



# Agroclimatic Suitability of *Hylocereus undatus* (Haw.) Britton & Rose in the Yucatan Peninsula

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## Abstract

*Hylocereus undatus*, also known as dragon fruit, is a crop of growing interest in the Yucatan Peninsula due to its nutritional value, demand in national and international markets, and ability to adapt to seasonal conditions. However, the orderly expansion of its cultivation requires identifying the areas with the greatest productive potential, considering the agroecological factors that determine its development. The objective of this study was to identify the areas with the best agroecological conditions for the development of dragon fruit cultivation under seasonal conditions and to identify areas of high and medium potential in the Yucatan Peninsula. The first step is to consider agroecological zoning to determine where the areas of high and medium potential, the subject of this study, are located. To locate them, climate, digital elevation, and soil databases were used, which were processed in the QGIS Biatowiza 3.22 Geographic Information System with a free license through intersections and map algebra, using as initial information the optimal agroecological requirements of the crop, per cycle, to develop under seasonal conditions. Based on the methodology used, it was determined that in the Yucatan Peninsula, there are more than 159,396 hectares of high potential for dragon fruit cultivation under seasonal conditions and more than 1,058,193 hectares of medium potential.

## Subject Areas

Agricultural Engineering

## Keywords

Dragon Fruit, Regionalization, Geographic Information System

## 1. Introduction

*Hylocereus* spp. is an exotic fruit that comes from a succulent cactus belonging to the Cactaceae family and the Caryophyllales order. It is a group of climbing cacti, native to the tropical and subtropical regions of America, which is currently widely consumed in these regions around the world [1]-[3]. The genus *Hylocereus* comprises several species of agronomic importance, among which *Hylocereus undatus*, commonly known as pitahaya, stands out. This fruit is known by different names depending on the country where it is grown, such as pitajaya in Colombia, Belle de nuit in France, flor de cáliz in Venezuela and Puerto Rico, dragon fruit or Belle of the night in English-speaking countries, Distelbrin in Germany, and pitahaya or fruta de dragón in Peru, among others [4].

Its fruits, which are visually appealing due to their external coloration (caused by their high betacyanin content, which gives them an intense color in the skin and pulp) and the fleshy consistency of the pulp [5] [6], are appreciated in both local and international markets for their nutritional value and functional properties. In fact, pitahaya provides vitamins (A and C), minerals (potassium, iron, calcium, phosphorus, zinc, sodium, and magnesium), dietary fiber, and antioxidant compounds that contribute to the prevention of chronic degenerative diseases such as cancer, diabetes, and cardiovascular, respiratory, and gastrointestinal pathologies [7]-[11]. In addition, the flowers and stems have traditional medicinal uses, with hypoglycemic, diuretic, and healing properties attributed to them [12].

The consumption of dragon fruit has gone beyond fresh fruit, expanding into various agro-industrial products like juices, jellies, jams, soft drinks, ice cream, yogurt, cocktails, sweets, and digestive supplements [13]. Due to this versatility, the crop has become a valuable resource with high potential in the exotic fruit markets. Worldwide, at least 14 species of the genus are recognized, with *H. costaricensis*, *H. megalanthus*, *H. monacanthus*, and *H. undatus* being the most widely grown [9]. In countries such as Costa Rica and Nicaragua, varieties like “Rosa”, “Cebra”, “Orejona”, “San Ignacio”, “Nacional”, “Crespa”, and “Lisa”, all with red skin and red flesh, dominate the market, while the “Amarilla” variety (*H. undatus* subsp. *luteocarpa*), with yellow skin and white flesh, is also highly valued [14] [15].

From a physiological and agronomic perspective, dragon fruit is characterized as a resilient and adaptable crop. It can tolerate high temperatures of up to 40°C and thrives in nutrient-poor soils, conditions that limit the production of many other crops [16]. This hardiness has enabled it to spread to various regions of the world, including Asia (Vietnam, China, Thailand, and Malaysia), Oceania (Australia), the Middle East (Israel), as well as Latin American countries such as Mexico and Colombia [17]-[19]. In Asia, particularly in Vietnam, dragon fruit became a commercially significant crop in 1995, consolidating its position as the world’s leading producer, with annual production exceeding 600,000 tons. China, for its part, has recently exceeded 1.6 million tons, positioning itself as the leader in production and export [20].

The growing demand for dragon fruit is related not only to its direct consumption but also to its potential in the food and pharmaceutical industries. Its bioactive compounds, such as betacyanins and betaxanthins, which are water-soluble pigments, possess antioxidant properties that promote health and are used as natural colorants [3] [6] [21]. This added value, combined with the plant's ornamental beauty and its growing acceptance in European and North American markets, has boosted its global commercialization. In terms of production, dragon fruit yields vary between 10 and 30 t·ha<sup>-1</sup>, depending on factors such as agronomic management, soil type, climatic conditions, and orchard age [22]. However, the crop faces significant challenges in terms of standardizing management practices, harvesting and post-harvest technology, and fruit storage, given that its shelf life under environmental conditions is only 6 to 8 days [23] [24].

The short post-harvest life generates economic losses and limits the capacity to export to distant markets, making research into preservation and packaging technologies a priority [25] [26]. In Mexico, the cultivation of dragon fruit holds significant cultural and economic value, as it is grown in both traditional systems and on commercial plantations [27]. The Yucatan Peninsula, in particular, has agroecological conditions that could favor the expansion of *H. undatus* cultivation. Its karstic soils, warm subhumid climates [28] [29], and defined rainy and dry seasons constitute an ideal setting for evaluating the adaptation of the species. This is compounded by the need to diversify agricultural production in the region in response to climate change challenges, including prolonged droughts and rising average temperatures. The dragon fruit, due to its hardiness and tolerance to water stress, is emerging as a sustainable production alternative for small and medium-sized producers.

Despite the importance of dragon fruit, there are still gaps in information regarding its agroclimatic suitability across different regions of Mexico. Previous studies have mainly concentrated on variety characterization, post-harvest analysis, or genetic improvement [30] [31], but limited research has integrated physiological and edaphoclimatic variables to identify areas with the highest production potential.

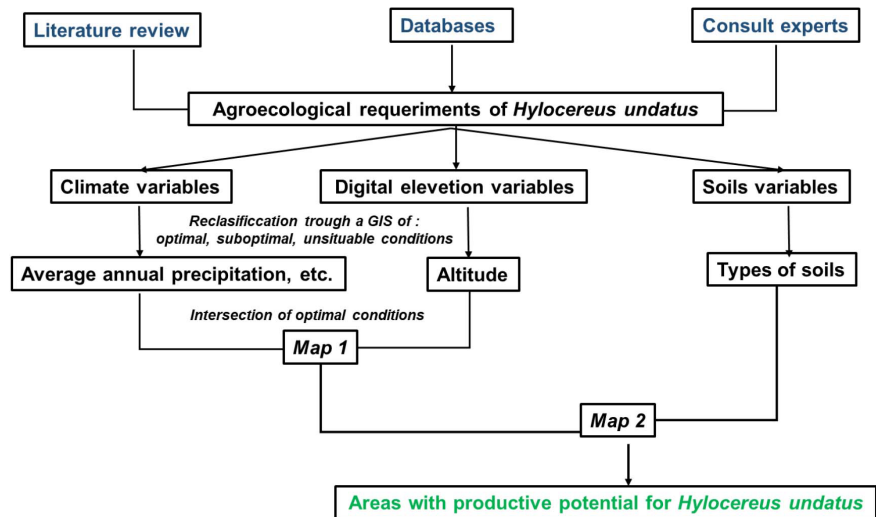
In this context, the objective of this study was to identify the areas with the best agroecological conditions for the development of dragon fruit cultivation under seasonal conditions and to identify areas of high and medium potential in the Yucatan Peninsula.

## 2. Materials and Methods

### 2.1. Geographic Information and Map Algebra

A geographic information system and map algebra were utilized. Map algebra is a tool that combines different territorial layers or variables to generate alternative maps linked to specific characteristics of the land [32]. In this case, map algebra was used to identify the most suitable areas for dragon fruit production under rainfed conditions, employing an ecological criterion that integrated climate, soil,

slope, and altitude data. This ecological criterion considered the combined cartography of climate, soil, slope, and altitude.



**Figure 1.** Methodological scheme to determine the potential areas of *Hylocereus undatus*.

With the help of symbols, the most suitable areas were distinguished as high-potential ones, and the least suitable ones as unsuitable ones. In this study, three fundamental stages (**Figure 1**) were considered to define the grade of potentiality: 1) to identify altitude, temperature, precipitation, and soil requirements for dragon fruit cultivation; 2) to locate databases of agroclimatic conditions for the Yucatan Peninsula; and 3) data processing.

## 2.2. Determining Agroecological Needs for *Hylocereus undatus*

The variables used included the agroclimatic requirements of dragon fruit in the Yucatan Peninsula, specifically average temperature, altitude, precipitation, light, and soil (**Table 1**). Agroclimatic data were obtained from bibliographic sources [33]-[36] and databases, including Ecocrop, which identified over two thousand plant species. Opinions from some dragon fruit experts were also considered. The database of agroclimatic and geographic conditions of Mexico was also consulted. For soil conditions, the World Reference Base for Soil Resources [37] was used in vector format [38] at a scale of 1: 250,000. The climatological data were obtained using WorldClim version 2.2.0 [39], specifically for average temperature and precipitation. The Digital Elevation Model, with three-second data of altitude values, was acquired from the National Institute of Statistics and Geography [40] in raster format, with a resolution of 225 m<sup>2</sup> per pixel. Several geospatial databases were considered. Soil information was taken from the World Reference Base for Soil Resources (WRB), published by the FAO (2007) [38], in vector format and at a scale of 1:250,000. Climate data was obtained from the WorldClim version 2.2.0 database, which provides 30-second data (~1 km<sup>2</sup>), specifically including average temperature and precipitation during the crop cycle. The Digital Elevation Model

(DEM) was obtained from INEGI in raster format with a resolution of  $90 \times 90$  m ( $8100 \text{ m}^2$ ). The slope map was generated based on INEGI DEM; water bodies were extracted from INEGI 1:50,000 topographic maps. The mangrove area was obtained from INEGI land use and vegetation maps at a scale of 1:250,000. Urban and rural areas were identified using INEGI 2010 dataset (1:250,000), and protected natural areas were derived from the 2010 dataset (1:250,000). This cartography was obtained from the Geoportal of the National Biodiversity Information System (SNIB) of the National Commission for the Knowledge and Use of Biodiversity (CONABIO).

To justify the threshold values used in this study, several bibliographic sources were considered. Yellow pitahaya grows at altitudes between 800 and 1,850 m, while red pitahaya grows from 0 to 800 m [41] (OIRSA, 2003). The optimal average annual temperature is  $25^\circ\text{C} - 30^\circ\text{C}$  for red pitahaya and  $18^\circ\text{C} - 25^\circ\text{C}$  for yellow pitahaya [41] (OIRSA, 2003), although the crop can tolerate very hot climates with temperatures above  $38^\circ\text{C} - 40^\circ\text{C}$  [42] (Le Bellec *et al.*, 2005). Regarding precipitation, optimal conditions range from 600 to 1300 mm with alternating dry and wet seasons [43]. Still, the crop has been reported to grow under annual rainfall of 300 to 1000 mm [44] (Bárcenas *et al.*, 2001) and is recognized as drought-resistant [45] (Castillo *et al.*, 2005). For soils, optimal development occurs in sandy loam textures with a pH between 6.5 and 7.0 [41] [46] (Acuña *et al.*, 2002; OIRSA, 2003) and a depth greater than 150 cm, although the crop can also develop in shallower soils [38].

### 2.3. Database Processing

The procedure involved classifying the climatic and soil attributes required for dragon fruit cultivation under rainfed conditions. Vector format was employed for analysis, interpolation, cutting, and intersections, allowing each dataset (entities associated with specific attributes) to retain its spatial characteristics and geometry. Map algebra refers to the set of techniques and procedures in Geographic Information Systems (GIS) that derive new information from mathematical, logical, or statistical operations applied to one or more layers of geospatial data, either in raster or vector format. By combining attributes and spatial relationships, these operations generate thematic layers that represent synthetic variables or modeled phenomena [47].

In this study, vector data geometry was implemented by intersecting edaphic and climatic layers, while mangrove areas, protected areas, and urban and rural settlements were excluded. The slope map was generated from the INEGI Digital Elevation Model (DEM), water bodies were extracted from INEGI topographic maps (1:50,000 scale), mangroves from INEGI land use and vegetation maps (1:250,000 scale), and urban, rural, and protected areas from the 2010 INEGI datasets (1:250,000 scale). All cartographic information was obtained from the Geoportal of the National Biodiversity Information System (SNIB) of CONABIO and was processed and reclassified using QGIS 3.22.14 Batioweiza software [48].

Map algebra was performed using vector data, with the union tool used to combine all parameters. Each variable was classified as optimal, suboptimal, or unsuitable based on literature and expert opinion. The intersection of variables under optimal conditions identified high-potential areas, while intersections of suboptimal conditions indicated medium-potential areas. All variables contributed equally to the analysis; the key was overlaying optimal and suboptimal conditions to define high- and medium-potential zones, and areas with unsuitable conditions were excluded.

**Table 1.** Agroecological requirements of *Hylocereus undatus*.

Variable	Unit	Condition		
		Optimal	Suboptimal	Not suitable
Average annual temperature	°C	25 - 30	18 - 25 30 - 35	<18 >35
Altitude	m	0 - 800	800 - 1200	>1200
Average annual Precipitation	mm	1000 - 1300	600 - 1000 1300 - 1800	<600 >1800
Soil	Types	Fluvisols Luvisols Nitisols	Cambisols Regosols Phaeozems Leptosols	Solonchaks Vertisols Gleysols Arenosols Calcisols
Texture	Type	Loam Clayey loam	Loam Clayey loam	Clayey
Depth	m	>1	1 a 0.40	<0.40
pH	Indicator	6.0 a 7.0	5.5 a 5.9 7.1 a 8.0	<de 5.5 >de 8.0
Ligth hours per year	Ligth hours	>3000	2500 a 3000	<2500
Drainage	Type	Efficient drainage	Efficient drainage	Poor drainage

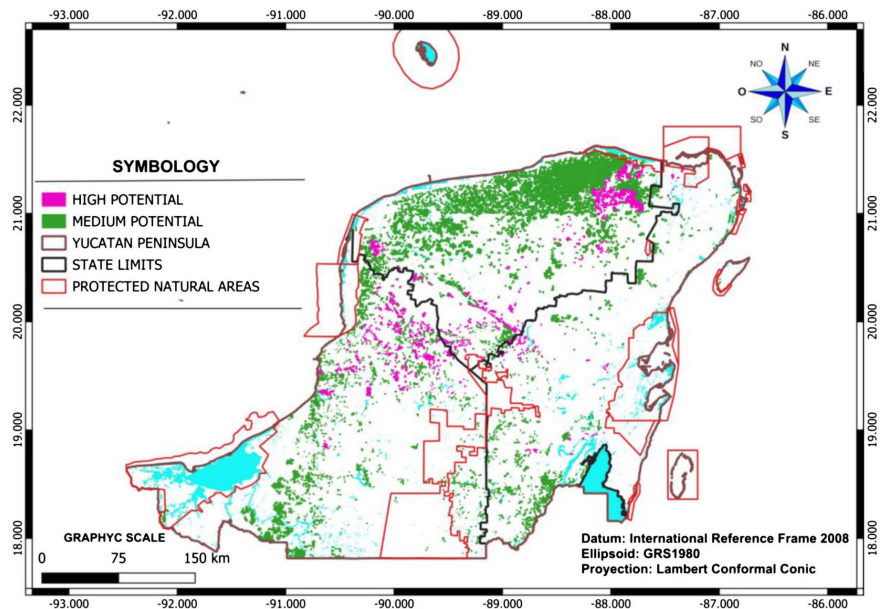
### 3. Results

The potential areas for dragon fruit (*H. undatus*) cultivation in the Yucatan Peninsula were determined by applying a suitability analysis that integrated climatic, edaphic, and topographic variables. Only land with potential for agricultural, livestock, or forestry activities was considered; areas within urban and rural settlements, as well as protected natural areas, were excluded to ensure realistic estimates of land availability for productive purposes.

#### 3.1. High-Potential Areas

The spatial distribution of high and medium-productive potential zones for *H. undatus* under rainfed conditions is presented in **Figure 2**. High-potential areas (pink) correspond to locations where the combination of environmental factors, such as optimal mean annual temperature (between 25°C and 30°C), adequate

rainfall distribution, and favorable soil depth and texture, creates conditions conducive to achieving yields at or above regional averages. Medium-potential areas (green) present conditions that are generally suitable, although one or more variables may be slightly suboptimal, which could potentially affect yield stability. In contrast, unsuitable areas (white) reflect environmental constraints, including low annual precipitation (<600 mm), shallow or rocky soils, and zones prone to seasonal flooding, which limit the viability of commercial dragon fruit production.



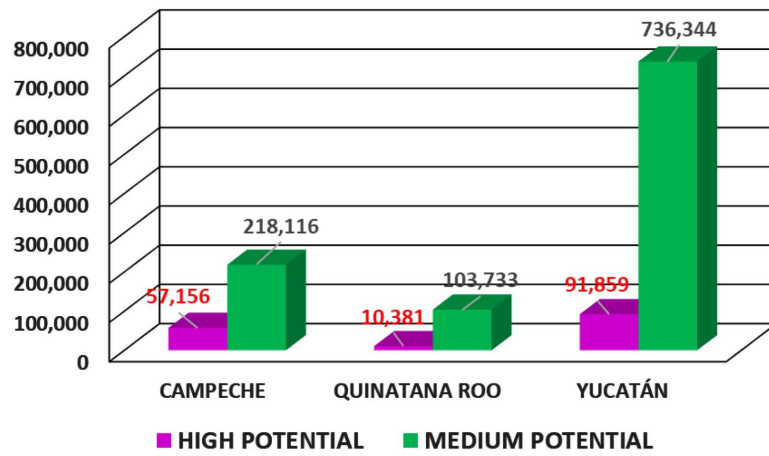
**Figure 2.** Distribution of areas with productive potential for *Hylocereus undatus*.

In the Yucatan Peninsula, high-potential areas for the establishment of *H. undatus* are concentrated in specific municipalities across the three states. In the state of Campeche, these include the municipalities of Calkiní, Campeche, Champotón, Tenabo, Dzitbalché, Hecelchakán, Hopelchén, and Seybaplaya. In the state of Quintana Roo, the most favorable zones correspond to Bacalar, Felipe Carrillo Puerto, José María Morelos, Lázaro Cárdenas, and Othón P. Blanco. In the state of Yucatan, the municipalities with high productive potential are Temozón, Tinum, Peto, Maxcanú, Espita, Tzucacab, Chemax, Yaxcabá, Oxkutzcab, Tizimín, Tixcacalcupul, Ticul, Temax, Valladolid, Sudzal, Sotuta, Chankom, Celestún, Calotmul, Dzitás, Kantunil, Tahdziú, Tekom, Akil, Halachó, Muna, and Santa Elena.

Quantitatively, the analysis identified 159,396 ha of land classified as having high productive potential, distributed as follows: 35.86% in Campeche, 6.51% in Quintana Roo, and 57.63% in Yucatán. The extent of medium-potential land is considerably larger, covering 1,058,193 hectares, with 20.61% located in Campeche, 9.80% in Quintana Roo, and 69.59% in Yucatán (Figure 3). These proportions indicate that, while optimal conditions are relatively limited, a substantial land base with moderately favorable conditions exists that could be improved

through agronomic management practices, such as supplemental irrigation, soil fertility enhancement, or integrated pest management.

Overall, these findings underscore the presence of extensive territories suitable for the expansion of dragon fruit cultivation in the Yucatan Peninsula. The predominance of medium-potential zones suggests that targeted interventions could significantly increase the crop's productive capacity in the region. This spatial information provides a valuable tool for regional agricultural planning, guiding investment decisions, promoting crop diversification, and supporting the design of sustainable rainfed production systems adapted to local agroecological conditions.



**Figure 3.** High and medium potential areas for *Hylocereus undatus* in the Yucatan Peninsula.

### 3.2. Validation with Current Production Areas

The areas producing pitahaya under seasonal conditions in the case of Yucatán are currently located in four municipalities: two in the south of the state, Peto and Tzucacab, where there are areas of high potential, and two other municipalities in the west of the state, Halachó, which also has areas of high potential, and Tetiz, which is located in areas of medium-potential. The eastern region of the state has the largest area of high potential; however, it is not currently planted under seasonal conditions. In the case of Quintana Roo, the productive areas are located in the central and southern municipalities of the state, such as Felipe Carrillo Puerto, José María Morelos, Othón P. Blanco, and Bacalar. The municipality with the most significant areas of high potential is Morelos. In the case of the state of Campeche, there are 57,000 hectares of high-potential land and 218 hectares of medium-potential land, mainly located in the north-central part of the state. However, no areas have been planted with this crop.

## 4. Discussion

In Mexico, commercial production of this crop has a limited geographical distribution, reflecting both its regional importance and the constraints on its expansion.

sion at the national level. The area planted for commercial purposes is mainly concentrated in the state of Oaxaca, with 1083.00 ha, followed by Jalisco, with 289.99 ha, and Puebla, with 200.20 ha. On a smaller scale, planted areas are reported in Nayarit (25.50 ha), Yucatan (25.00 ha), and Morelos (14.00 ha) [49]. Pitahaya cultivation in Mexico has a historical background dating back to pre-Hispanic times, when it was mainly produced in family gardens within the Mayan area [50]. However, the establishment of plantations for commercial purposes is relatively recent. The first recorded plantation in Mexico was established in Tabasco in 1986 [51], while specialized cultivation began in the Yucatan Peninsula around 1995 [52]. However, currently, only the state of Yucatan has commercial dragon fruit plantations [49], despite the other two states that make up the peninsula having the productive potential for their establishment.

The cultivation of *H. undatus* demonstrates a strong ability to adapt to various environments and agroecological conditions [53], which makes it a potential alternative in productive conversion processes in Mexico [54] and other tropical and subtropical regions. Its low water needs and capacity to grow in different soil types [55] make it a practical option amid climate variability and the challenges faced by traditional agriculture [54]. This adaptability enables it to thrive in a wide range of environments, from coastal zones to intermediate altitudes [53]. However, despite this versatility, temperature and relative humidity are crucial factors in establishing and maintaining productivity.

Authors such as Abogado & Castañeda (2012) [56] note that *H. undatus* can grow from sea level to an altitude of almost 2000 m, with rainfall ranging from 300 to 1000 mm per year; however, the greater availability of moisture tends to increase phytosanitary problems. In terms of temperature, the optimal range for adaptation is between 17°C and 30°C [44]. These values are consistent with the observations of Cáliz de Dios *et al.* (2005) [57], who note that optimal crop development is achieved in warm subhumid climates, characterized by annual rainfall between 650 and 1500 mm. This is consistent with the results of this study, in which the estimated suboptimal climatic conditions represent the most significant proportion of areas with medium potential for crop establishment, concentrated mainly in the northeastern region of the state of Yucatan, as well as in the south of the state of Quintana Roo and in the northwest and south of the state of Campeche.

On the other hand, the reproductive stage of dragon fruit is vulnerable to climate factors, especially temperature, relative humidity, and photoperiod, which are crucial for proper crop establishment and management. Flowering usually happens during the summer months, aligning with the rainy season, and can last between four and seven cycles over eight months [58].

In Israel, for example, continuous flowering has been documented with between one and eight cycles per season, depending on local conditions [59]. In Brazil, Marques *et al.* (2011) [60] reported three to four cycles between summer and fall, while in Mexico, Castillo *et al.* (2005) [45] observed that flowering cycles are

concentrated from May to September, coinciding with the onset of the rainy season. In general, flowering is induced by long days and temperatures near 30°C, accompanied by relative humidity between 60% and 80% [61]-[65]. These environmental conditions not only regulate the frequency of cycles but also directly influence fruit quality and yield. In the Yucatan Peninsula, the rainy season begins between May and June and ends in October and November [65].

The crop's thermal tolerance limit has been extensively documented. Nerd *et al.* (2002) [61] reported that maximum temperatures of 38°C during the productive stage significantly reduce yield, whereas higher yields are achieved at temperatures close to 32°C. Similarly, Silva *et al.* (2015) [66] observed that high temperatures inhibit flower production, highlighting the importance of keeping the crop within suitable temperature ranges to ensure both productivity and flowering stability. Conversely, temperatures below 18°C and frost events are highly detrimental to the species, limiting its distribution to areas with milder climates [44]. In the Yucatan Peninsula, temperatures are highly seasonal, with averages ranging from 16 to 18°C in the coldest month (February) and highs of nearly 36°C during the warmest month (May) [67]. Overall, the region has a warm to very warm climate, with average annual temperatures ranging from 26°C to 28°C, which are favorable for pitahaya development.

In terms of its geographical distribution, *H. undatus* grows mainly in the center and southeast of the country, associated with tropical evergreen and semi-deciduous forests [57]. Wild populations have been reported in the states of Campeche, Tabasco, and Yucatan, confirming their adaptation to the climatic and edaphic conditions of the region [54] [68]. Commercial plantations have been established in the states of Oaxaca, Jalisco, Puebla, Nayarit, Yucatan, and Morelos [49]. Pitahaya is grown at altitudes ranging from 0 to almost 2000 meters above sea level, in areas with annual rainfall of 300 mm to 1000 mm, as higher humidity can cause phytosanitary problems in the plantation [56].

## 5. Limitations of the Study and Future Work

The current study aims to identify the regions with the most favorable conditions for dragon fruit production in the Yucatan Peninsula. One of its limitations is the scale of the mapping used, as it cannot identify areas smaller than 1 hectare, meaning it only identifies large areas.

For subsequent, specific studies on crop development in the region, work can be conducted at the plot level, complemented by characteristic climate data and soil analysis.

## 6. Conclusions

The Yucatan Peninsula has a considerably large area with potential for establishing dragon fruit (*Hylocereus undatus*) under seasonal conditions, with 159,396 ha of high potential and 1,058,193 ha of medium potential.

The state of Yucatan has the highest proportion of high-potential land (57.6%),

followed by Campeche and Quintana Roo, which highlights the importance of this crop for regional agricultural diversification.

There are optimal and suboptimal agroecological conditions for producing *Hylocereus undatus* under seasonal conditions in the Yucatan Peninsula.

## Conflicts of Interest

The authors declare no conflicts of interest.

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