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REVIEW

Prickly Pear Cactus : An Excellent Crop to Mitigate Climate Change

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ABSTRACT

Significant variations in global temperatures and weather patterns over time are known as climate change. Although it occurs naturally, human activities—particularly the burning of fossil fuels, deforestation, and industrial processes—are accelerating these changes, which have various detrimental effects on the environment. This review aims to highlight the edapho-climatic requirements of this cactus and the advantages and challenges of its cultivation to mitigate climate change. The prickly pear cactus is a plant with numerous financial and environmental advantages. It needs well-draining, sandy or gravelly soil to avoid root rot and do best in full sun. With a strong tolerance for dryness, they thrive in arid or semi-arid regions with scorching summers and prefer sparing watering. Despite being suited to tropical climates, some species can tolerate freezing temperatures and sporadic frost. Once established, these hardy plants require little care and thrive in nutrient-poor soils, which makes them perfect for xeriscaping or challenging growing environments. Because of its high water use efficiency ratio and low water requirements, prickly pear can be grown in marginally dry and semi-arid areas. The cactus does contribute to the ecological and socioeconomic fight against climate change. For instance, it supports sustainable agriculture, biodiversity preservation, soil restoration, carbon sequestration, and effective water usage. Demarcating dry and semi-arid zones and fostering employment in these areas is beneficial from a socioeconomic standpoint. The prickly pear's traditional cultural heritage supports its current economic function as a crop that can withstand drought. While ecological threats necessitate balanced management, this adaptability promotes sustainable growth. Innovations in bioenergy and value-added goods build on its historical applications, increasing its socioeconomic advantages and,

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eventually, its worldwide significance.

Keywords: Prickly Pear; Ecology; Climate Change; Carbon Sequestration; Biomass; Cultivation

1. Introduction

There are over 1,600 species and 130 genera in the *Cactaceaes* family, 300 of which are in the *Opuntia* genus[1, 2]. The prickly pear cactus, *Opuntia ficus indica*, is found in the Mediterranean region, Central and South America, and South Africa[3]. According to[4], Mexico has the highest concentration of species diversity. Prickly pear cacti have remarkable environmental adaptability. They grow in a wide range of climates, from regions with little rainfall to those with more than 500 mm of precipitation annually, and at elevations ranging from below sea level to more than 4,500 m in the Andes[4]. According to Rebman et al.[4], prickly pear cacti can range in height from 3 cm to over 20 m, and the biggest ones can weigh several tons. The cactus pear crop has several ecological and economic benefits. It is also gaining popularity in numerous countries because of its ecological, environmental, and socioeconomic benefits, including erosion and desertification control, as well as fruit-producing feed[5]. Its ecological benefits are due to its crassulacean acid metabolism, which facilitates CO_2 absorption at night, reducing water loss during photosynthesis[1, 6, 7]. Prickly pear cactus is suited for growth in marginal dry and semi-arid environments because of its low water requirements and high-water use efficiency ratio[8, 9]. The Food and Agriculture Organization recommends cactus pear as a potential crop in light of global climate change[8, 10]. According to Reis et al.[11], cactus pear is a low-input crop that can be grown sustainably and yield both fruits and cladodes that are edible to both people and animals. Since it can survive in arid climates and have the capacity to sequester carbon, prickly pear is particularly useful in reducing the effects of climate change. This review examines at how the prickly pear, *Opuntia ficus-indica*, is both a species limited by ecological and socioeconomic issues and a resilient crop for adapting to climate change. Well-known for its capacity to flourish in saline, nutrient-poor, and arid soils, the cactus helps preserve soil, sequester carbon, and support sustainable agricultural systems in areas with limited water[12, 13]. Its thin root system, sensitivity to salt thresholds, and soggy conditions, however, restrict its cultivation in some areas[14]. Furthermore, despite the ecological advantages of its drought tolerance, conflicts develop due to its potential for invasion and rivalry with other land uses[15]. This analysis emphasizes the necessity of striking a balance between its environmental potential and its practical and socioeconomic limitations to maximize the plant's contribution to climate-resilient agriculture.

2. Prickly Pear's Reproductive Biology and Ecophysiology Under Cultivation

The prickly pear (*Opuntia ficus-indica* (L.) Mill.), a crassulacean acid metabolism plant (CAM), shows notable differences in plant survival and development as well as harvest potential when grown in different environments. The ecological success of opuntias, especially *Opuntia ficus-indica*, is largely due to the peculiarity of their daily methods of water loss and carbon assimilation, both of which take place mostly at night. Similar to other CAM plants, the prickly pear opens its stomata at night to fix CO_2 and store malate in the vacuoles of the chlorenchyma cells. Because nighttime temperatures are lower than daytime temperatures and relative humidity is usually higher, CAM plants transpire three to five times less than C3 and C4 plants[16]. The outcome is a notable increase in water-use efficiency and the plant's ability to thrive in mostly dry environments with either prolonged drought and high temperatures or limited water input (200–300 mm annually). Adaptation strategies that are effective in arid conditions are not always necessary in high temperatures. Even though it happens at night, environmental elements including light, air temperature, nutrients, soil salinity, and plant hydration state have a big influence on acid accumulation and CO_2 uptake[16]. In fact, in the areas of origin of the central Mexican plateau (1800–2200 m above sea level), the peak daily temperature of the hottest month does not exceed 35 °C, the average annual temperature is between 16 and 18 °C, and the rainfall is less than 500 mm[17]. While the dry season in the coast of the Mediterranean coincides with the hottest days while fruit is growing and vegetative development is ongoing, the Mexican plateaus experience a cold winter and a very humid and wet warm season during which fruit and vegetative growth takes place[18]. In Sicily, wherein *Opuntia ficus-indica* is planted for its fruit, the average yearly temperature ranges from 15 to 18 °C, reaching a high of 37°C in August. Every year, the area receives roughly 500 mm of rainfall[12]. Opuntia ficus-indica is widespread in North Africa[19], in the high plateaus (2000–2500 m above sea level) in South Africa, and Tigray in Ethiopia. However, regions such as the Sahelian belt do not have it, nor California's Mojave desert, or India's Rajasthan desert where the highest daily summer temperatures are higher than 42 °C and the rainfall is lower than 350 mm[20]. The study by Le Houérou[21] addresses crops in Aziza (Libya) where maximum temperatures could surpass 50 °C. Cladodes of *Opuntia ficus-indica* cannot endure temperatures beyond 70 °C[14].

Due to their quick growth and capacity for vegetative propagation through the stems (short duration until harvest), edible opuntia are a good choice for both greenhouse and plant factory production[14, 22, 23]. Although the most popular technique for cultivating edible opuntia nowadays is open-field cultivation, hydroponics and environmental control in greenhouses and plant factories may be useful strategies to boost production and quality and promote use[22]. The proliferation of prickly pear can occur via cladodes and pepins[14, 22–24]. Daughter cladodes (new stem nodes) are stacked on top of mother cladodes (older ones) to produce edible opuntia. After that, the daughter cladode is separated from the mother cladode, dried in a dark environment for about a week, and utilized as a seedling for setting. Given that the size of the seedling significantly affects the growth and future generation of the daughter cladode, it is best to utilize a stem node that has a dry weight of 70 to 100 g or more, or a surface area of 500 cm^2 or more[25]. In order to avoid wilting, the harvested stem nodes should be dried standing vertically. An efficient method of preventing disease after setting is to sterilize the stem nodes at this time. For setting, it is advised to plant the stem nodes up to one-third of their length. While placing them shallow may result in their wilting, placing them deep may decrease the surface area available for photosynthesis[26].

Fruits of *Opuntia ficus-indica* can be harvested from July to November in the northern hemisphere (Mexico, California, and Mediterranean Basin) and from January to April in the southern hemisphere, depending on genotype and genotype/environment interaction. Induced or spontaneous reflowering can prolong the ripening season to January–February in the northern hemisphere and September–October in the southern hemisphere. In Salinas, California, flowering has been nearly constant[27], allowing for a longer ripening time.

3. Edapho-Climatic Conditions

3.1. Soil Types

Despite its great soil adaptability, *Opuntia ficus-indica* is particularly sensitive to anoxia due to its shallow root structure, which makes it susceptible to salinity and water saturation[14]. The plant may withstand difficult substrates, however it prefers light, sandy-loamy, or stony soils with low clay content (<20%), little organic matter (0.1–1.8%), and mild acidity (pH 5.1–6.7). For example, it can adapt to soils with low fine particles (<10%) or heavy calcium carbonate (>40%) or unbroken hard rock within the top 25 cm[14]. Waterlogged conditions hinder root respiration and encourage rot, hence hydromorphic or poorly drained soils are inappropriate[14].

Regardless of its adaptability, soil chemical composition has critical restrictions. Despite the pH-restricted growth of many *Opuntia spp*, *Opuntia ficus-indica* may thrive in calcareous soils. The best fruit quality requires high levels of potassium and calcium[12, 28], and mild salinity (up to 70 mol m^{-3} salt) or well-drained soils with gypsum[12, 13]. When compared to non-saline environments, growth decreases by 40% at 30 mol m m^{-3} NaCl (1.76 ppt) and by 93% at 100 mol m^{-3} (5.85 ppt), indicating that salinity thresholds are stringent[28]. As a result, commercial cultivation is recommended at ≤50 mM NaCl[14], with a 50–70 mM absolute top limit to prevent yield loss and canopy damage.

Soil compatibility is further determined by root development. The 60–70 cm deep superficial roots require soils devoid of high water tables or impervious layers. Root asphyxiation is made worse by excessive clay (>20%) or inadequate drainage, although low organic matter and high structural macroporosity (air volume) soils are tolerated. In order to ensure balanced nutrient intake and maintain production, calcium and potassium availability must satisfy edaphic demands[12, 28]. **Table 1** lists the soil types and functional characteristics suitable for cultivating *Opuntia ficus-indica*.

Table 1. Functional characteristics and soil classes suitable for growing *Opuntia ficus-indica* [14]

Functional Features	Measure	Classes			
		S1 Better Suited	**S2 Suited**	**S3 Less Suited**	**N Not Suited**
Minimum temperature	°C	>3	>3	>-3 ; <3	<-5
Mean temperature	°C	18 to 23	15 to 18	10 to 15	<10
Annual rainfall	Mm	>400	>400	200 to 400	<100
Texture		From sandy to mixed	Clay-loam	Clay-loam	
Depth		Irrelevant	Irrelevant	Irrelevant	Irrelevant
Skeleton		Irrelevant	Irrelevant	Irrelevant	Abundant
Carbonates		Irrelevant	Irrelevant	Irrelevant	Irrelevant
Acidity	pH	5 to 8	5 to 8	5 to 8	<5 ; >8
Organic matter	%	<0.5	<0.5	>0.5	>0.5
Available calcium (Ca)		Significant	Significant	Medium	Deficient
Available potassium (K)		Significant	Significant	Medium	Deficient
Electric conductivity (EC)	dS m^{-1}	<2	2 to 4	4 to 7	>7
Sub-surface groundwater		Absent	Absent	Absent	Present

3.2. Temperature

The subtropical arid locations where prickly pears are grown experience scorching summers, warm winters (average air temperature greater than 10 °C), a distinct dry season lasting two to five months, and 100 to 600 mm of yearly rainfall. It can adapt well to even the worst environments (poor agricultural potential, saline soils, and arid climate). Low winter temperatures, with a tolerance threshold of -10 °C, are the main factor limiting its spread. Some species, including *Opuntia ficus-indica*, *Opuntia dillenii*, and *Opuntia compressa* vr. Helvetica, may tolerate temperatures below 10 °C in Mediterranean nations. For example, the plant is grown for fruit production in Sicily, Italy, which has a Mediterranean environment with scorching and warm summers, and rainy winters. July and August see 25 °C, while October and November, when the fruit is growing, see 15 °C. The average annual temperature is 16 °C. Rainfall ranges from 400 to 600 mm annually, and the dry season lasts four months, from June to September. As an additional illustration, the Negev desert in Israel, where the species is grown, experiences average monthly temperatures ranging from 13 °C in January to 25 °C in June through October. The annual rainfall is between 40 and 200 mm. Lastly, rainfall in South Africa varies by region, with winter occurring in the Western Cape and summer in the Eastern Cape and Northern Province. While the subtropical zones close to the Tropic of Capricorn in the north of the country are home to principal fruit crops, the two most important areas for specialty crops are the Northern Province and the Ciskey region. These provinces see very variable rainfall, mostly in winter (under 500 millimeters per year), and long, scorching summers and moderate winters [29, 30]. The typical monthly temperature fluctuates between 10 °C in the winter and 26 °C in the summer, as well as between 14 °C and 25 °C during the ripening and growth of fruit. The average yearly temperature is over 15 °C in all regions. Less than 1000 meters above sea level is the temperature limit for cactus development in Morocco [13]. Different species have different levels of sensitivity to cold, which might occasionally restrict their ability to propagate. Conversely, the species *Opuntia humifusa*, which is native to Ontario in Canada and 25 states in the United States, can tolerate temperatures as low as -24 °C [31]. In Canada, *Opuntia fragilis* can withstand temperatures as low as -40 °C [32]. The cladodes' water content is what causes this resistance; the less water there is, the more resilient the species is to cold [16]. High temperatures cause bud differentiation and decreased floral bud production [33, 34]. The Canary Islands and the Catamarca Valley in northwest Argentina, when winter temperatures fall below 200 hours, are really home to fruiting cactus plantations. The plant may reach its maximal photosynthetic activity at 25 °C during the day and 15 °C at night because to CAM metabolism. Poor plant development, poorer productivity, and eventually low harvest value result from a net decrease in carbon absorption caused by higher daytime temperatures or lower nighttime temperatures [14].

In addition to reducing photosynthetic activity by up to 70%, temperatures above 30 °C also shorten the third phase of fruit growth, which is when the majority of the edible flesh growth occurs. This results in advanced and early ripening as well as a decrease in size, firmness, and sugar content. Fruit that has been exposed to high temperatures during development is more susceptible to low temperatures (under 8 °C) while being stored after harvest[18]. However, daily temperatures under 15 °C cause the fruits to develop more slowly, ripen later, and have a thicker, lower-soluble-solids skin with a poorer color[12, 33, 35]. Fruits and cladodes tissus are irreversibly damaged by temperatures below 0 °C, even for four hours. The production of high-quality fruit is severely hampered by high temperatures in regions with hot, dry summers. In fact, the optimal daily temperature for CO_2 uptake decreases from 17°C in moist conditions to 14°C after seven weeks of desertification[14]. Temperatures during the fruit development phase and blooming times affect the number of days needed to attain commercial harvest maturity, but the thermal time, expressed in growing degree hours (GHD), from flowering to harvest remains constant at 40–43 × 103[35, 36]. Detached cladodes exposed to cold winter temperatures yielded the greatest number of fruiting buds the next spring, according to Nerd et al.[37]. Likewise comparable outcomes have been documented by Gutterman[38], who evaluated detached cladodes under 18 different light/temperature combinations and found that they produced much more fruit when grown outdoors with 8 hours of light and mild temperatures than when grown in heated greenhouses with 8 hours of light. According to Nobel et al.[34], detached cladodes kept at 15-5 °C produced more fruit than cladodes kept at 25-15 °C (day-night temperatures). The study by Potgieter et al.[39] state that fruit productivity is strongly influenced by the environment, with regions of South Africa experiencing hot summers and cold winters producing the highest fruit yields. Additionally, they reveal a substantial genotype x environment interaction, suggesting that cultivars vary in how much heat is needed to produce the best fruit. However, in the Catamarca valley in northwest Argentina and the Canary Islands, where the total number of winter vernalization units is less than 100, the prickly pear bears fruit. It can also re-flower multiple times in a single season, either naturally in California or Chile or artificially in Israel or Italy[12, 35]. Since these out-of-season flowerings seem to have nothing to do with endodormancy, the resting period may be the result of ecodormancy rather than genuine rest or endodormancy. The initial spring wave of flowers and cladodes may be replaced by another wave of fruit for *Opuntia ficus-indica*[18]. The plant's capacity to bloom again is influenced by temperature. In actuality, the temperature at the time of suppression has a significant impact on how the plant reacts to spring flowering suppression (SFP). Higher temperatures (greater than 30/20°C day/night) produce more new cladodes than fruit, whereas lower temperatures (les than 20/15°C day/night) may not result in fresh budding[40–42].

3.3. Rainfall

Because of its crassulacean metabolism, the prickly pear may grow in regions with annual rainfall of no more than 200–300 mm. The cactus grows in semi-arid regions in Mexico's native highlands, where summer rainfall is concentrated during the fruit-development season. The dry season runs concurrently with a long, hot summer in the Mediterranean basin, the Middle East, North and East Africa, Argentina, California, and Chile. For instance, the Santiago metropolitan region in Chile, where the mean monthly air temperature is 10 °C during the winter (August) and 22 °C during the summer (January), is where fruiting cacti like prickly pear are produced. With an average of 350 mm of rainfall per year, the dry season lasts four to five months[43]. From an ecological perspective, prickly pears can be utilized to develop unproductive, arid marginal land because they are a crop that can withstand climatic change. They are renowned for their ability to adapt to desert settings and withstand drought. Low rainfall in Mexico's Milpa Alta region has resulted in significant losses since the introduction of fodder crops like maize. Together with other woody species, Prickly pear cacti have been effectively employed in Somalia's dune-fixing program and in a number of other nations to combat soil erosion[44]. Prickly pear cacti are crucial to the ecology of the Sidi-Ifni region of southern Morocco, as they aid in soil conservation and erosion prevention[21].

3.4. Light

Sunny climates are ideal for most cactus species. Healthy plants thrive in bright light and long days[45]. Unfavorable effects of shade include the elongation of internodes and a type of raquette depigmentation[9]. The nighttime opening of stomata is more dependent on the daily value of the photosynthetic photon flux (FPP) than on its instantaneous value, and light and CO_2 uptake occur at different times. PPF

= 3 mol.m^{-2}.day^{-1} is the compensation point. The point of saturation is reached when PPF = 30 mol.m^{-2}.day^{-1}. CO_{-2} assimilation is 90% of its optimum at FPP = 22 mol.m^{-2}.day^{-1} [46]. The cladodes can be planted in large quantities on culture panels to maximize the available area. Artificial light can also be used to grow the plants at relatively low light intensities [22].

3.5. Altitude

Different elevations are suitable for the growth of *Opuntia ficus-indica*. It can be found at elevations between 500 and 800 meters in the Meknes region and between a few meters and 700 meters in the Sidi Ifni region of southern Morocco [47], and from 480 to 760 meters above sea level in northern Morocco [48]. *Opuntia ficus-indica* is planted between 250 and 600 meters above sea level in Italy [49]. *Opuntia ficus-indica* grows between 1,800 and 2,400 meters above sea level in the central plateaus of Mexico [50]. *Opuntia ficus-indica* is found in many different types of climates and at elevations that range from below sea level to more than 4,500 meters in the Andes [4]. According to Koalaga et al. [51], the altitude may influence the content of some polyphenols of the cactus pear fruits.

4. Cactus and Climate Change Mitigation

4.1. Carbon Sequestration

One of the primary causes of the increase in atmospheric carbon (C) concentration is anthropogenic activity, which has been endangering and harming many species across the globe. With significant geographical and temporal diversity across the globe, terrestrial ecosystems in general are in charge of exchanging carbon and energy with the atmosphere, resulting in yearly sequestration of 3.2 ± 0.6 Pg C [52–55]. Cactus plantings play a vital part in the carbon cycle. By recycling carbon (CO_2) into the atmosphere and building block nutrients into the plants, they aid in the completion of the life cycle [56]. Similar to other plants, CAM plants like prickly pear uses photosynthesis to take up carbon dioxide (CO_2) from the atmosphere. They can nonetheless help sequester carbon even though their total biomass is lower than that of huge trees, particularly in semi-arid and arid regions with little other vegetation. Prickly pear helps sequester carbon, but it does it in a different way than forests and big trees [9, 56–58]. It contributes in the following ways to this process :

4.1.1. Crassulacean Acid Metabolism (CAM) Photosynthesis

Prickly pears use Crassulacean Acid Metabolism (CAM), a specific type of photosynthesis which allows them to open their stomata at night to minimize water loss. This adaptation is particularly efficient in arid environments and enables them to fix carbon even under extreme conditions. Like other plants, prickly pear cacti absorb carbon dioxide (CO_2) from the atmosphere via photosynthesis [26, 59, 60]. Cactus pears and other plants with CAM photosynthesis have lower water loss and are more efficient at using carbon and water than plants with C3 and C4 photosynthesis, which helps them survive in environments with high stress levels, mostly abiotic [23, 26, 60, 61].

4.1.2. Biomass Accumulation

The soil microorganism biomass, the most active part of the soil organic reservoir, is responsible for the bulk of biogeochemical processes in earth's ecosystems, including the formation of minerals, organic matter disintegration, and, ultimately, primary productivity [62, 63]. Biomass development on poor-quality land is necessary to satisfy future energy needs and minimize resource conflicts [60]. Despite often having lower biomass than trees, cactus can store carbon in their stems and roots. This biomass helps store carbon over time, particularly in areas with little other vegetation. Plants that use CAM generate less trash. However, being perennial plants, forage cactus pear contribute to root exudates and deposition because their root systems remain active over time [57, 64].

4.1.3. Soil Carbon Storage

By improving the structure and quality of the soil, prickly pear cactus can increase the soil's capacity for storing carbon. By preventing soil erosion and deterioration, they help preserve the amount of organic carbon in the soil. Arable soils typically lose all of their organic carbon, which raises the amount of CO_2 released into the atmosphere. Prickly pear cactus and agave are examples of perennial plants that can help maintain the soil's overall organic carbon content [57, 64].

4.1.4. Longevity and Resilience

Cactus pears are long-lived and resilient plants, capable of surviving in harsh conditions for many years. This longevity means they can sequester carbon over extended periods, contributing to long-term carbon storage [65–68]. While prickly pear cacti are not as effective as forests in sequestering large amounts of carbon, they are crucial in dry and semi-arid areas where they are often the dominant vegetation. Their role in carbon sequestration is part of a broader ecological function that supports climate change mitigation efforts, particularly in desert and degraded landscapes [57, 62, 64].

4.2. Water Efficiency

Prickly pears are highly efficient in water use, making them ideal for areas affected by drought and desertification [8, 10]. The prickly pear is a CAM plant (Crassulacean Acid Metabolism) grown in a wide range of environments. Like other CAM plants, the prickly pear opens its stomata at night to fix CO_2 and accumulate malate for storage in the vacuoles of the chlorenchyma cells. Since night-time temperatures are lower than daytime temperatures, and relative humidity is generally higher, transpiration in CAM plants is three to five times lower compared to C3 and C4 plants [16, 58, 69]. Plants with succulent CAM tissues can preserve water balance and support a carbon acquisition technique known as "drought avoidance" [70, 71]. Their ability to store water and survive in harsh conditions helps maintain vegetation cover, which can prevent soil erosion and degradation. Because of their CAM photosynthetic path, which better transforms CO_2 and water into plant material, prickly pears consume less water than C4 or C3 plants [10, 72, 73]. The CAM pathway's primary uptake of CO_2 by night, while temperatures are low, reduces the need for evaporation across the open stomata, making it a significant adaptation for water-use efficiency [7, 16, 74, 75]. Succulent CAM species' parenchymal water-storing tissue serves as a buffer against times of water scarcity stress, and rectifier-like root hydraulic conductivity responses enable plants to benefit from short windows of water availability by lowering retrograde plant-soil water losses [16, 74, 76].

4.3. Biodiversity Support

The continuous growth of the human population and the demand for land resulting from food production and consumption are the main causes of the loss of natural habitat and the replacement of it by agricultural systems [77]. Currently, human-caused changes in land use have significantly reduced biodiversity throughout greater than 58% of the surface of the Earth [78]. The loss of biodiversity is mostly caused by landscape fragmentation, which reduces the capacity of landscapes to provide essential ecological services and ecosystem activities. Invasive alien species can further reduce biodiversity in landscapes that have been substantially disrupted and fragmented by human activity [79]. Agroecosystems known as prickly pear cultures are made up of perennials with morphological and physiological characteristics that, in many situations, enable them to develop faster and produce more than other plants cultivated in dry conditions and on low-fertility lands [80, 81]. Prickly pear cacti provide animals with a wealth of resources throughout the season of flowering and fruiting. Fruits provide food for birds and mammals, while flowers draw pollinators like bees and bats. Furthermore, year-round plant cover with a complex structure is maintained by prickly pear fields, providing a haven for a variety of biological groups, including plants, birds, and rodents [82–85]. Because they serve as ecosystem service providers and repositories of biodiversity, these agricultural systems have enormous conservation potential. As the key pollinators of prickly pear cacti, bees are a significant component of worldwide biodiversity [86]. Due to their key role in the ecological process of pollination, they are crucial to the reproductive success of most native and domesticated plants [87]. Prickly pears have also been shown to have beneficial effects on various ecosystem services, including carbon sequestration, nitrogen cycling, soil protection, and covering argan trees, natural grasses, and forbs [88–92]. Despite its virtues for maintaining biodiversity, the invasiveness of prickly pear cacti and their effects on several ecosystem functions have been acknowledged globally, particularly in semi-arid regions with irregular rainfall [14, 69, 93]. The significance of include this invasive prickly pear cacti in animal diets must be understood. The employment of livestock in prickly pear cacti control techniques may help to decrease the plant's invasiveness and abundance while also supplying a steady supply of feed throughout the dry season [93].

4.4. Land Restoration and Erosion Control

Degraded areas can be restored with the help of prickly pear cacti for land restorations [89]. Prickly pear cactus can contribute to the restoration of the ecosystem and allow for further reordering of carbon by stabilizing and improving soil quality [59, 79]. Prickly pear cacti are attracting attention, especially in arid and semi-arid regions, due to their potential role in sustainable land management and state management v [14, 88, 91, 92]. It's an interesting tool to use for soil Stabilization and Erosion Control. The fibrous root system of prickly pears binds to soil, preventing erosion in damaged area [14, 94]. For example, in semi-arid areas of Mexico, prickly pear cacti are utilized to restore degraded soils [14]. In arid regions, its succulent stems improve soil moisture by storing water [95, 96]. According to a 2014 study conducted in Tunisia, prickly pears cut runoff in damaged soils by 40% [1]. Prickly pear cacti have been used to repair damaged regions in Morocco with the overall benefit of conserving the soil and increasing its productivity. Prickly pear cacti-planted areas in the Rhamna region showed a greater species variety than cultivated or grazed ground, which is subject to degradation from wind and water. In contrast to plantations of eucalyptus, cactus fields produce three times as much biomass from natural plants [97–99]. In the arid and semi-arid steppes of northern Algeria, [100] evaluated the effects of prickly pear plants on plant variety and soil properties by measuring the following physicochemical properties of the soil: pH, electrical conductivity, organic matter, total and active $CaCO_3$, total nitrogen, plant-available phosphorus, and the carbon/nitrogen ratio. They found that prickly pear plantations considerably increased vegetation cover, species abundance, species richness, and organic matter in comparison to the unplanted rangelands, regardless of the climate zone.

4.5. Sustainable Agriculture

A multifaceted idea, agricultural sustainability is a set of management techniques that work with natural processes to protect all resources, lessen waste and environmental impact, prevent issues and promote agricultural ecosystem resilience, self-regulation, development, and continuous production for the satisfaction and sustenance of all [101]. The ability of agriculture to consistently supply food and other resources to a growing global population is essential to human existence and, by extension, to all human endeavors. Among the numerous issues that threaten agriculture's ability to meet human needs now and in the future are climate change, a high rate of biodiversity loss, land degradation from soil erosion, compaction, salinization, and pollution, the depletion and pollution of water resources, rising production costs, a steadily declining number of farms and, as a result, poverty, and a decrease in the population of rural areas [102–106]. Aside from dealing with these issues, agriculture has a major portion of the blame for them all because of the way it has been practiced in recent decades [107, 108]. Some cacti, like the prickly pear, are used in sustainable agricultural practices. They can be grown for food, fodder, and other products, providing economic benefits while maintaining low water and resource use. One example of a basic conservation compromise is the prickly pear, which is being used as a rehabilitation tool in large-scale projects in Africa [109] and help sustain the agricultural socio-economical structures in many hot and dry regions [91, 110]. Indeed, in arid regions at risk from climate change, the growing of cactus pear under sustainable and controlled conditions has been proved to support conservation agriculture by Belay [111] in the Tigray region of northern Ethiopia and by Thomas et al. [112] in the regions of the Mashreq and Maghreb (Jordan, Iraq, Syria, Lebanon, Algeria, Tunisia, Libya, and Morocco) with low rainfall.

4.6. Cultural and Economic Value

Land degradation occurs on all continents and affects millions of people, including a significant portion of the poor in arid regions [2]. In many regions, prickly pear cacti have cultural significance and economic value, which can incentivize conservation and sustainable management practices that contribute to climate change mitigation [8, 14, 99]. As a "plant of life," the prickly pear bridges the gap between modern economics and traditional practices [113].

4.6.1. Cultural Value

National Identity Symbol: Mexico's creation myth is around the prickly pear: the Aztecs constructed Tenochtitlan (present-day Mexico City) after seeing an eagle perched on a cactus eat a serpent, a sight that is depicted on the Mexican flag [114, 115]. This firmly establishes the plant in

Mexico's cultural legacy and represents tenacity and persistence[116, 117].

Rituals and Traditional Medicine: Prickly pear is utilized as a treatment for a variety of illnesses in many nations. For instance, cactus fruit and flowers are employed as anti-diarrheal or anti-ulcerogenic drugs in traditional sub-Saharan medicine. Cladode sap was used to treat whooping cough, and the blossoms were also taken orally as an anti-hemorrhoidal medicine[8, 14, 24, 118, 119]. Native American tribes including the Aztecs were among the indigenous groups who employed prickly pear pads, or nopales, to treat diabetes, inflammation, and burns. Warm pads helped breastfeeding women lactate, and its juice was given to wounds[116, 117, 120]. Because of its hallucinogenic qualities, the peyote cactus (*Lophophora williamsii*), a cousin of Opuntia, has been utilized in religious ceremonies, especially in the Native American Church[15].

Heritage in Culinary Arts: Mexican cuisine relies heavily on prickly pear fruits (tunas) and pads, which are used in salads, tacos, and drinks. Candy, jams, and drinks like the Prickly Pear Margarita can all benefit from the natural coloring and flavoring that the fruit's juice provides[116, 120]. Mexican food was recognized by UNESCO in 2010 as an intangible cultural heritage of humanity. Aguamiel, cactus pear (or prickly pear), corn, chocolate, pineapple, and other indigenous foods are used to make fermentations, which are the primary traditional Mexican culinary skills. This process produces a wide range of authentic fermented dishes and drinks that are still in demand today[121].

Art and Festivals: Since pre-Columbian times, harvest rituals honoring the prickly pear have been recorded as a way to express thanks for its abundance. Its function in native rites was observed by explorers such as Cabeza de Vaca[116, 117, 120]. In Uitenhage, there has been a prickly pear festival for a few years[122].

4.6.2. Economic Value

Employment and Agriculture: Around 20,000 families are supported by the more than 12,000 hectares of prickly pear farming in Mexico, which produces 300,000–500,000 tonnes a year. In dry places, it also provides revenue for smallholder farmers in Brazil and Morocco[113]. Because of its ability to sustain drought, the plant is a climate-resilient crop that is essential for ensuring food security in places like Ethiopia and Brazil[113]. Prickly pear cacti are a significant source of animal feed and, by encouraging intensive livestock farming, they help to maintain the amount of vegetative cover in rural regions[92, 94, 97]. According to Ntsonge et al.[123], *Opuntia ficus-indica* has the economic potential to alleviate poverty and unemployment in the Eastern Cape since its market helps those who would otherwise be forced into extreme poverty. The cactus's adaptability to arid and semi-arid zones demarcates these marginalized zones and fosters employment. The farmers of these regions often form cooperatives to process their products and become more competitive in the market. These products include seed oil, fruit or cladode jams, cladode powder, fruit and cladode juices, alcoholic beverages, natural liquid sweeteners, and dried flowers. In addition, the production of fodder enables them to feed livestock, thus contributing to sustainable agriculture[14, 24, 99, 124–127]. The prickly pear is also used by farmers to delimit fields and act as a barrier against animals[2, 94, 98].

Industry of Food: Juices, jams, and dietary supplements can be made from fruits and pads, or they can be sold fresh or dry. Products made from prickly pears are becoming more and more popular worldwide due to consumer desire for "superfoods" high in antioxidants, vitamins C and B, and minerals like calcium and potassium[14, 113, 128].

Pharmaceuticals and Cosmetics: Indigenous groups, on the other hand, consume large amounts of prickly pears in the form of fresh or dried fruits. In these populations, the cactus racket, fruits, and flowers are consumed for their interesting antioxidant, pectic polysaccharide, and fiber content. Recent scientific reports have highlighted that natural cactus molecules may have a high potential interest in human health and medicine[51, 129, 130]. In general, in herbal medicine, the extraction of bioactive compounds from solid permeable plant materials using solvents is a key step in the manufacture of rich phytochemicals. The species O. ficus indica is known for its high content of polyphenols with antioxidant and anti-inflammatory properties[131, 132].

Circular Economy and Biofuel: Prior studies have demonstrated that the biomass of some cactus pear species, including (*Opuntia ficus-indica L.*) Mill and (*Nopalea cochenillifera L.*) Salm-Dick, has great potential as a feedstock for the fermentation and hydrolysis of their cladodes to produce ethanol and biogas[133–135]. Cactus biomass is transformed into biogas and ethanol in Brazil and Mexico, providing a sustainable substitute for fossil fuels. For instance, Nopalimex in Mexico uses cactus waste to power municipal cars [113, 114, 128, 136].

The Industry of Cochineal Dye: The cochineal insect (*Dactylopius spp.*), which consumes prickly pears, has historically generated a valuable crimson dye for clothing. Although demand for cochineal has decreased due to synthetic dyes, it is still useful for natural food coloring and cosmetics [14, 114, 136].

4.7. Conflicts and Challenges

4.7.1. Invasiveness

The invasiveness of prickly pears and their economic advantages conflict in places like South Africa and Australia. Sometimes, eradication attempts (like those for cactus moths) cause livelihood disruptions [113, 137]. As long as the prickly pear is grown in private gardens or in sustainable agroforestry and silvopasture systems, these ecosystem services can be provided. Commercial monoculture crops, however, have the potential to hasten environmental deterioration. Furthermore, land infestation could result from the species' invasiveness. In order to maintain environmental sustainability in the future, prickly pears must be planted carefully due to the possible threats to natural ecosystems [91].

4.7.2. Pest Threats

The prickly pear can be affected by a number of pests and diseases: cactus mildew, rust, ceratite, the cochineal insect (*Dactylopius spp.*) [13]. Prickly pear crop losses of 70–100% can be attributed to biotic factors, such as the cactus moth (*Cactoblastis cactorum*), which calls for integrated pest management [113].

Cactus Rust: It shows up as tiny, round, yellow spots that sometimes spread into asymmetrical, filthy, or pale white areas. Two-year-old cladodes are primarily affected because they generate few cladodes after being assaulted and eventually dry out. The removal of the parasitized cladodes and copper-based treatments are efficient ways to control it, which primarily occurs in moist regions [13].

Cactus Mildew: The disease is characterized by brownish patches that invade the fruit and raquettes and blisters that lift the epidermis. The disease's susceptibility differs depending on the variety. Affected plant parts are chopped off and burned as part of preventive control [13].

Ceratite: A fruit fly from the Mediterranean region that can seriously harm poorly maintained plants. It is simple to eradicate this insect with a synthetic insecticide [13].

Cochineal Insect or Mealybug: Although generally polyphagous, some species of mealybug are specific parasites and attack a single species of cactus. Some inert cactus cultivars are resistant to mealybugs. Controlling mealybugs requires treatment with white oils or parathion [13].

Cactus Moth (*Cactoblastis cactorum*): *Cactoblastis cactorum* is one of four known cactophagous species in the genus and is indigenous to southern Brazil, Uruguay, Argentina, and Paraguay [138, 139]. In contrast to its congeners, which are host-specific (i.e., monophagous) and have restricted geographic ranges, *C. cactorum* is oligophagous, using a variety of Opuntia cactus species as hosts [138, 139]. The female of this cactus-feedind phycitid moth, like many other cactophagous moths [140], produces 200–300 eggs in total, and the eggs are laid on stacked spine-like "eggsticks," each holding 60–100 eggs [139, 141, 142]. Bypassing the plant's protective defenses, newborn larvae collectively penetrate into cactus cladodes through a single entry hole [143], and eat communally for two months during the summer and four months during the winter [141, 142]. Later, they leave to pupate in leaf litter or soil [141, 142]. In Australia since the 1920s and in Africa south of the Sahara since the 1930s, it has been employed as a biological control agent against a number of invasive species of *Opuntia cactus* [144].

5. Conclusion

In conclusion, prickly pear cacti prefer full sun and require well-draining, sandy, or gravelly soil to prevent root rot. They require little moisture and are incredibly drought-tolerant, growing well in desert or semi-arid areas with hot summers. Even though they are suited to warm climates, some species can tolerate frost and cold temperatures. These hardy plants thrive in low-nutrient soils and require little care once established, which makes them perfect for xeriscaping or challenging growing environments. Cultivating prickly pear cacti is an effective and inexpensive way to combat climate change. It is a plant characterized by a special CAM metabolism, which allows it to withstand violent conditions and adapt to arid, semi-arid zones. This metabolism allows him to efficiently master water reserves and reduce carbon, which contributes to soil recovery. Its fibrous roots help prevent soil erosion and combat desertification. On a socio-economic level, the cactus enables rural populations to exploit arid soils, while providing interesting outlets: all parts of the plant are industrially exploitable. However, the use of the cactus as a bulwark against climate change needs to be carefully studied to avoid the plant becoming an invasive species. The cactus provides a wide range of habitats and foods to support various biological ecosystems. Healthy ecosystems are resistant to climate change and can maintain better carbon storage. In general, prickly pear cacti are not an independent solution for climate change, but a key part of a comprehensive strategy that aims to preserve ecosystem, sustainable land management and biological diversity.

Author Contributions

Conceptualization: D.Y.K., Z.M., and M.I.; Investigation: K.Y.D., and L.A.H.; Project administration: Z.M., and M.I.; Methodology : D.Y.K., Z.M., and L.A.H.; Resources: Z.M., M.I., L.A.H., and D.Y.K.; Software: Z.M., and D.Y.K.; Supervision: Z.M., and M.I.; Validation, Z.M., and M.I.; Writing—original draft: D.Y.K. All authors have read and agreed to the published version of the manuscript.

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The data presented in this study are available on request from the corresponding author.

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Confict of Interest

The authors declare that they have no conflict of interest.

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