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Potential of *Opuntia cochenillifera* (L.) Mill as a Sustainable Forage Resource to Improve Livestock Productivity in Tropical Regions

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ABSTRACT

Tropical regions are increasingly vulnerable to climate change, which threatens forage availability and livestock productivity due to drought, land degradation, and water scarcity. *Opuntia cochenillifera* (L.) Mill, a drought-tolerant forage cactus, emerges as a promising solution for resilient and sustainable livestock feeding systems. This review explores its botanical and agronomic characteristics, nutritional profile, and environmental adaptability. *Opuntia cochenillifera* demonstrates high water-use efficiency, biomass productivity, and nutritional value, making it suitable for arid and semi-arid regions. Its integration into silvopastoral and agroforestry systems enhances environmental sustainability through improved soil health, reduced erosion, and potential carbon sequestration. The cactus also offers economic benefits by lowering feed costs and supporting year-round livestock productivity. However, limitations such as low protein content, potential invasiveness, and high-input management needs remain challenges to be addressed. Future research should focus on genetic improvement, biotechnology applications, and supportive agricultural policies to promote widespread adoption. Overall, *Opuntia cochenillifera* holds considerable promise for advancing climate-smart and sustainable livestock systems in tropical regions.

Keyword: Opuntia cochenillifera, Sustainable Forage, Tropical Livestock, Drought Tolerance, Biomass Productivity

1. Introduction

Tropical regions face significant challenges due to climate change, which exacerbates forage scarcity. Climate change impacts include increased frequency of extreme weather events such as droughts and cyclones, which destroy crops and pasturelands, making freshwater unavailable for human and animal populations [1] ; [2] ; [3]. These conditions threaten food security and the sustainability of agricultural systems, necessitating the development of resilient and sustainable feed resources [4] ; [5]. To address these challenges, there is a growing need for feed resources that are both resilient to environmental stressors and sustainable over the long term. Sustainable agricultural practices focus on improving resource efficiency, adopting techniques that generate landscape-scale resilience, and using a combination of evaluation and planning strategies to advance knowledge of crop and livestock interactions [6] ; [7]. Resilient feed resources must withstand disturbances and continue to function effectively, ensuring food security and supporting rural livelihoods [8] ; [9].

Opuntia cochenillifera (forage cactus) is emerging as a promising alternative forage due to its adaptability to arid and semi-arid climates. This cactus species is native to Mexico and is widely cultivated in regions such as Brazil, Mexico, Northern and Southern Africa, and Western Asia [10] ; [11]. Opuntia spp. are known for their resistance to drought and ability to grow in unsuitable soils, making them ideal for areas affected by climate change [12] ; [13]. The plant's high content of specific compounds, such as proline, indicaxanthin, and betanin, enhances its adaptation to unfavorable conditions [14]. *Opuntia cochenillifera* can be used as fodder, providing a nutrient-rich, low-cost feed that reduces water consumption and environmental impact [15]. It has been shown to improve the quality of animal by-products and support the development of livestock sectors in dry areas, thereby empowering farmers' livelihoods. Additionally, ensiling Opuntia cladodes helps conserve forage and maintain its nutritional value throughout the year [16].

The objectives of this review are to assess the potential of *Opuntia cochenillifera* as a resilient and sustainable forage resource in tropical regions; evaluate the nutritional benefits and practical applications of *Opuntia cochenillifera* in livestock diets; identify gaps in current research and propose future directions for optimizing the use of *Opuntia cochenillifera* in sustainable agricultural systems; discuss the environmental impact and economic viability of integrating *Opuntia cochenillifera* into existing agricultural practices. This review aims to provide comprehensive insights into the role of *Opuntia cochenillifera* in addressing forage scarcity and enhancing the resilience and sustainability of agricultural systems in tropical regions.

2. Method

This systematic literature review (SLR) was conducted to evaluate the potential of *Opuntia cochenillifera* (L.) Mill as a sustainable forage resource in tropical livestock systems. The review followed a structured and reproducible approach, emphasizing transparency and comprehensive data coverage. Literature searches were primarily carried out using the Scopus database due to its extensive indexing of peer-reviewed publications in agricultural and environmental sciences. Additional sources such as ScienceDirect, SpringerLink, and Google Scholar were used to capture supplementary and emerging literature. A systematic search was executed using a combination of keywords and Boolean operators: *("Opuntia cochenillifera" OR "forage cactus" OR "cactus pear") AND ("livestock productivity" OR "sustainable feed" OR "forage quality" OR "animal nutrition" OR "climate resilience") AND ("tropical regions" OR "semi-arid" OR "arid zones")*. The search was limited to articles published between 2003 and 2025. The lower boundary of 2003 was chosen to capture two decades of research progress, including foundational studies that examined the agronomic and nutritional characteristics of *Opuntia* species. This period also aligns with the growing global discourse on climate change adaptation in agriculture. The upper boundary of 2025 was set to include the most recent literature and ensure that the review reflects current research trends and updated insights, particularly in the context of climate-smart agriculture and sustainable livestock development.

Inclusion criteria comprised peer-reviewed journal articles, review papers, and relevant conference proceedings that addressed the use of *Opuntia cochenillifera* as livestock feed in tropical, arid, or semi-arid regions. Studies were considered if they contained data on agronomic traits, nutritional composition, environmental impacts, or economic assessments. Articles not written in English, those unrelated to agricultural use, or those published in non-scientific formats were excluded. All identified articles were imported into Mendeley for reference management and duplicate removal. A two-step screening process was applied: first by reviewing titles and abstracts, then by assessing the full texts of the remaining articles. The selection process followed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure methodological rigor. A total of 80 articles were included in the final synthesis. From each study, relevant data were extracted on research location, study design, species characteristics, nutritional evaluations, management practices, and implications for sustainability. The findings were organized thematically to address the review objectives and to identify key knowledge gaps and future research directions.

3. Result and Discussion

3.1. Botanical and Agronomic Characteristics of Opuntia cochenillifera

Opuntia cochenillifera belongs to the genus Opuntia within the family Cactaceae, which is native to Central America [17]. The genus includes approximately 200 species, characterized by significant morphological variation and frequent hybridization [18] ; [19] ; [20]. Opuntia species are known for their flattened cladodes (pads) covered with areoles and tiny spines called glochids. The flowers are typically yellow and cup-shaped, lacking true petals [10]. Specific morphological traits such as cladode size, spine number, and pollen characteristics are diagnostic at the species level [21] ; [22] ; [23].

Figure 1. *Opuntia cochenillifera* (L.) Mill

Opuntia cochenillifera is highly adaptable to various climate zones, including arid, semi-arid, and temperate regions [24]. It thrives in dry, warmer, and open areas, making it suitable for cultivation in regions prone to desertification [25]. The species exhibits crassulacean acid metabolism (CAM), which enhances water-use efficiency and allows survival in extreme drought conditions [26] ; [27]. *Opuntia cochenillifera* can be cultivated using low technological inputs such as mechanization and fertilization, but higher inputs can improve productivity [28]. It is often grown in monocropping systems but can also be intercropped with other species [29]. Propagation is typically done through cladode cuttings, which can be managed to optimize growth and yield [30]. Effective management practices include irrigation, fertilization, and harvest management. Nitrogen fertilization and optimal planting density significantly affect growth and chemical composition [31]. Harvesting younger cladodes can improve nutritive value.

Opuntia cochenillifera shows high biomass productivity, especially under high-intensity cultivation systems with irrigation and fertilization [32]. Biomass productivity can reach up to 50 Mg ha^{-1}/y^{-1}/under optimal conditions [33]. The harvest cycle can be managed to optimize yield. Biennial cutting frequency results in higher Cladode Area Index (CAI) values and productivity [34]. Harvesting at night and managing cladode size can also affect yield [31]. The species demonstrates high water-use efficiency and satisfactory biomass production even during prolonged drought periods [35]. Agronomic performance is influenced by environmental conditions and management practices, including irrigation and fertilization. More details about the Botanical and Agronomic Characteristics of *Opuntia cochenillifera* can be seen in Table 1.

Table 1. Botanical and Agronomic Characteristics of *Opuntia cochenillifera* (L.) Mill in Tropical Livestock Systems

Aspect	Details
Taxonomy	Genus: Opuntia, Family: Cactaceae [17]
Morphology	Flattened cladodes, areoles with glochids, yellow cup-shaped flowers [10]
Climate Adaptability	Thrives in arid, semi-arid, and temperate regions [24] ; [17]
Stress Resistance	CAM metabolism, high water-use efficiency [26] ; [27]
Cultivation Techniques	Low to high technological inputs, monocropping, intercropping [25] ; [28] ; [29]
Propagation Methods	Cladode cuttings [30] ; [36]
Management Practices	Irrigation, fertilization, harvest management [28]
Biomass Productivity	Up to 50 Mg $ha^{-1}y^{-1}$ [33]
Harvest Cycles	Biennial cutting, night harvest, cladode size management [31] ; [34]
Agronomic Performance	High water-use efficiency, satisfactory biomass production [35]

3.2. Nutritional Profile and Feed Value of Opuntia cochenillifera

Opuntia cochenillifera, like other Opuntia species, has a rich nutritional profile. The moisture content is notably high, often exceeding 90% [37]. The crude protein content varies but can be significant, with some studies reporting values around 7.54% to 9.07% [38]. The fiber content is also substantial, with crude fiber ranging from 16.26% to 21.00% and soluble fiber from 15.08% to 16.33% [39]. The energy content, measured in terms of caloric value, is approximately 349.07 Kcal. Mineral content includes calcium, potassium, magnesium, and iron, with potassium being particularly high [40].

When compared to conventional tropical forages, Opuntia species, including O. cochenillifera, show a highwater content and significant crude protein levels, making them a valuable forage, especially in arid regions [41]. The digestibility of Opuntia combined with other forages like Napier grass or berseem hay is high, maintaining positive nitrogen balance in livestock [42]. However, the fiber digestibility can be lower when combined with certain straws.

Opuntia species contain some anti-nutritional factors such as tannins, trypsin inhibitors, and oxalates, though these are generally present in low amounts [43]. Strategies to mitigate these factors include processing methods like drying and fermentation, which can reduce the levels of these compounds and improve the overall nutritional quality [44]. Several methods are used to process and preserve *Opuntia cochenillifera* silage, ensiling Opuntia can help preserve its nutritional value and make it more palatable for livestock. Drying, techniques like lyophilization, vacuum drying, and convection drying are used to produce powdered forms of Opuntia, which can be used in various applications [45] ; [46]. Mixing with supplements, combining Opuntia with other forages and supplements can enhance its nutritional profile and improve digestibility. Microencapsulation, this method is used to preserve sensitive components like betalains and carotenoids, enhancing the shelf life and usability of Opuntia products in food formulations [47] ; [48]. More details about the nutritional profile and feed value of *Opuntia cochenillifera* can be seen in Table 2.

Table 2. Botanical and Agronomic Characteristics of *Opuntia cochenillifera* (L.) Mill in Tropical Livestock Systems

Nutrient	*Opuntia cochenillifera*	Conventional Tropical Forages
Water Content	>90% [37] ; [40] ; [38]	Lower
Crude Protein	7.54% - 9.07% [41] ; [38]	Variable, often lower
Crude Fiber	16.26% - 21.00% [39] ; [38]	Variable
Soluble Fiber	15.08% - 16.33% [38]	Variable
Energy (Kcal)	349.07 [39]	Variable
Minerals	High in K, Ca, Mg, Fe [39]; [40] ; [38]	Variable
Anti-Nutritional Factors	Low tannins, trypsin inhibitors, oxalates [39] ; [43]	Variable
Processing Methods	Silage, drying, microencapsulation [47]; [45] ; [48] ; [42] ; [46]	Variable

3.3. Environmental and Economic Benefits of Opuntia cochenillifera

Opuntia spp. are highly adaptable to extreme environments, including high temperatures, low rainfall, saline soils, and severely degraded soils with limited nutrient supply [14] ; [17] ; [49] ; [50]. This adaptability makes them suitable for cultivation in arid and semi-arid regions, contributing to soil health and preventing erosion [14] ; [49]. Opuntia can be integrated into silvopastoral systems, which combine trees, forage crops, and livestock. These systems enhance land productivity, biodiversity, and ecosystem services [51] ; [52] ; [53] ; [54]. Opuntia's use as livestock fodder during dry seasons reduces the need for expensive supplements and conventional diets [14] ; [55] ; [50]. Opuntia can be part of agroforestry systems, which include silvoarable and silvopastoral practices. These systems improve soil fertility, reduce the need for herbicides, and enhance water-use efficiency [56] ; [57] ; [58] ; [59] ; [60].

Opuntia cultivation is economically viable for smallholder farmers due to its low water requirements and ability to thrive in poor soil conditions [61] ; [62]. The use of Opuntia as fodder reduces feed costs and improves livestock productivity. High-intensity Opuntia production systems have shown high economic viability, with significant returns on investment [25]. Smallholder farmers benefit from reduced production costs and increased profitability, especially during drought periods [63] ; [64]. Opuntia spp. contribute to carbon sequestration through their biomass production and soil health improvement [65] ; [62]. Silvopastoral systems incorporating Opuntia can sequester carbon in perennial vegetation, aiding in climate change mitigation. Integrating Opuntia into livestock diets can potentially reduce methane emissions from ruminants, contributing to lower greenhouse gas emissions.

3.4. Challenges and Limitations of Opuntia cochenillifera

There is moderate genetic diversity within Opuntia cultivars, which can make it challenging for farmers to distinguish between different genotypes, potentially hindering large-scale adoption [66]. species, including *Opuntia cochenillifera* , have a high potential for invasiveness, which can pose significant ecological and management challenges [67] ; [14]. While high-intensity production systems are economically viable, they require significant inputs such as mechanization, fertilization, and irrigation, which may not be accessible to all farmers [25]. Opuntia species generally have low protein content (around 5%), which necessitates supplementation when used as animal fodder [68]. This limitation can affect its acceptance as a primary feed source. The nutrient content of Opuntia can vary significantly based on environmental conditions and management practices, which can affect its reliability as a consistent feed source [12] ; [69].

Spiny varieties of Opuntia can cause physical harm to animals, leading to lesions in the mouth and esophagus, which can result in serious health issues. Overuse of Opuntia in animal diets can lead to digestive problems, although specific details on toxicity are not extensively covered in the abstracts [50]. There is a need for more focused breeding programs to develop spineless, high-yield, and nutritionally superior cultivars. The use of biotechnological tools in breeding has been limited and requires further exploration. Effective management strategies for pests and diseases, such as the cochineal insect, are crucial for maintaining healthy Opuntia plantations [70] ; [71]. Research into sustainable agricultural practices, including the optimization of water use and fertilization, is essential to enhance the productivity and environmental sustainability of Opuntia cultivation [72].

3.5. Future Prospects and Research Directions of Opuntia cochenillifera

Opuntia cochenillifera shows significant promise for integration into climate-smart livestock systems due to its high water-use efficiency and ability to thrive in arid and semi-arid conditions [49] ; [72]. Its cultivation can enhance livestock feed security by providing a reliable source of fodder during dry seasons, reducing the need for expensive supplements [14] ; [50]. Additionally, *Opuntia cochenillifera* has been noted for its high dry matter yield and palatability, making it a valuable feed option [28]. *Opuntia cochenillifera* can play a crucial role in enhancing livestock feed security in tropical regions. It is highly productive and maintains its nutritive value over extended periods, which is beneficial for logistics and reducing transportation costs [73]. The plant's ability to grow in degraded soils and its resistance to pests further support its use in tropical livestock systems [74]. Moreover, its high acceptability among dairy cows and resistance to carmine cochineal insects make it a reliable feed source.

There are significant opportunities in biotechnology and genetic improvement of *Opuntia cochenillifera*. Research has highlighted the potential for using biotechnological techniques such as hybridization, mutation induction, and polyploidy to develop new genotypes with enhanced productivity and resilience [75] ; [69]. DNA-based studies and molecular markers can help assess genetic variability and improve breeding strategies. Additionally, the use of biotechnology to profile and identify the plant's rich nutrient and phytochemical content can lead to new applications in various industries [76]. To effectively scale the use of *Opuntia cochenillifera*, several policy recommendations can be considered: support for research and development, invest in research to explore the full potential of *Opuntia cochenillifera* in livestock systems and biotechnology. Training and extension services, provide training for farmers on best practices for cultivating and using *Opuntia cochenillifera* as livestock feed [77]. Incentives for sustainable practices, offer incentives for adopting high-intensity production systems that are economically and energetically efficient [25]. Integrated pest management, promote the use of biological control methods to manage pests and reduce reliance on toxic insecticides. Climate-Smart agriculture policies, develop policies that support the integration of climate-smart crops like *Opuntia cochenillifera* into livestock systems to enhance resilience to climate change [78].

4. Conclusion

Opuntia cochenillifera (L.) Mill presents significant potential as a resilient and sustainable forage resource for improving livestock productivity in tropical regions. Its exceptional adaptability to arid and semi-arid environments, high water-use efficiency through CAM metabolism, and capacity to grow in degraded soils make it a strategic crop in the face of climate change and forage scarcity. With substantial biomass productivity and a favorable nutritional profile, it supports livestock health, particularly during dry seasons when conventional forage is limited. Additionally, its integration into silvopastoral and agroforestry systems enhances environmental resilience and contributes to soil conservation, carbon sequestration, and reduced greenhouse gas emissions. Economically, *Opuntia cochenillifera* offers a low-cost feed alternative that supports smallholder farmers, especially under high-input systems. However, challenges such as low protein content, genetic limitations, invasive potential, and management requirements need to be addressed through targeted research and policy support. Future efforts should focus on biotechnological improvements, breeding programs for spineless and nutrient-rich varieties, and climate-smart policies to promote its large-scale adoption. Overall, *Opuntia cochenillifera* stands as a valuable component in developing sustainable livestock systems that are both environmentally sound and economically viable in tropical climates.

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