered around 1995, were utilized to represent the historical climate for the study[45].

The identical variables were employed for future modeling. The global distribution of *A. aculeata* for 2050, 2080, and 2100 was projected under the A2 SRES scenario using the Global Climate Model (GCM), CSIRO-Mk3.0 (CS) from the Center for Climate Research, Australia[46]. The CS climate system model incorporates comprehensive data from the atmosphere, land surface, oceans, and sea ice, providing essential variables for

Climex modeling, including temperature, precipitation, and humidity[46]. According to projections using the CS model, there is an expected temperature increase of 2.11°C and a 14% reduction in precipitation[47].

The A2 SRES scenario is characterized by a growing population and high greenhouse gas emissions, considering factors such as economic development and technological advances[48]. In comparison, the A1B scenario represents a balance in energy supply between fossil fuels and alternative sources, resulting in moderate emissions[49]. The A2 scenario is widely used in crop modeling studies[49], in addition to identifying the climatic limits for macaúba in a potentially more hostile future, which is why it was used in this study.

The Growth Index models employed time series (TS) datasets sourced from the Climatic Research Unit at the University of East Anglia (CRU), version TS4.02, encompassing monthly climate variations spanning from 1901 to 2017. These datasets include variables such as the frequency of frost days, average daily temperature, maximum daily temperature, vapor pressure, and potential evapotranspiration, derived from approximately 4000 meteorological stations[50]. Specifically, data from January 1, 2016, to December 31, 2016, was utilized, including monthly maps.

Results

The global distribution study of *Acrocomia aculeata* identified 381 occurrence points across 23 countries. Mexico (30.0%), Brazil (24.7%), and Colombia (13.12%) had the highest number of records (Fig. 2a). The Ecoclimatic Index (EI) assessment revealed that about 14.4% of the world's area is highly suitable for this species ($EI \geq 30$), 9.1% is moderately suitable ($0 < EI < 30$), and 76.5% is considered inadequate ($EI = 0$). The model indicates high climate suitability in tropical regions but not in temperate regions like Europe and North America (Fig. 2b).

Overall, the potential distribution of *A. aculeata* was limited by cold and drought stress. Regions in the northern hemisphere (North America, European and Asian countries) and southern South America were considered unsuitable due to cold stress. In relation to drought stress, limitations in the growth of the species are observed in desert areas such as the African continent, the Asian and Mediterranean regions, Australia and the United States of America (Supplementary Material 1).

Brazil was chosen to validate the model because *A. aculeata* is native to the Americas, and there is a vast native population of the species in the country[51], which suggests the macaúba's climatic suitability in the region. Around 97.88% of the occurrence points in Brazil are found in very suitable regions and 2.12% in regions with moderate suitability, which validates and demonstrates high reliability in the final model (Fig. 3).

Indonesia (35%), Costa Rica and Nigeria (20%), the United States of America (20%), Brazil, Colombia and Sweden (10%) are the countries with the highest rate of mandatory addition of biodiesel to diesel, and therefore, the largest consumers of biofuel. Agricultural areas in South America, Europe, Australia, India, and the United States of America are climatically suitable for planting macaúba. However, as an alternative, large areas suitable for the presence of *A. aculeata* are predominantly covered by arboreal vegetation, natural or planted. Furthermore, the suitability of the species is also evident in pasture regions and with low vegetation cover. The occurrence of the species is restricted in areas with exposed soil or deserts due to unfavorable soil and climate conditions (Fig. 4).

Climex projections under the CSIRO SRES A2 scenario for 2050, 2080, and 2100 indicate a decrease in areas highly suitable for the establishment of *A. aculeata* compared to the current model (Fig. 5). The most significant reductions are observed in Brazil, Sub-Saharan Africa, and India. Conversely, the model predicts an increase in moderately suitable areas in northern Mexico and highlights a prevalence of high suitability in Indonesia.

The growth index values for *A. aculeata* generated in the Climex software approach 1 in a large part of the Brazilian territory between November and April remain high for South Asian countries throughout the year. In the Sub-Saharan Africa region, the growth rate maximizes between April and December, while in the northern hemisphere countries, the rate reaches significant values from April to September (Fig. 6).

Discussion

The occurrence of *A. aculeata* is restricted to the Americas, with a significant presence in regions characterized by tropical climates with dry, monsoon and humid winters (Aw, Am and Af) and humid temperate climates (Cfa)[23,56]. High climate suitability is observed in regions of Sub-Saharan Africa, southern Asia and northern Oceania due to the climatic similarity with Mexico and Brazil (Aw, Am and Af)[56], reinforcing the global potential for cultivation of this species. Furthermore, regions with a semi-arid climate (BSh) were considered moderately suitable for the occurrence of *A. aculeata*, due to the species' location in northeastern Brazil[28].

In the generated model, high climate suitability is observed in the South Asian region. We highlight Indonesia as a notable example, where the high demand for biodiesel and the relevant mandatory blend in diesel (35%), together with the current dependence on palm oil[52–54,57], offers a strategic opportunity for macaúba cultivation. The high climate suitability for *A. aculeata* in the country, combined with the need to diversify sources and the search for sustainable alternatives, indicate macaúba as a viable option to increase biodiesel production, reducing pressure on food crops[58].

In Sub-Saharan Africa, where small producers predominantly lead biodiesel production, the introduction of macaúba is considered a strategy to overcome challenges related to raw material scarcity[59]. In addition to mitigating this problem, macaúba cultivation can boost local biodiesel production, contributing to poverty reduction and economic development[59].

Brazil is the third largest consumer of biodiesel in the world, which is mostly derived from soybean crops[60]. However, according to the model generated, the country has high climatic suitability for planting macaúba. Macaúba has a high oil yield (5 to 6.2 t ha^{-1})[18,21], adapts to marginal soils, can be used in agroforestry systems and the recovery of degraded areas[22], in addition to the use of their by-products in agricultural sectors and the production of other biofuels[61,62]. Despite challenges such as the lack of zoning, low fruit quality and irregular

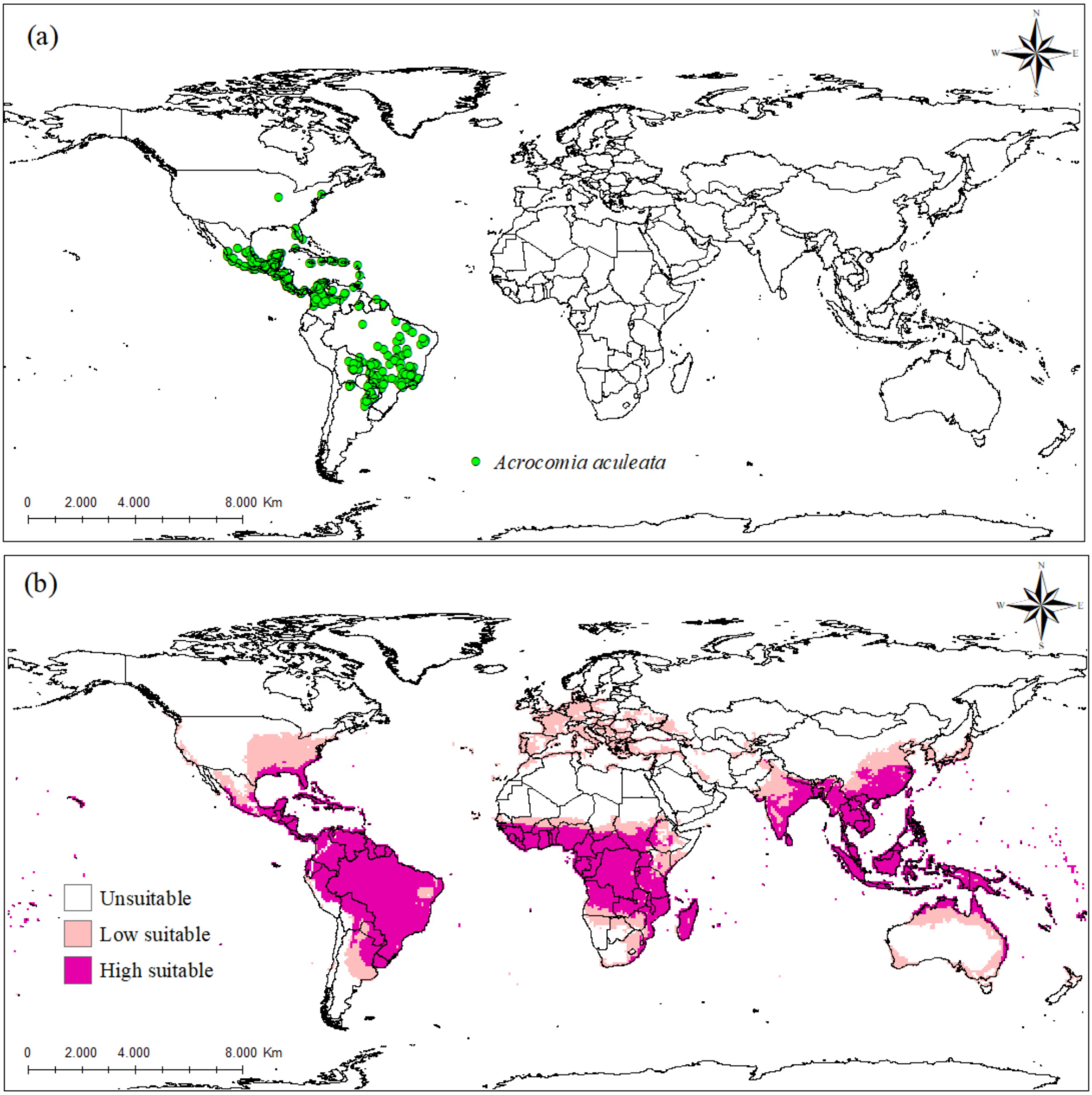

Fig. 2. (**a**) Known global distribution of *Acrocomia aculeata* plants and (**b**) Ecoclimatic Index (EI) for *A. aculeata*, modeled using Climex. Inadequate areas in white (EI = 0), moderate adequacy in light pink (0 < EI < 30), and very adequate dark pink (30 ≤ EI ≤ 100).

harvesting, research focused on optimizing processes can make large-scale production of biofuels derived from macaúba viable in the country, contributing to the diversification of the energy matrix[22].

The planting of crops aimed at producing biofuels, such as *A. aculeata*, induces indirect changes in land use, requiring the implementation of strategies to mitigate possible losses in agricultural and preserved regions[63,64]. In agricultural areas that are climatically suitable for macaúba cultivation, such as in South America, Australia, the United States of America, Europe and India, intercropped planting appears as an approach to optimize land use[65]. This practice reduces direct competition for space, favors production diversification and contributes to producers' income[66]. Similarly, the implementation of macaúba in forest stands in regions such as Indonesia, China, the African continent, and pasture areas contributes to improvements in soil, water quality and biodiversity conservation[67]. The versatility of macaúba is highlighted by its adaptation in different regions, expanding the possibilities of use without compromising the use of agricultural land.

Macaúba is a perennial species, has a long life cycle and the beginning of production varies between 4 and 6 years, and can remain productive for up to 100 years[22,68], Therefore; understanding the climatic suitability of macaúba over the years is important to determine the ideal planting locations. Overall, future projections using

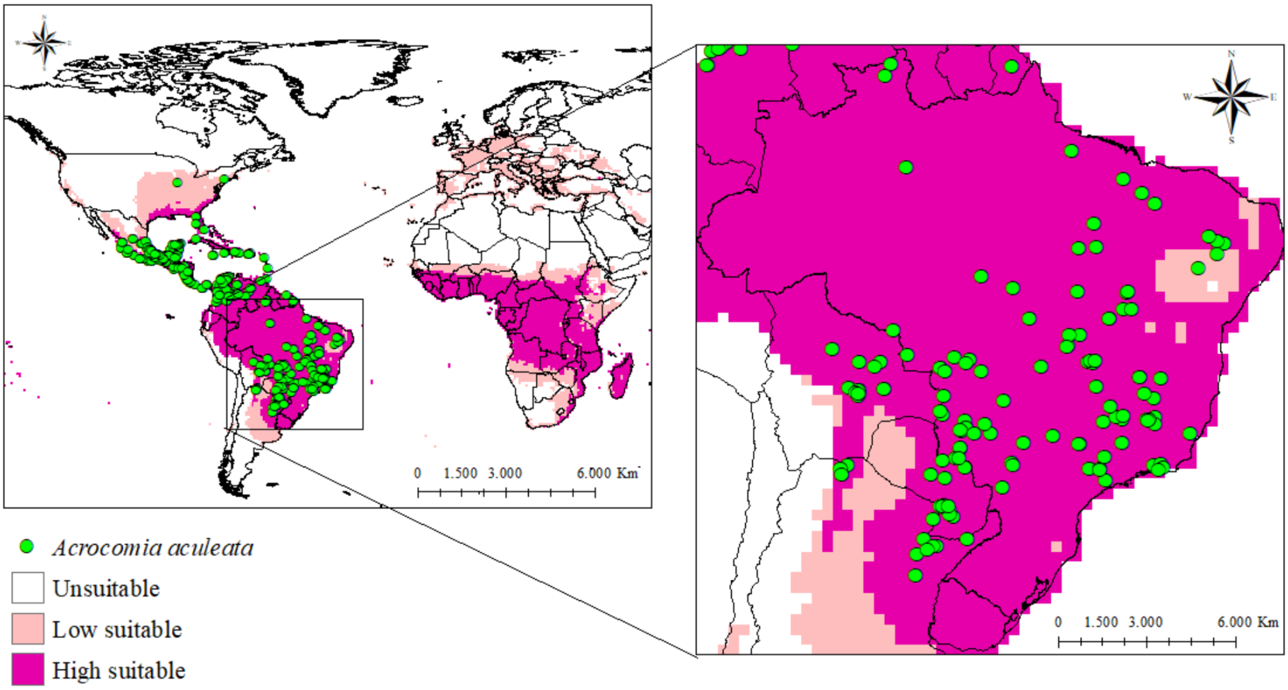

Fig. 3. Current distribution of *Acrocomia aculeata* in the validation region, Brazil, based on the Ecoclimatic Index (EI). Inadequate areas in white (EI = 0), moderate adequacy in light pink (0 < EI < 30), and very adequate dark pink (30 ≤ EI ≤ 100).

Climex under CSIRO SRES A2 scenario for the years 2050, 2080 and 2100 demonstrate lower climate suitability for *A. aculeata*. This is mainly due to the increase in temperatures and reduction in rainfall[25], which may restrict the development of the species, especially in semi-arid climates. The results suggest that Brazil, by 2080, will have high climate suitability throughout its territory, with a reduction predicted for 2100 in certain regions. The high suitability over the years for Indonesia is another indication of the high potential for planting and producing biofuels derived from macaúba in the region.

One of the restrictions on macaúba planting is the species' climatic zoning, determining the most appropriate time for cultural practices such as planting and harvesting[22]. Therefore, studies of space-time dynamics allow us to determine the best location and period[27] based on climate suitability and seasonal changes. The growth index generated suggests that the most suitable period for planting macaúba in Brazil is between November and May. Similarly, production peaks must occur within this period when temperature and humidity conditions are ideal for the development of *A. aculeata* in almost the entire territory. Sub-Saharan Africa follows the same pattern as Brazil, and in the South Asian region, the growth rate remains high throughout the year.

Conclusions

The global distribution results indicate that macaúba has high climatic suitability in tropical and subtropical regions, especially in the Americas, sub-Saharan Africa and parts of Asia. However, future projections under climate scenarios indicate reductions in the species' climate suitability, mainly due to increased temperatures and reduced rainfall. These projected climate changes could impact global biodiesel production, emphasizing the importance of adaptive strategies for macaúba cultivation.

In addition to the climatic aspect, considerations about the global distribution of macaúba highlighted strategic regions, such as Brazil and Indonesia, as potential areas for large-scale cultivation, taking into account the demand for biodiesel and the need to diversify sources. However, we emphasize that this study identified gaps in knowledge, especially regarding the detailed ecological requirements of macaúba and its performance under various climatic conditions, highlighting the need for future research.

This work offers an integrated approach between bioenergy, climate change and biodiesel, contributing to informed decision-making and targeted policies that promote the global transition to more sustainable energy sources.

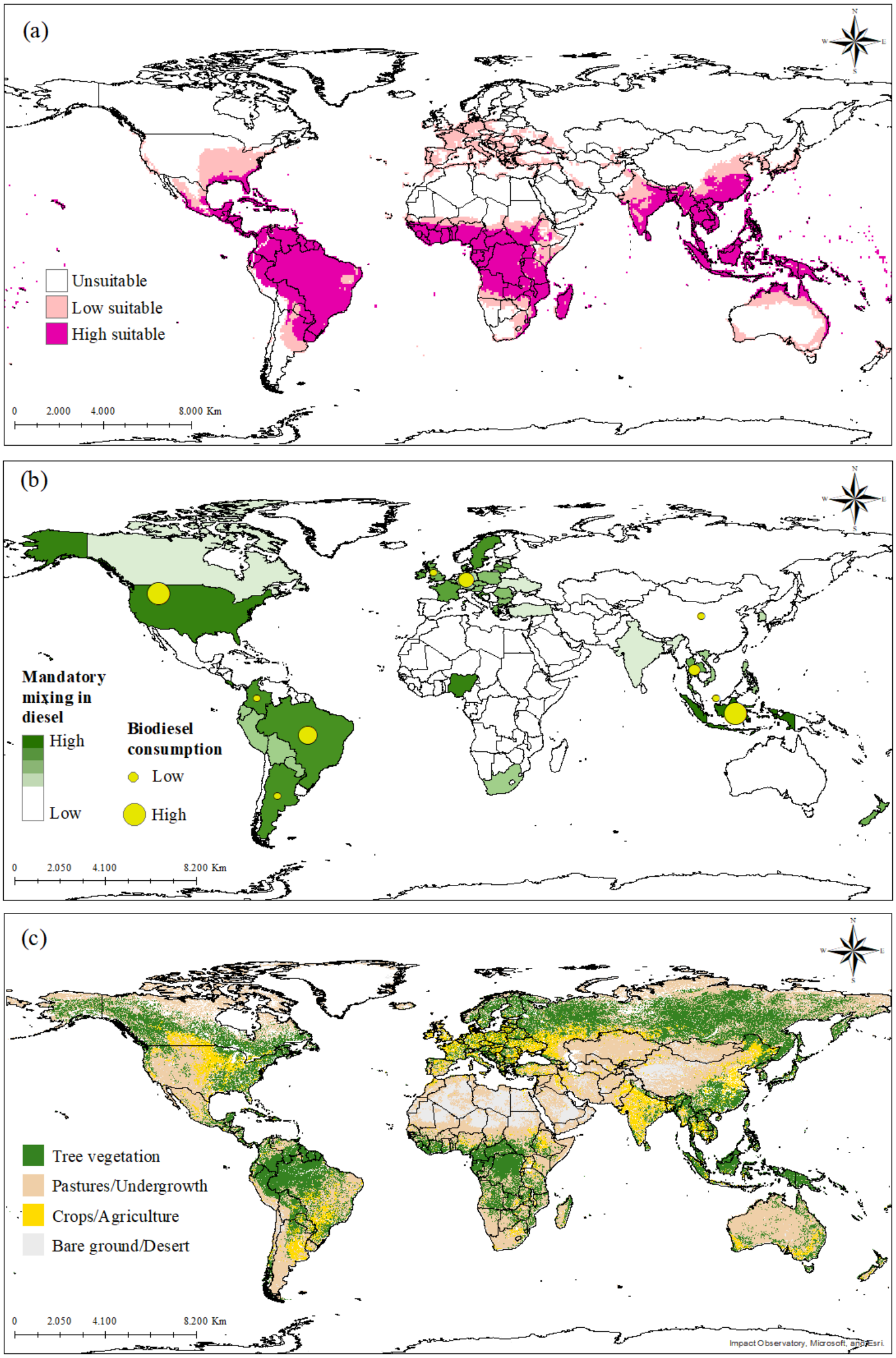

Fig. 4. (a) Current distribution of *Acrocomia aculeata* and Ecoclimatic Index (EI). Inadequate areas in white ($EI = 0$), moderate suitability in light pink ($0 < EI < 30$), and very suitable dark pink ($30 \leq EI \leq 100$). (**b**) biodiesel consumption and mandatory percentage of biodiesel mixture in diesel. Areas in green represent higher levels of consumption, while larger circles indicate a higher mandatory rate. Source:[52–54]. (**c**) Global land use map in 2022. Areas with natural or planted green tree vegetation; pastures or undergrowth in beige; agricultural areas and areas intended for food production in yellow; and areas with exposed soil or deserts in gray. Source:[55].

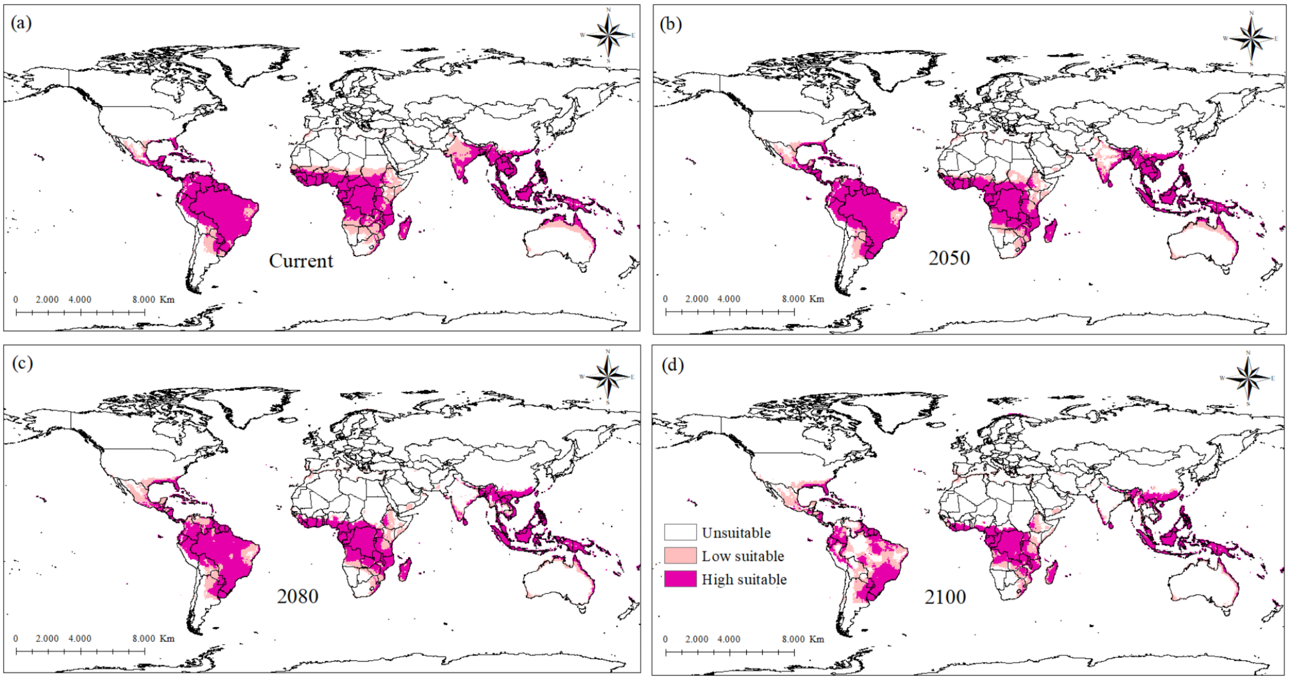

Fig. 5. Current (**a**) and projected Ecoclimatic Index (EI) using Climex under CSIRO SRES A2 scenario for the years 2050 (**b**), 2080 (**c**) and 2100 (**d**) for *Acrocomia aculeata*. Inadequate areas in white (EI = 0), moderate adequacy in light pink (0 < EI < 30), and very adequate dark pink (30 ≤ EI ≤ 100).

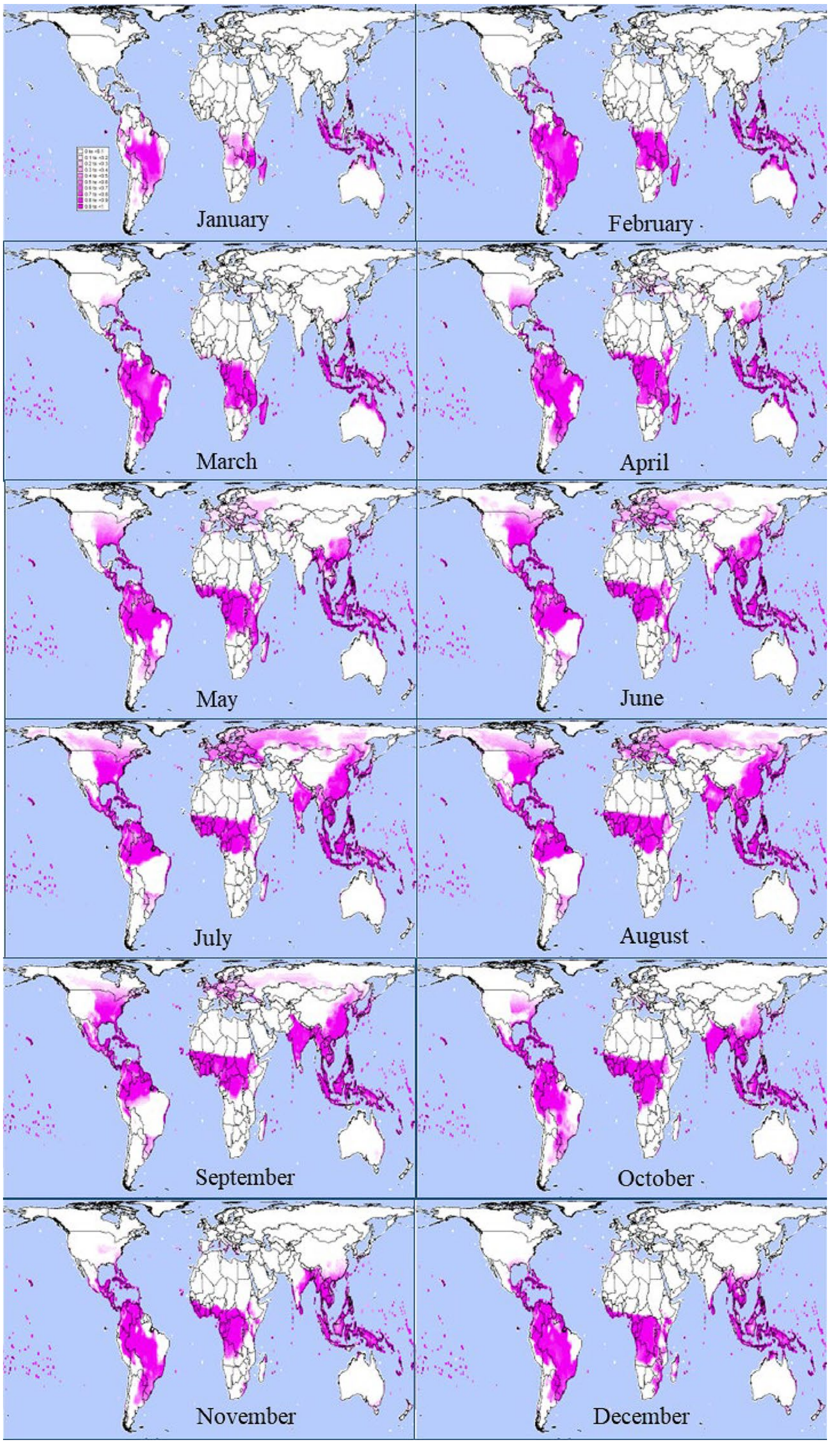

Fig. 6. Monthly variation in the growth index (GI) performed in Climex for *Acrocomia aculeata* in the period from January 1 to December 31, 2016. Purplish areas correspond to GI values close to 1, and white areas are equivalent to values close to 0.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions
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Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to G.M.B.

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