GSC Advanced Research and Reviews

eISSN: 2582-4597 CODEN (USA): GARRC2

Cross Ref DOI: 10.30574/gscarr

Journal homepage: https://gsconlinepress.com/journals/gscarr/

(Review Article)

Importance of prickly pear (*Opuntia* spp) cultivation for sustainable agricultural systems and climate change resilient

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GSC Advanced Research and Reviews, 2025, 23(03), 117-123

Publication history: Received on 25 April 2025; revised on 04 June 2025; accepted on 06 June 2025

Article DOI: https://doi.org/10.30574/gscarr.2025.23.3.0154

Abstract

The cultivation of prickly pear (*Opuntia* spp) represents a strategic alternative for the development of sustainable and climate-resilient agricultural systems. Its ability to adapt to extreme conditions such as poor soils, prolonged droughts, and high temperatures, combined with its metabolism, allows it to maximize the use of water and nutrients, contributing to soil conservation and mitigating erosion and climate impacts. Furthermore, it plays a significant role in food security due to its nutritional and forage value, as well as its potential for biofuels and phytoremediation.

Mexico is the world leader in prickly pear production, with more than 864,000 tons annually, distributed across 27 states, generating significant income for approximately 20,000 producers. Its marketing, traditionally fresh, has diversified into the food, pharmaceutical, cosmetic, and energy sectors, opening international markets such as Europe and Asia. Furthermore, prickly pear cultivation has a strong cultural and historical component in Mexico, linked to national identity and ancestral practices. However, it faces challenges such as pests, diseases, and limitations in the value chain, including quality and traceability issues. The lack of technical, economic, and regulatory resources hinders its sustainable expansion. Therefore, public policies, research, and technical support are needed to enhance its comprehensive use, fostering an agroecological transition that promotes economic, social, and environmental resilience in vulnerable regions.

Keywords: Agroecology; Opuntia; Climate Change; Sustainability

1. Introduction

Climate change is a risk factor that can affect the success of strategies aimed at reducing poverty, improving public health, and human development in general, increasing the population's susceptibility. Furthermore, this phenomenon primarily affects food security, making farmers vulnerable, as they depend heavily on natural resources, their geographic locations, and the poverty they experience. Although farmers' use of various strategies to cope with climate variability has proven effective and resilient, these strategies will not be sufficient in the face of the harshness of climate change and the global demand for food, posing a direct threat to food security [1-3].

However, while the environmental benefits of sustainable agriculture are indisputable, its implementation faces various challenges for producers. Failure to adapt to new climatic conditions would lead to social, economic, and environmental instability, leading to massive migrations from rural areas to cities. In the face of the socio-ecological challenges posed

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by climate change and the urgent need to strengthen climate resilience, some researchers have proposed incorporating agroecology into more sustainable models, in order to improve human and environmental health while meeting the sustainable development goals [4,5].

Agroecology has emerged as a scientific field encompassing a range of agricultural practices and a social movement, seeking to comprehensively transform agriculture to address diverse challenges. This approach promotes diversified cropping systems, nutrient recycling, soil health, and biological pest control, in addition to including social dimensions such as knowledge co-creation and knowledge sharing among farmers [6-8].

The incorporation of diverse native and resilient crops in Mexican agricultural systems is of great importance, since these are already domesticated plants that are mostly adapted to extreme conditions of temperatures and droughts, resistance to pests and diseases, poor and even contaminated soils [9]. Agroecology, by promoting diversified agricultural systems adapted to local conditions and resource availability, highlights the importance of traditional and resilient native crops that have made it possible to satisfy the vital needs of the population [10], such as the case of the cultivation of prickly pear (*Opuntia* spp). This xerophytic plant has developed anatomical, morphological and physiological adaptations that make it successful in arid environments with severe water stress, irregular rainfall and poor soils prone to erosion [11,12].

This review will provide a detailed analysis of the importance of prickly pear (*Opuntia* spp) cultivation in building sustainable and climate-resilient agricultural systems. This cactus's ability to thrive in extreme aridity, its water-use efficiency, and its contribution to food and feed security make it a valuable resource for addressing environmental challenges and ensuring agricultural production, generating economic and social opportunities in vulnerable regions.

2. Economic benefits of prickly pear cultivation

The prickly pear is a plant native to tropical and subtropical America and is currently distributed in numerous countries on all continents, whether cultivated or growing wild [13]. Mexico, thanks to its climatic diversity, is a world leader in cactus production with 777,000 tons annually. Its three main types are: vegetable cactus, forage cactus, and prickly pear cactus. The main producing states are Mexico City, Morelos, and the State of Mexico [14]. Prickly pear production and marketing are primarily fresh, but other industrial sectors have begun to produce cactus-derived products, such as food and beverages, pharmaceuticals, cosmetics, energy, natural additives, construction, and textiles, among others [15]. European and Asian markets have shown interest in this crop, primarily due to its nutraceutical properties. China is the main interested party in importing this product from Mexico, proposing agreements with Mexican producers to guarantee supply for its industrialization [16,17].

National prickly pear production has maintained growth rates in the last three decades, reaching a volume of 864,243 tons in 2020, with the participation of around 20,000 producers on an approximate area of 12,618 hectares distributed in 27 states [18]. This crop has become a highly profitable activity for people who traditionally cultivate it as small businesses, since it represents 5.1% of the total horticultural production in Mexico since exports to the United States alone contribute around 8 million dollars annually [19]. Thanks to this, highly marginalized families generate extra income by adding value to the prickly pear with products that stand out mainly in dishes, juices, processed foods, among others, promoting endogenous development in certain communities [20].

3. Social contributions of the prickly pear

In Mexico, the prickly pear cactus has historically been a representative symbol, as it is the only nation that uses this plant in its national emblem. This symbol highlights the importance of the founding of Tenochtitlán, where an eagle perched on a prickly pear cactus devouring a snake was found. The prickly pear has been important in the Mexican diet throughout history, with evidence found in excavations in Tehuacan, where remains of fruit seeds and fossilized prickly pear leaves dating back 7,000 years were found [21]. In addition to being consumed as food, this crop was used as a medicine, in beverages, in dyes, in magical and religious practices, and even as a material for building homes since pre-Hispanic times, playing a strategic role in food security and in the preservation of ancestral cultural practices [22,23].

The importance of prickly pear as food is that it has a high-water content of 88 to 93% and this will depend mainly on the environmental conditions that develop, but its main attraction is the content of fibers, vitamins, chlorophyll and minerals that help to strengthen mainly the liver and pancreas thanks to its hypoglycemic properties for the control of diabetes [24]. Prickly pear plays a crucial role in food security for several reasons, especially benefiting low-income communities, since they take advantage of all the derivatives of the crop for self-consumption and to feed their livestock herds, providing nutrients and digestible energy more efficiently than with grasses and legumes, satisfying the demand for forage mainly in semi-arid regions [25].

Currently, thanks to its chemical properties, prickly pear has found innovative applications in various industries such as pharmaceuticals, food and cosmetics. In addition to having compounds that can be extracted and used for the preparation of natural additives, this plant stands out for the propagation of the insect *Dactylopius coccus*, commonly known as cochineal, which produces a natural pigment with wide artistic and industrial demand, obtaining an average of 3,500 tons per year, fluctuating in price between $19.00 and $40.00 dollars per kilogram depending on the international market trend [26]. The production and trade of the insect articulated the economy of various indigenous peoples of Oaxaca, Tlaxcala and Puebla, bringing benefits due to its great international demand, since the importance of natural products has not been replaced by any other branch of artificial production [27].

4. The prickly pear and environmental sustainability

For several years, farmers have sought strategies to coexist with environmental adversities, as these techniques adapt to future climate change scenarios to achieve good crop production yields [28]. The prickly pear stands out for its notable contribution to environmental sustainability, becoming a fundamental tool to face ecological challenges such as the global increase in CO_2. It is one of the few species that can successfully establish themselves in the short term under environmental conditions with a high degree of biotic and abiotic disturbance. It is also a great accumulator of biomass due to its resource conversion capacity, which is five times greater than other plants, thanks to its crassulacean acid metabolism, presenting greater efficiency in the use of water and nutrients [29,30]. Similarly, through agronomic practices with the cultivation of prickly pear, erosion can be controlled, surface runoff reduced and some effects of drought mitigated, this allows the conservation of soil and water, improving the productivity and sustainability of regions mainly with water stress [31].

In the search to mitigate these negative impacts due to global warming and anthropogenic pollution, several investigations and technologies have been developed that include the use of prickly pear as a biofuel for the production of heat, electricity and fuel in a sustainable and ecological way, representing a viable option in rural areas where resources are limited [32,33]. Similarly, in recent years the prickly pear has had greater boom in phytoremediation processes in soil, water and air, since they have superficial and massive roots that can extend to extract various contaminants found at different depths of the soil, biotransformation of xenobiotic aromatic compounds and accumulation of heavy metals by the synthesis of fixing peptides [34].

This comprehensive use of prickly pear cultivation in sustainable agroecological systems reinforces its fundamental role in the transition toward more resilient models with a low ecological footprint.

5. Challenges of prickly pear cultivation

Despite being a plant that does not require many conditions for cultivation, prickly pear faces several challenges that limit its full and sustainable use. These problems include vulnerability to pests such as the borer weevil (*Cactophagus spinnolae* Gyll), the gray stink bug (*Chelenidia tabulata* Burn), the zebra worm (*Olycella nephelepsa*), and diseases such as gold disease, which is caused primarily by fungi such as *Alternaria* and *Hansfordia*. These diseases are reported more frequently when temperatures rise, posing threats to production, especially when adequate practices to mitigate their reproduction are lacking [35]. Another important challenge is the marketing and distribution of the product, since, although the demand for the prickly pear vegetable is growing, it is mainly based on quality criteria intended for human consumption, which limits its expansion, so it is sought to strengthen regulations, programs with financial mechanisms and good traceability of the agri-food chain, in order to reduce product losses [36,37].

Agricultural production in Mexico faces significant environmental challenges stemming from soil degradation, pollution, the presence of invasive species, climate change, and the loss of ecosystem services, all of which are caused by the fragmentation and deterioration of natural ecosystems. While the effects of environmental change vary by species, with the response to climate change dependent on genotype, local conditions, and agricultural management, mechanisms are being sought to enable the adaptation of cultivated plants (Figures 1 and 2). From an agroecological perspective, several practices can be implemented to improve soil conditions, which foster and enhance agroecosystems. However, the socioeconomic and cultural circumstances of producers limit the viability of these strategies, which will be reflected in the medium to long term [38,39].

Figure 1 Biomass development (root) under the effects of abiotic stress

Figure 2 *Opuntia* spp., plants inoculated with plant growth-promoting bacteria for bioremediation processes of soil contaminated with crude oil

6. Conclusion

In conclusion, it is proposed that in the face of these challenges, it is crucial to promote certain research, improve production techniques, and implement public policies to strengthen the production of this crop, achieving resilience to these changes in the economic, social, and environmental spheres, benefiting both the producer and consumer of prickly pear.

Compliance with ethical standards

Acknowledgments

To the institution for the facilities granted to carry out this work.

Disclosure of conflict of interest

The authors declare that they have no competing interests.

Author's contributions

All authors contributed equally to the conception and development of the work.

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