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Closing the Loop in Opuntia Cultivation: Opportunities and Challenges in Residue Valorization

Alan Jesús Torres-Sandoval [1], Yolanda Donají Ortiz-Hernández [2,*], María Elena Tavera-Cortés [3], Marco Aurelio Acevedo-Ortiz [1,*] and Gema Lugo-Espinosa [1]

[1] Secretaría de Ciencias, Humanidades, Tecnología e Innovación—Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional Oaxaca, Santa Cruz Xoxocotlán 71230, Mexico; atorress1404@alumno.ipn.mx (A.J.T.-S.); glugoe@ipn.mx (G.L.-E.)
[2] Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional Oaxaca, Santa Cruz Xoxocotlán 71230, Mexico
[3] Instituto Politécnico Nacional, Unidad Profesional Interdisciplinaria de Ingeniería y Ciencias Sociales y Administrativas, Ciudad de México 08400, Mexico; mtavera@ipn.mx
* Correspondence: yortiz@ipn.mx (Y.D.O.-H.); macevedoo@ipn.mx (M.A.A.-O.)

Abstract

Global food systems face growing pressure from population expansion and climate change, making the identification of resilient crops a priority. The nopal cactus (*Opuntia* spp.) stands out for its capacity to thrive in arid environments and for its cultural and economic importance in Mexico. This study analyzes worldwide research trends and evaluates evidence from Mexico to identify opportunities and strategies for closing production cycles through residue valorization. Scientific output over the past decade shows steady growth and a thematic transition from basic agronomic and compositional studies toward sustainability, bioactive compounds, and circular economy approaches. In the Mexican context, applied studies demonstrate that *Opuntia* spp. cladodes residues can be transformed into composts with C/N ratios between 12 and 26, improving soil organic matter and nutrient availability. Biofertilizers produced through anaerobic fermentation enhanced phosphorus solubility in alkaline soils, while direct residue incorporation increased carrot and tomato yields up to threefold. Farmers recognize these practices as low-cost and compatible with local systems. Nevertheless, the lack of standardized protocols and scalable models limits widespread adoption. Strengthening research collaboration, policy incentives, and technology transfer could position Mexico as a leader in sustainable Opuntia value chains and advance circular economy practices in smallholder farming systems.

Keywords: Opuntia; waste valorization; composting; bibliometrics; systematic review; circular economy; sustainable agriculture; food security

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1. Introduction

Faced with increasing pressure on global food systems, driven by rapid population growth and the challenges posed by climate change, identifying resilient crops capable of withstanding harsh environmental conditions has become a pressing priority. In this context, the nopal (*Opuntia* spp.) stands out as an exceptional resource, uniquely adapted to thrive in arid and semi-arid regions [1]. Its stems, known as cladodes are photosynthetic and function as natural water reservoirs, a physiological feature that underpins its remarkable drought tolerance and productivity under adverse conditions. The Food and Agriculture Organization of the United Nations (FAO) has highlighted its potential to strengthen food

security, recognizing its remarkable adaptation to drought, efficient use of water, and versatility as food for humans and livestock [1,2].

Mexico is the center of *Opuntia* spp. biological diversity and domestication [3]. National production of nopalitos (young pads) surpasses 860,000 tons annually, cultivated on more than 12,600 hectares [4]. Leading production areas include Morelos, Estado de México, and Mexico City, with Milpa Alta alone accounting for 22% of national output, supporting over 7000 families and preserving strong cultural and ecological traditions [5–7]. Thus, Opuntia plays a dual role in Mexico: it is both a staple food and a symbol of national identity, while also representing an expanding agro-industrial sector with significant economic potential. However, this growing industry faces important challenges, such as the lack of standardized cultivation and processing practices and the environmental impacts of intensive production. Addressing these requires research that validates the crop's benefits while also developing strategies to ensure sustainable production and safe commercialization.

A central challenge is how to expand the economic use of *Opuntia* spp. without compromising its cultural and ecological foundations. The objective of this study is to evaluate global research trends on *Opuntia* spp. and to examine practical evidence from Mexico in order to identify opportunities, limitations, and strategies for closing production cycles through residue valorization in nopal cultivation. To achieve this objective, the study combines an analysis of international scientific production between 2014 and 2024 with a targeted assessment of applied cases of residue utilization in Mexico, with particular attention to composting and related processes. This dual perspective makes it possible to identify global research trajectories while also evaluating practical experiences that can inform the sustainable management of cladodes residues.

To guide this effort, the study addresses three research questions: (a) What are the prevailing scientific trends and thematic priorities in *Opuntia* spp. research worldwide? (b) What evidence exists in Mexico regarding residue valorization, and what are the key agronomic and product-quality outcomes of these interventions? (c) How do these local practices align with or diverge from international innovation pathways, and what opportunities and barriers influence their adoption at scale? By answering these questions, this work seeks to generate actionable insights for sustainable residue management and the development of integrated value chains. In doing so, it fills a critical knowledge gap, linking international innovation with local practices to promote low-cost recycling technologies, improve soil health, and strengthen the resilience of smallholder production systems in Mexico.

2. Materials and Methods

This study employed a mixed methodological design to analyze global scientific production on *Opuntia* spp. and to evaluate evidence of residue valorization practices in Mexico. The approach combined a bibliometric mapping of research outputs with a structured screening of empirical studies, enabling both an international overview and a context-specific assessment. Together, these methods provided complementary insights into how global trends connect with local practices in composting and biofertilizer development.

2.1. Global Research Analysis

The global dimension of Opuntia research was examined using bibliometric techniques to characterize publication dynamics, citation patterns, and thematic clusters [8–10]. Indicators such as publication growth, citation impact, and keyword co-occurrence were assessed to identify influential authors, institutions, and research areas. Scopus served as the primary database, with queries designed to retrieve records from titles, abstracts, and

keywords. The search combined Opuntia-related terms ("nopal", "prickly pear", "cactus pear") with thematic terms such as "sustainability", "food security", "climate change", "soil", "fodder", "animal feed", "economic", and "application".

The dataset covered publications from 1 January 2014, to 31 December 2024, excluding 2025 due to incomplete data. Only articles and book chapters in English and Spanish were included to allow international comparison. Data processing and visualization were carried out with Bibliometrix (version 4.4.3) for descriptive statistics [11], and VOSviewer (version 1.6.20) was used to generate keyword co-occurrence and collaboration network visualizations [12]. A minimum threshold of five keyword occurrences was set for mapping, and institutional networks were analyzed to highlight research communities.

2.2. Screening of Empirical Evidence on Residue Valorization

To complement the global analysis, a structured screening of empirical evidence was conducted to evaluate cladodes residues valorization through composting in Mexico. The screening procedure was informed by PRISMA guidelines [13] but applied in the context of this study as a tool to identify relevant primary research. Records were retrieved from Scopus, PubMed, and Lens.org without publication date restrictions, using the terms: (nopal OR "Opuntia ficus-indica" OR "prickly pear") AND (compost OR "composta" OR composting) AND (Mexico OR México).

Inclusion criteria focused on original empirical research providing primary data, including peer-reviewed articles and thesis chapters. Eligible studies assessed aerobic composting processes using cladodes residues as primary substrates, co-substrates, or additives, and reported process variables (e.g., temperature, pH, C/N ratio) or final product quality (e.g., nutrient content, soil or crop effects). All studies had to be conducted in Mexico and published in Spanish or English.

Exclusion criteria ruled out reviews, opinion papers, editorials, and conference abstracts lacking complete methodology or results. Studies on non-composting uses of Opuntia (e.g., fodder, food, medicinal, cosmetic) were excluded unless composting was a central or secondary focus.

The selection process was carried out in CADIMA using a two-phase protocol: (i) screening of titles and abstracts to remove duplicates and apply inclusion/exclusion criteria, followed by (ii) full-text assessment to confirm eligibility. A PRISMA flow diagram was generated to document each step. To ensure methodological rigor, two researchers independently conducted the screening within the CADIMA platform. Discrepancies were resolved through discussion, and when consensus could not be reached, a third reviewer provided the final decision. Although Cohen's kappa was not formally calculated due to the small number of included studies ($n = 5$), this double-screening and consensus approach strengthened reproducibility and minimized selection bias.

For data extraction, a structured form captured identification details (authors, year, country), study context (objectives, design), intervention characteristics (residues, composting method, duration), and outcomes (effects on soil, conclusions). Due to heterogeneity in design, substrates, and parameters, results were synthesized narratively and thematically, comparing composting methods, product characteristics, and reported effects.

Therefore, the objective of this study is to evaluate global research trends on *Opuntia* spp. and to examine practical evidence from Mexico in order to identify opportunities, limitations, and strategies for closing production cycles through residue valorization in nopal cultivation. The complete datasets supporting the global research analysis (Table S1) and the empirical evidence screening (Table S2) are provided as Supplementary Materials to ensure transparency and reproducibility.

3. Results

3.1. Description and Evolution of Scientific Production on Opuntia spp.

3.1.1. Main Information

The Scopus search yielded a corpus of 789 documents published between 2014 and 2024, reflecting a robust and consistent growth in scientific attention to *Opuntia* spp., with an annual growth rate of 16.79%. This growth underscores the global recognition of Opuntia as a relevant species for food security, climate resilience, and sustainable agricultural practices (Figure 1).

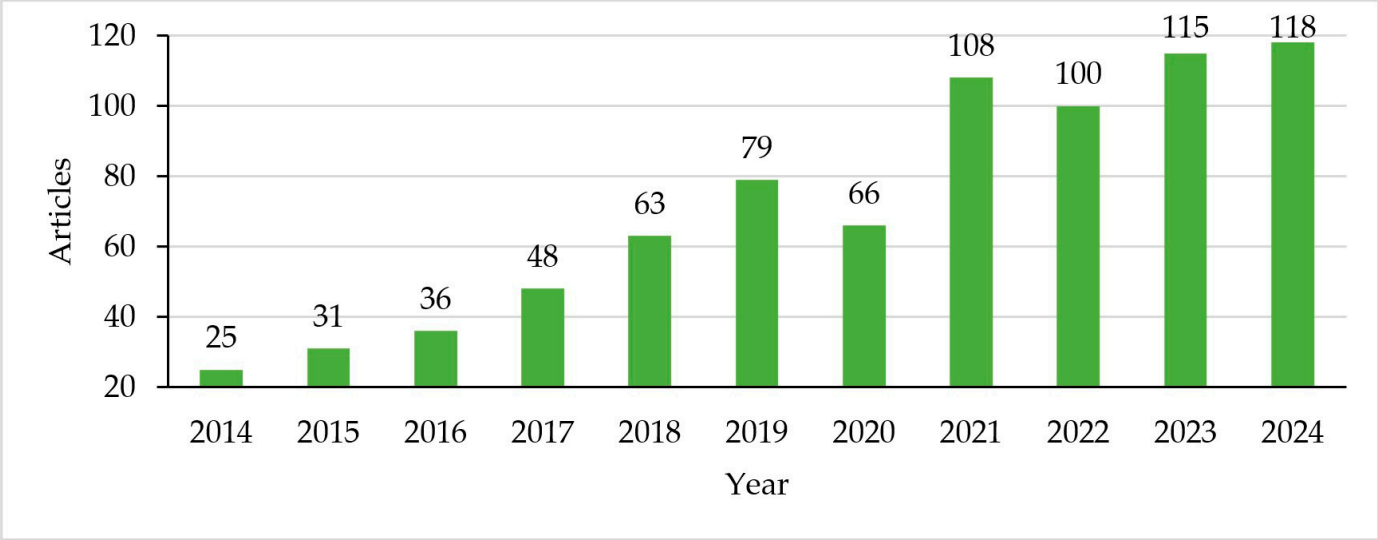

Figure 1. Annual Evolution of Research Publications Related to *Opuntia* spp. (2014–2024).

The trajectory shows steady growth, from 25 publications in 2014 to 118 in 2024, despite a slight dip in 2020 likely attributable to the COVID-19 pandemic. After 2021, output recovered and accelerated, reflecting renewed global attention to climate resilience and sustainable crops. This expansion frames our empirical focus on waste valorization as timely and aligned with the field's pivot toward sustainability. The fourfold increase also signals a consolidated trend toward integrating Opuntia research into discussions on sustainability, waste management, and resource efficiency.

Geographically, scientific production is concentrated in specific regions (Table 1). Mexico leads with 155 documents, followed by Italy (91) and Brazil (72). Other countries such as India, Morocco, and South Africa also contribute significantly, while Switzerland's single publication reached 252 citations, reflecting its global impact [14].

Table 1. Scientific production by country on *Opuntia* spp.

Country	Total Citations	Average Citations	Documents
Mexico	1976	12.70	155
Italy	1189	16.50	91
Brazil	922	10.10	72
India	893	28.80	31
Morocco	668	15.90	42
South Africa	620	23.00	27
Egypt	520	19.30	27
Tunisia	376	13.40	28
Algeria	373	12.00	31
Switzerland	252	252.00	1

The data show two important tendencies. First, countries like Mexico and Brazil have made significant investments in addressing local agronomic challenges, often linked to food security and resource management. Second, Italy's high average citation rate indicates that its research has become a reference point for connecting Mediterranean agricultural systems to broader debates on resilience and waste valorization. Mexico's average citation rate is lower than Italy's, suggesting differences in international visibility and research impact. This gap reflects not only reduced research visibility but also differences in how studies are positioned and disseminated internationally. Italian teams frequently participate in long-standing European consortia, benefiting from strong funding frameworks, access to high-impact journals, and multidisciplinary collaborations that integrate agronomy, chemistry, and bio industrial applications. By contrast, Mexican research is often carried out through smaller, project-based efforts that focus on local agronomic feasibility and sustainability but show limited integration into global innovation networks. These structural differences, particularly access to stable funding, international partnerships, and English-language dissemination channels, help explain why Mexico's substantial scientific productivity has not translated into equally high citation impact.

Meanwhile, India and South Africa, though publishing fewer documents, have positioned themselves in specialized, high-impact niches, often focusing on food, nutritional chemistry, and drought resilience, which gives them disproportionate influence relative to their output. The case of Switzerland illustrates another dynamic: although contributing only one document, its review on invasive alien species by Shackleton et al. (2019) [14] generated substantial influence, demonstrating how comprehensive syntheses can shape global conversations and set the agenda for subsequent research.

3.1.2. Publication Sources and Leading Authors

The analysis of scientific production reveals key publication sources and the leading researchers in the field of Opuntia research. Table 2 lists the top sources, with the Journal of the Professional Association for Cactus Development as the leading outlet, publishing 19 documents. This is followed by journals such as Acta Horticulturae (17 documents), *Opuntia* spp.: Chemistry, Bioactivity and Industrial Applications (16 documents), and Journal of Food Processing and Preservation (13 documents), while Agronomy has published 10 documents reflecting the topic's relevance in specialized research.

Table 2. Top 10 sources in research on Nopal.

Sources	Documents
Journal of the Professional Association for Cactus Development	19
Acta Horticulturae	17
Opuntia spp.: Chemistry, Bioactivity and Industrial Applications	16
Journal of Food Processing and Preservation	13
Tropical Animal Health and Production	13
Polymers	11
Agronomy	10
Foods	10
Revista Brasileira de Engenharia Agricola e Ambiental	9
Revista Caatinga	9

The most productive authors include De Wit, M. (17 publications), who has extensively investigated chemical composition and industrial applications in South Africa; Donato, S. (13), focused on agronomic optimization in Brazil; and Welti-Chanes, J. (10), based in Mexico, who has advanced studies on food processing and value chains (Table 3).

Table 3. Top 10 Authors in Research on Nopal.

Authors	Documents
De Wit, M.	17
Donato, S.	13
Hugo, A.	13
Louhaichi, M.	13
Hassan, S.	12
Welti-Chanes, J.	10
Edvan, R.	8
Fouché, H.	8
Venter, S.	8
Da Silva, J.	7

Table 3 indicates that a small set of authors concentrates a sizable share of output in the Opuntia field. This concentration suggests both thematic leadership and path dependence in collaboration networks. A South African group (De Wit, Hugo, Fouché, Venter) accounts for approximately 42% of top-author documents and is closely associated with industrial and biochemical lines of work (seed oils, mucilage/viscosity, composition and quality assessment), which tend to publish in higher visibility journals and connect to food, cosmetic, and pharmaceutical applications. Brazilian leaders (Donato, Da Silva, Edvan; approximately 26% of the total) are predominantly agronomic, emphasizing plant spacing, fertilization, irrigation, and forage performance. Mexico appears in the top 10 through Welti-Chanes, whose work connects Opuntia to value-added processing and food systems, yet Mexican leadership is otherwise underrepresented among the most prolific authors, reflecting the broader finding that Mexico's contribution is strong in volume but less embedded in global innovation stream.

Mexico and Brazil concentrate on the plant's agronomic and food security applications. The Sankey diagram (Figure 2) visually links these authors to the specific topics they investigate and their countries of affiliation, showcasing the structure of knowledge networks in the field. This structure underpins our subsequent analysis by indicating where expertise and potential partners for residue valorization are concentrated.

The diagram highlights the geographical and thematic specialization within the research. South African research, led by De Wit, M., is heavily linked to keywords like "chemical composition," emphasizing Opuntia's role in nutritional applications. In contrast, Italian research, led by authors like Inglese, P. and Sortino, G., is more focused on value-added topics, such as the study of "phenolic compounds" and "antioxidant activity."

Brazilian authors like Donato, S. share thematic links with South Africa, yet focus on the agronomic aspects within the South American production context. Mexican authors, on the other hand, explore both the resilience of Opuntia crops and their potential for sustainable development and valorization, reflecting the broader cultural and economic importance of the species in Mexico.

The temporal analysis of research activity (Figure 3) reveals different productivity profiles among authors. De Wit, M. and Donato, S., for example, have maintained consistent publication output throughout the decade, with notable productivity peaks, such as De Wit's in 2018–2019. This reflects the sustained research efforts by established research groups [15–18]. De Wit has focused on Opuntia's industrial valorization, particularly in the food, cosmetic, and pharmaceutical industries, investigating aspects like prickly pear seed oil and the hydrocolloid properties of cladodes [18].

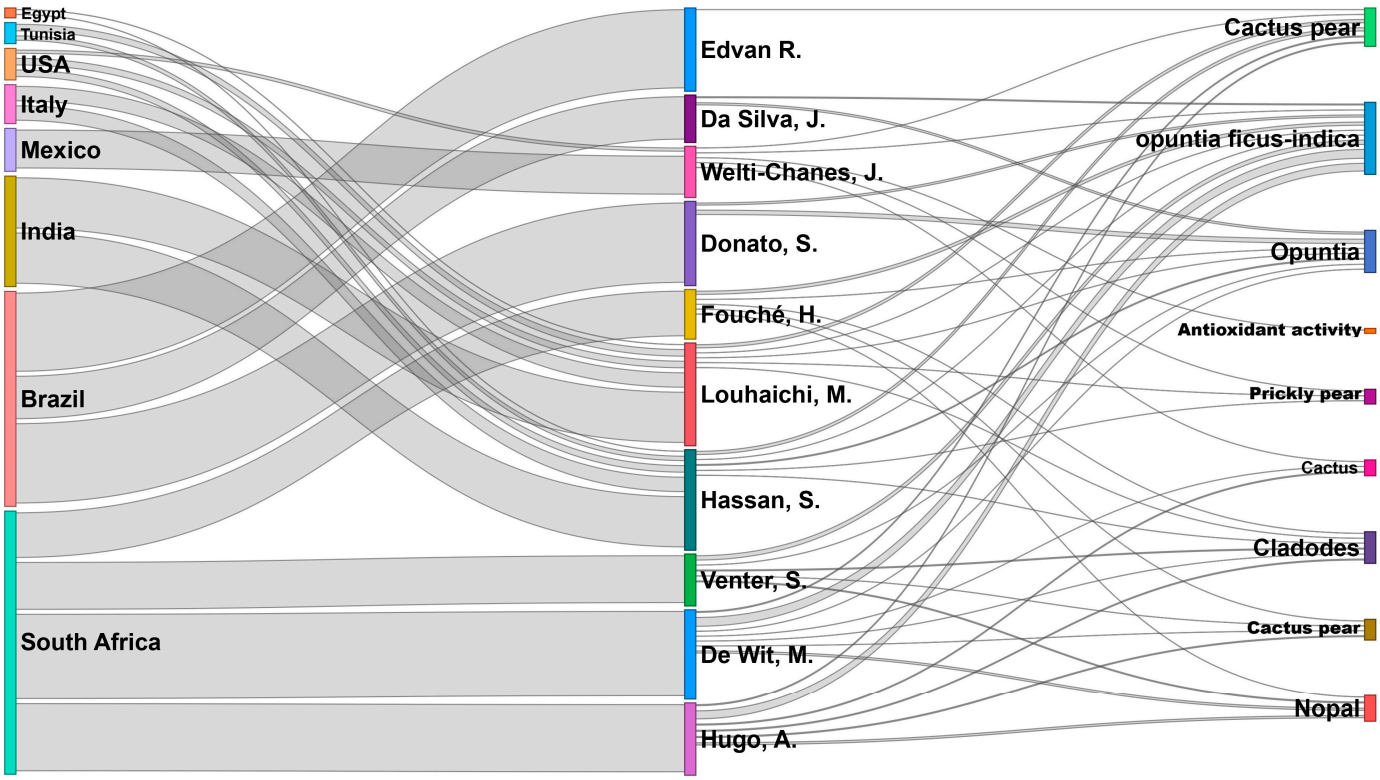

Figure 2. Sankey diagram showing the connections between countries (**left**), leading authors (**center**), and main research keywords (**right**) in *Opuntia* spp. studies. The width of the links reflects the intensity of the association, illustrating both collaboration patterns and thematic focus.

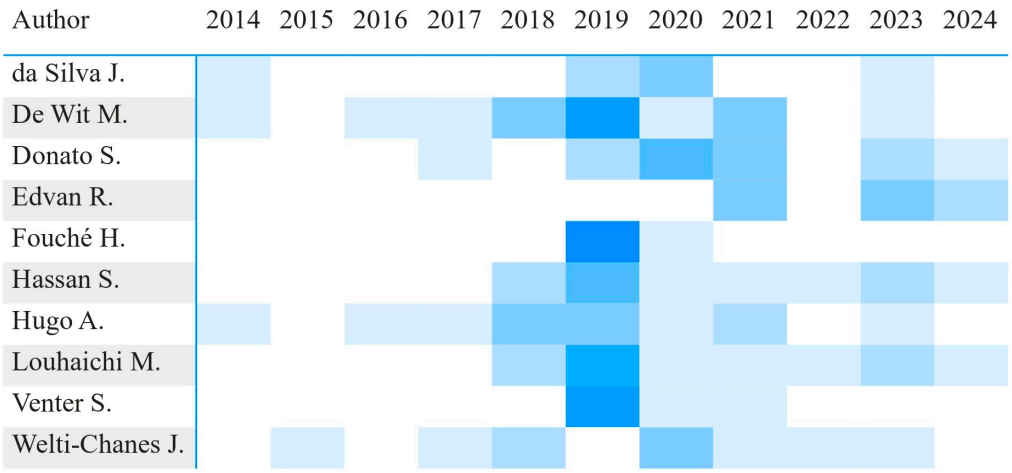

Figure 3. Scientific production of the main authors on *Opuntia* spp. studies over time. Each cell represents the number of publications by an author each year. The color intensity indicates productivity: light blue corresponds to lower frequencies (1 publication), while dark blue indicates higher frequencies (up to 7 publications).

In contrast, Donato, S.'s work centers on plant nutrition and agronomy, with a focus on optimizing nopal as a forage crop. His research evaluates how different agricultural practices, such as plant spacing and organic fertilization, impact plant production and nutrient extraction, aiming to ensure the sustainability of the production system [19,20]. In addition, authors like Fouché, H. and Venter, S. have shown bursts of productivity around 2019. This suggests concentrated research efforts during specific projects, such as Fouché's long-term studies on genotype-environment interactions in nopal cultivars,

and Venter's work on promoting *Opuntia* spp. studies as a multipurpose crop to combat food insecurity [21].

The coexistence of these clusters points to a fragmented but complementary research landscape. On one hand, long-standing collaborations contribute stability and continuity to the field, while on the other, the emergence of newer networks suggests growing interest in innovative applications and diversification of research themes. However, the limited connections between clusters highlight a challenge: knowledge produced in one research community is not always fully integrated with that of others. Strengthening cross-cluster collaboration could help bridge gaps between agronomic, biochemical, and sustainability-focused approaches, leading to more comprehensive strategies for the valorization of Opuntia and its byproducts (Figure 4).

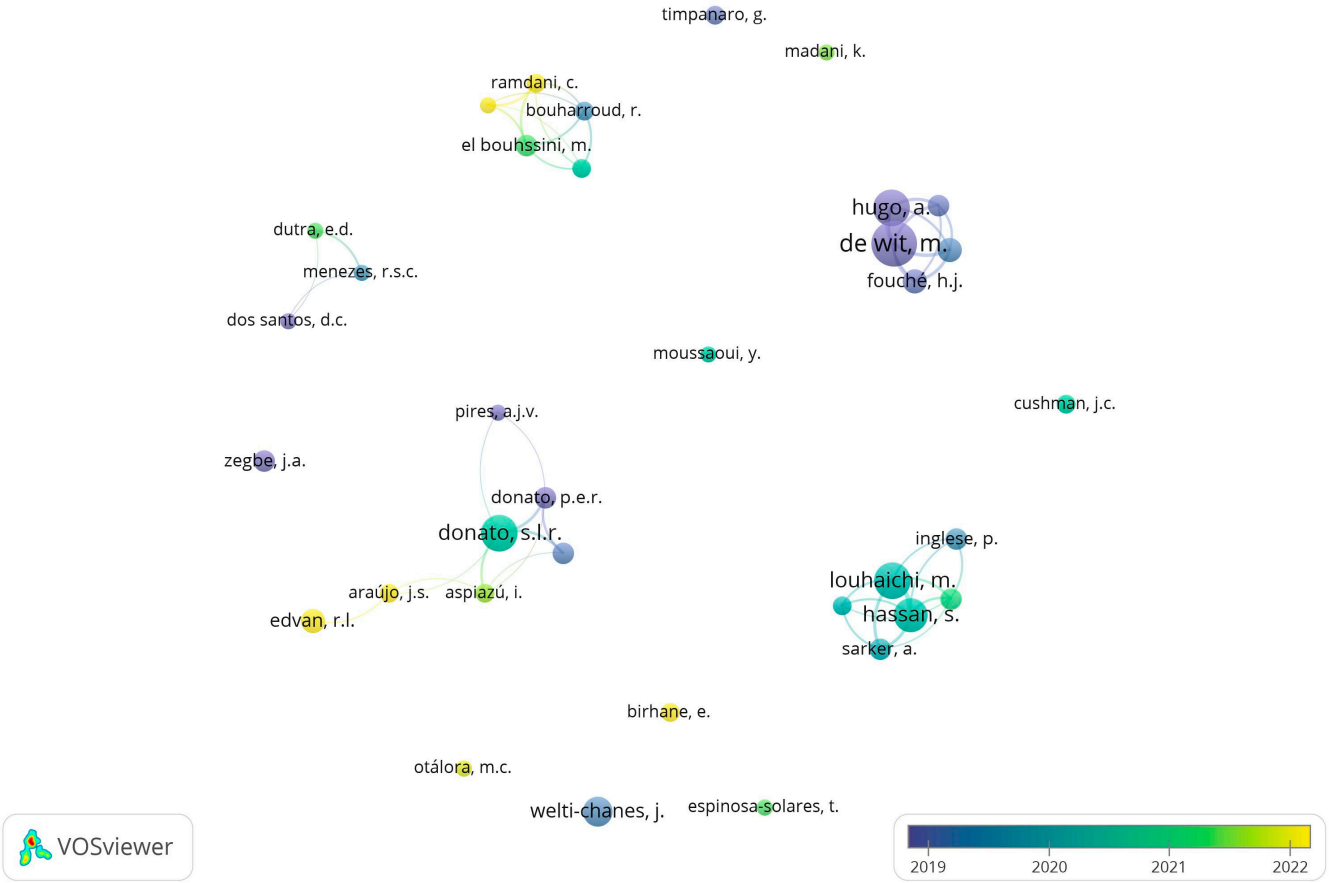

Figure 4. Collaboration networks between authors in *Opuntia* spp. studies research. Each node represents an author, with node size proportional to the number of publications. Links indicate co-authorship connections, while clusters of nodes show groups of researchers who collaborate frequently. Colors correspond to the average year of publication, with darker tones (blue–purple) representing earlier collaborations (2019) and lighter tones (green–yellow) representing more recent ones (2022).

The co-authorship network among the most productive researchers in *Opuntia* spp. studies. The visualization reveals several well-defined clusters rather than a single cohesive global network, indicating a fragmented but potentially complementary research landscape. The largest and densest cluster is anchored by De Wit, Hugo, and Fouché in South Africa [15–18,21]. This group shows long-standing internal connectivity and continuity, largely focused on the biochemical and nutritional dimensions of Opuntia, including seed oil quality, mucilage properties, and industrial applications. The Brazilian cluster, built around Donato, Da Silva, Edvan, and Araujo, is moderately connected and focuses on

agronomy and forage systems, often with practical implications for animal feed and crop management [19,20]. The Mediterranean cluster, including Louhaichi, Hassan, Sarker, and Inglese, integrates agronomic and sustainability topics, with strong links between Italy and North Africa to address shared climatic and cropping challenges [2].

Mexico appears primarily in a smaller, emerging cluster around Welti-Chanes and Espinosa-Solares, oriented toward processing, food systems, and early sustainability narratives. However, this Mexican presence is peripheral and less connected to the larger, high-impact clusters in Europe and Africa.

The coexistence of these clusters suggests a field that is dynamic but loosely integrated. Long-standing collaborations provide stability and expertise within specific niches, while the emergence of new networks signals diversification and growing interest in innovative applications such as circular economy and residue valorization. Nevertheless, the limited bridges between clusters imply that knowledge transfer remains incomplete, breakthroughs in biochemical or processing domains may not reach agronomic researchers, and vice versa.

The geographical collaboration map (Figure 5) confirms that research on *Opuntia* spp. is highly international, yet it remains regionally segmented. These regional networks demonstrate strong intra-continental cooperation but also reveal limitations: while intensive within specific areas, cross-continental partnerships are comparatively scarce. The relative absence of connections between regions such as Africa, Latin America, and Asia suggests untapped opportunities for broader integration. Expanding these global linkages could strengthen comparative studies, promote knowledge transfer across different production systems, and foster more comprehensive approaches to waste valorization and sustainable management of Opuntia resources.

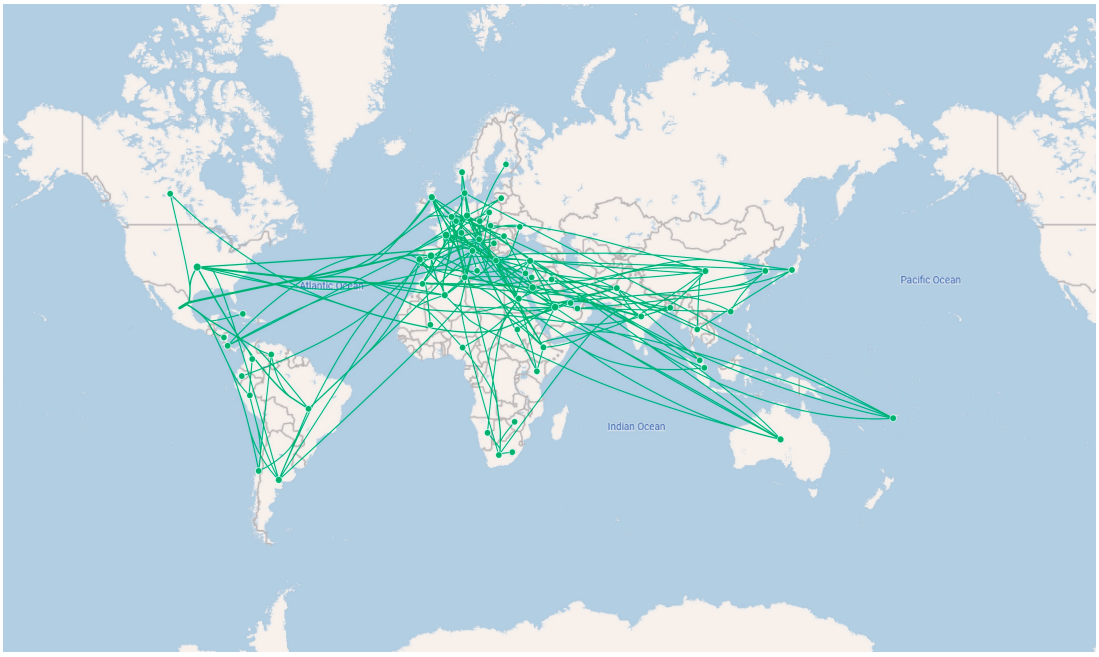

Figure 5. Geographical map of international collaboration networks in *Opuntia* spp. research (2014–2024). Each node represents a country, and connecting lines indicate co-authorship links between institutions from different countries. The density of connections illustrates the extent and intensity of cross-border research collaborations, highlighting regional hubs and transcontinental partnerships.

Opuntia spp. research is highly international but remains regionally segmented. In the Mediterranean region, Italy acts as the primary hub, driving collaborations that radiate into North Africa, notably Tunisia and Algeria, where the crop is important for dryland adapta-

tion and agronomic innovation. These links reflect historical academic exchange and shared climate challenges, allowing joint advances in water-efficient cultivation, phytochemical characterization, and value-added processing.

In the Americas, a clear North American axis is visible between Mexico and the United States, largely oriented toward agronomic improvement, drought tolerance, and sustainable production. Brazil, meanwhile, consolidates its position as South America's anchor, generating dense connections with regional partners to support forage systems and low input agronomy.

Despite this robust collaboration, the map exposes significant cross continental gaps. Networks linking Africa and the Mediterranean to Latin America are minimal, and ties between Latin America and Asia or Oceania are nearly absent. As a result, thematic innovations, such as Europe's nutraceutical and bio industrial focus or South Africa's biochemical characterization do not fully transfer to Mexico and Brazil, where studies remain mainly agronomic.

For Mexico in particular, the map reinforces earlier findings: although well connected to the U.S. and regionally active, it is weakly integrated into the European and African clusters that lead high-impact industrial and biochemical research. Expanding transcontinental partnerships could enhance methodology, increase international visibility, and support policy and funding alignment for circular economy practices. Promoting joint projects with Mediterranean and African groups would also enable comparative studies under similar semi-arid conditions and broaden the translational reach of Mexican residue valorization efforts.

3.1.3. Thematic Analysis of Keywords

The keyword co-occurrence network (Figure 6) highlights an interconnected research landscape structured around five primary clusters.

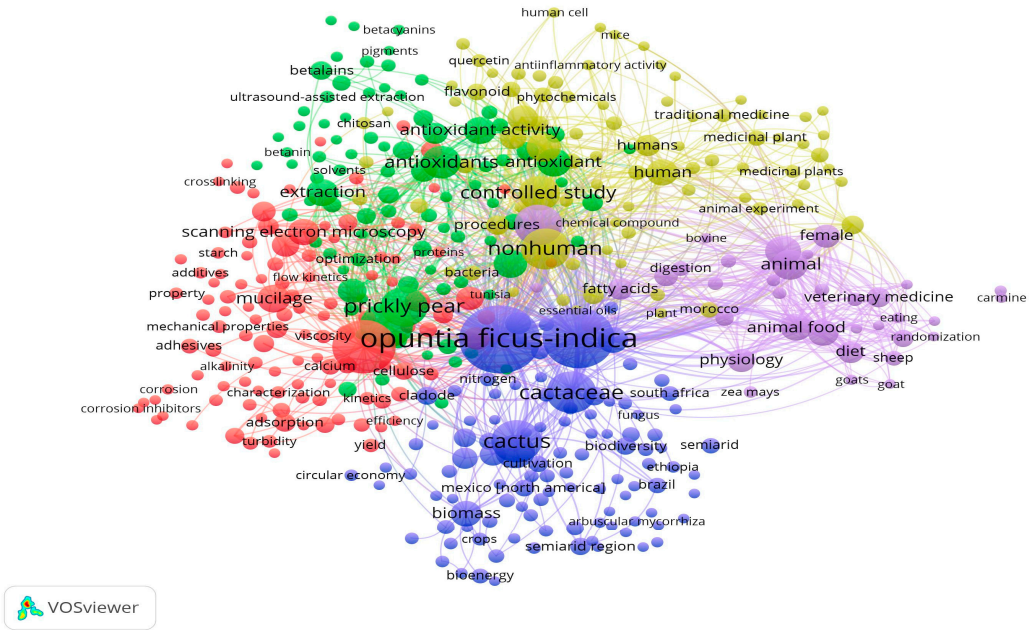

Figure 6. Keyword co-occurrence network of *Opuntia* spp. research (2014–2024). Node size reflects keyword frequency, while colors represent thematic clusters.

This thematic co-occurrence map illustrates the evolution of *Opuntia* spp. research, which has transitioned from agronomic studies and basic composition analyses toward specialized and value-added areas such as human health and sustainability.

Red Cluster: This cluster is one of the densest and centers around core terms like "Opuntia ficus-indica", "prickly pear", and "fruit". Associated keywords such as "phytochemicals", "polyphenols", "polysaccharides", and "betalains" indicate a strong focus on identifying and quantifying the chemical compounds of the plant.

Green Cluster: This cluster emphasizes "antioxidant activity", "phenolic compounds", "bioactive compounds", and "anti-inflammatory" properties. It reflects research into the functional health benefits of Opuntia, with terms like "anti-diabetic properties" and "food additives" highlighting its potential applications in the food and pharmaceutical industries.

Blue Cluster: Linked to the previous clusters through the term "Opuntia", this group centers on the agricultural and environmental aspects of the crop. Keywords like "cladode", "drought", "sustainability", and "water use efficiency" indicate research focused on agronomic management and the crop's role in sustainable agriculture, especially in the context of climate change resilience.

Purple Cluster: This cluster focuses on animal husbandry, with dominant terms such as "animal feed", "fodder", "cattle", and "ruminants". Research in this area is crucial for food security in arid regions, where Opuntia is used as a key nutrient source for livestock, particularly during droughts.

Yellow Cluster: Serving as a bridge between the other topics, this cluster includes terms like "chemistry", "human", "controlled study", and "metabolism". It encompasses research on the effects of young cladode consumption and the basic chemical studies supporting the other areas.

Beyond thematic structure, analyzing the temporal evolution of keywords provides further insight into how the research field has developed and which scientific trends are emerging. Figure 7 presents this dynamic trend, showing the period of activity of the most relevant terms from 2014 to 2024.

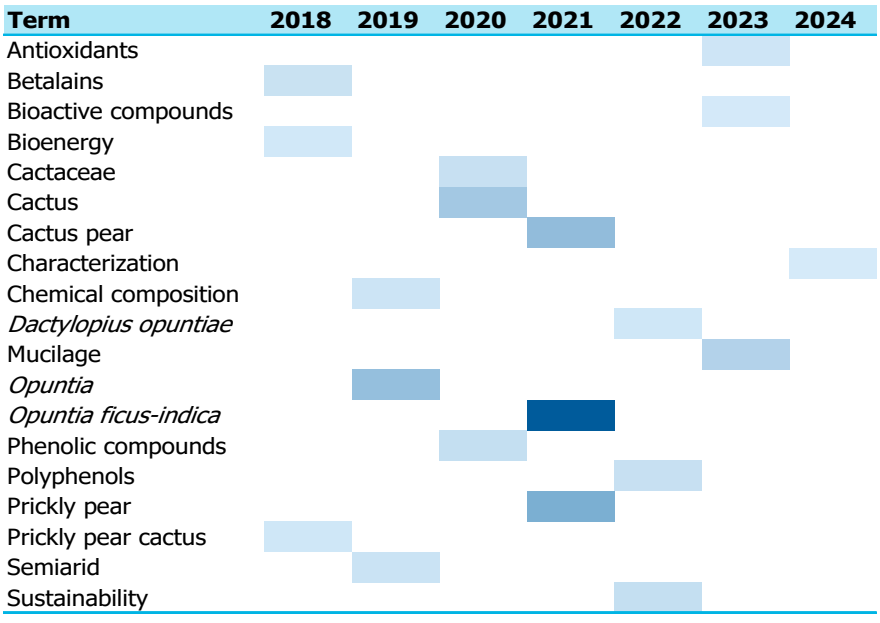

Figure 7. Temporal evolution of the main research terms in *Opuntia* spp. studies (2018–2024). Each row represents a keyword, and columns indicate the years of occurrence. The color intensity reflects frequency, with darker shades (blue) corresponding to higher values (over 100 occurrences) and lighter shades to lower values (as few as 6 occurrences). This visualization highlights shifts in thematic focus over time, showing the transition from foundational terms to more specialized topics in recent years.

A shift from foundational to more specialized research is evident over the years. In the early years of the period, terms like "betalains" and "prickly pear cactus" dominated,

reflecting an initial focus on characterization and general studies of the plant. Throughout the decade, core terms like "Opuntia ficus-indica", "prickly pear", and "cactus pear" remained consistently active, serving as the foundation for research development.

The most notable change occurred from 2021 to 2024. During this period, topics such as "bioactive compounds", "antioxidants", "mucilage", and especially "sustainability" gained prominence.

3.1.4. Analysis of the Most Cited Documents

The impact of a research field is often shaped by a set of key publications that become references for future studies. An examination of the most highly cited documents (Table 4) highlights the works that have had the greatest influence on the scientific community.

Table 4. Main Published Documents According to Citation Count.

Title	Reference	Source	Citations
Activated biochar derived from *Opuntia ficus-indica* for the efficient adsorption of malachite green dye, Cu + 2 and Ni + 2 from water.	Choudhary, M., 2020 [22]	Journal of Hazardous Materials	348
The role of invasive alien species in shaping local livelihoods and human well-being: A review.	Shackleton, R., 2019 [14]	Journal of Environmental Management	252
Production and Characterization of Cosmetic Nanoemulsions Containing *Opuntia ficus-indica* (L.) Mill Extract as Moisturizing Agent.	Ribeiro, R., 2015 [23]	Molecules	178
A Contemporary Review on Plant-Based Coagulants for Applications in Water Treatment.	Saleem, M., 2019 [24]	Journal of Industrial and Engineering Chemistry	143
Electrocoagulation-flocculation as a low-cost process for pollutants removal from urban wastewater.	Elazzouzi, M., 2017 [25]	Chemical Engineering Research and Design	117
Layer-by-layer Edible coatings based on mucilages, pullulan and chitosan and its effect on quality and preservation of fresh-cut pineapple (*Ananas comosus*)	Treviño-Garza, M., 2017 [26]	Postharvest Biology and Technology	111
Biomass characterization of Agave and Opuntia as potential biofuel feedstocks.	Yang, L., 2015 [27]	Biomass & Bioenergy	110
Quality enhancement of prickly pears (*Opuntia* sp.) juice through probiotic fermentation using *Lactobacillus fermentum*	Panda, S., 2017 [28]	LWT—Food Science and Technology	104
Green synthesis of surface-passivated carbon dots from the prickly pear cactus as a fluorescent probe for the dual detection of arsenic (III) and hypochlorite ions from drinking water.	Radhakrishnan, K., 2018 [29]	Royal Society of Chemistry Advances	97
Characterization of prickly pear short fiber and red onion peel biocarbon nanosheets toughened epoxy composites.	Ramaswamy, S., 2022 [30]	Polymer Composites	95

The most cited work is that of Choudhary M. et al. (2020), published in Journal of Hazardous Materials, with 348 citations [22]. This study addresses water pollution and demonstrates the synthesis of activated biochar from *Opuntia ficus-indica* cladodes, which effectively adsorb, remove organic dyes, and heavy metals from wastewater. This research is significant for offering a low-cost, biomass-based solution to a pressing environmental issue, positioning *Opuntia* spp. not just as an agricultural crop but as a critical raw material for bioremediation.

The second most cited work, by Shackleton R. et al. (2019) in Journal of Environmental Management, with 252 citations [14], discusses the role of invasive alien species in shaping local livelihoods. While not solely focused on Opuntia, the paper highlights the species as a key case study. It emphasizes *Opuntia ficus-indica's* dual nature: some varieties, like

Opuntia stricta, are problematic, while others, such as *Opuntia ficus-indica*, provide significant benefits as both food and forage, particularly in arid regions.

In third place is the study by Ribeiro R. et al. (2015), published in Molecules, with 178 citations [23]. This work explores the production of emulsions containing *Opuntia ficus-indica* extract as a moisturizing agent for skin. It is highly cited due to its contribution to linking the plant's chemical composition—rich in carbohydrates and polyphenols—to value-added applications in cosmetics, paving the way for the sustainable valorization of Opuntia biomass.

Other significant publications reinforce the versatility of *Opuntia* spp. Studies by Saleem M. (2019) [24] and Elazzouzi M. (2017) [25] explore its use in water treatment, offering a sustainable alternative to conventional chemicals. Yang L. et al. (2015) [27] highlight Opuntia's potential as a biofuel feedstock. Furthermore, Treviño-Garza M. et al. (2017) [26] demonstrate the use of its mucilage for edible coatings that extend the shelf life of fresh fruits, contributing to the reduction of food waste.

3.2. Empirical Evidence on Residue Valorization in Mexico

Global trends in *Opuntia* spp. research reveal a thematic transition from basic characterization toward sustainability-oriented approaches. In the Mexican context, however, residue valorization remains comparatively incipient despite its strategic potential for closing production cycles. Composting stands out as a promising avenue: it addresses seasonal waste streams, reduces reliance on mineral fertilizers associated with greenhouse gas emissions, and provides low-cost bio-inputs that can benefit small and medium producers in production centers such as Milpa Alta.

To ground these insights in practice, this study systematically examined the body of empirical evidence generated in Mexico. The objective was to determine what types of interventions have been tested, under which conditions, and with what agronomic and product-quality outcomes. This evidence-based assessment makes it possible to highlight feasible pathways and identify gaps for scaling residue valorization in real production systems.

3.2.1. Selection of Relevant Studies

A comprehensive literature screening identified 721 initial records across Scopus (n = 544), PubMed (n = 19), and Lens.org (n = 158). After removing 129 duplicates, 592 records were screened by title and abstract. Of these, 548 were excluded for not meeting the predefined inclusion criteria. The full texts of 44 articles were retrieved, although 5 could not be accessed. After full-text evaluation, 34 studies were excluded: 12 did not specifically address Opuntia cladodes residues, 18 did not involve compost preparation or application, and 3 were not original research articles. Ultimately, only 5 studies fulfilled all eligibility requirements and were included for detailed analysis (Figure 8).

This narrowing from hundreds of records to five eligible studies indicates a thin but actionable evidence base. For the purposes of this article, this compact corpus functions as a practical sample from which to infer (i) operational conditions that consistently yield agronomically useful products and (ii) design elements that merit standardization to enable replication and scale in Mexican Opuntia systems.

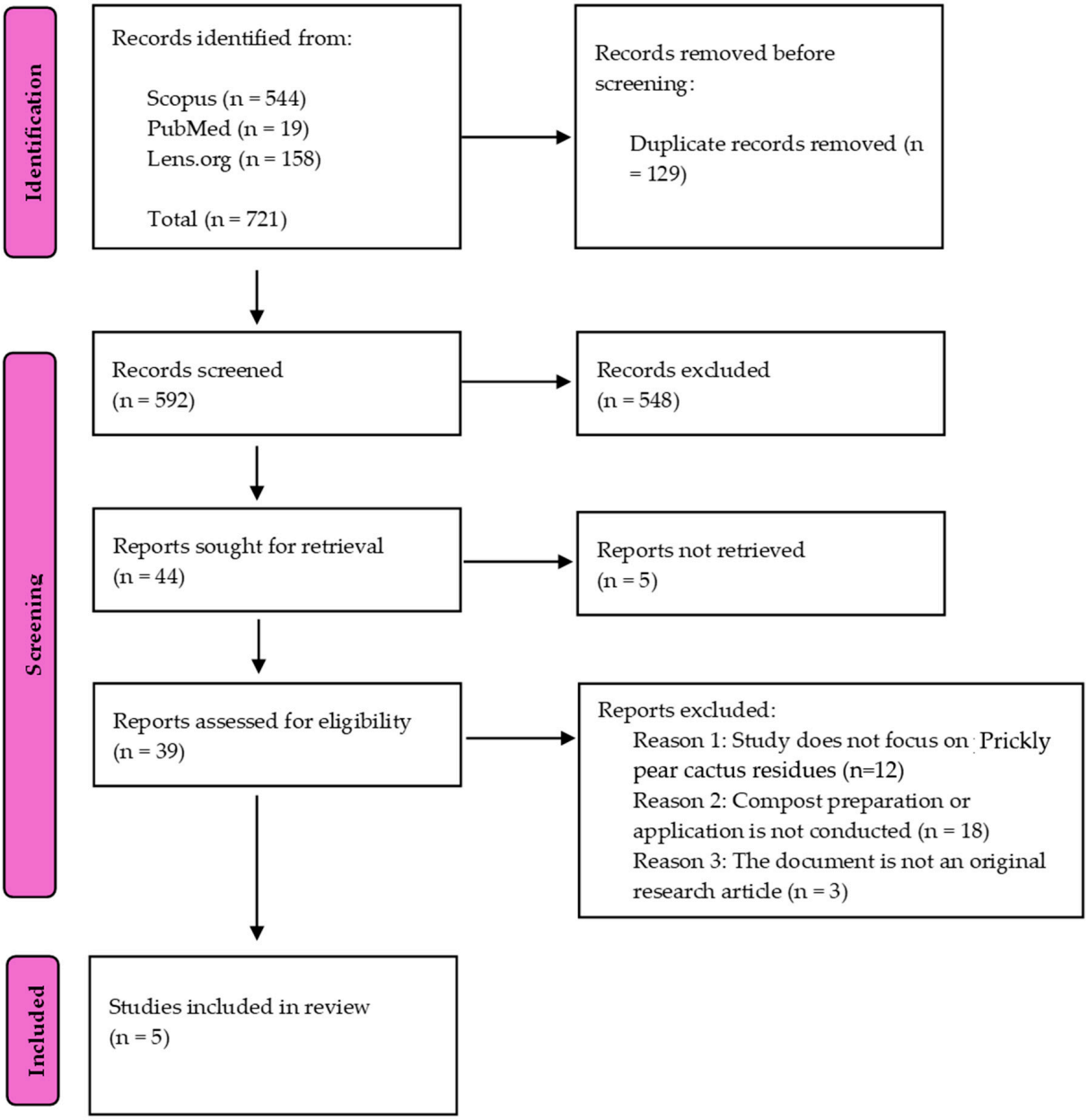

Figure 8. PRISMA Flow Diagram.

3.2.2. Characterization of the Mexican Studies

A total of five Mexican studies were analyzed, published between 2016 and 2025, covering a wide range of scopes and methodologies. Four were field trials with comparative experimental designs, while one presented a technical and economic assessment aimed at standardizing composting practices. Their objectives ranged from evaluating and optimizing composting processes to testing the agronomic performance of biofertilizers and assessing crop-level outcomes (Table 5). This diversity illustrates both the versatility of cladodes residues and the lack of a consolidated research agenda integrating agronomic, technical, and economic dimensions.

Table 5. Extracted Information Matrix.

Author and Year	Objective	Study Design	Intervention (Residues, Method, and Duration)	Application and Comparison	Quantitative Results and Observations	Key Conclusions
Escamilla-García et al. (2025) [31]	Standardize the composting process of cladodes residues for agricultural use.	Technical and economic analysis.	Windrow composting with manual turning using cladodes residues, cow manure, and grass for 120 days.	Not applicable. The study focused on compost production.	Final compost with a C:N ratio of 26.5 and 32.9% organic matter.	The standardized process is a technically and economically viable solution for the valorization of cladodes.
Cruz-Méndez et al. (2021) [32]	Evaluate cladodes residues and biochar-based biofertilizer to improve alkaline soils.	Greenhouse experiment with randomized block design.	Anaerobic fermentation of cladodes residues and rabbit manure for 50 days to produce a biofertilizer.	Applied to tomatillo crops, compared with chemical fertilization and a control.	Improved water retention capacity and available phosphorus in the soil.	The Opuntia biofertilizer is a suitable amendment for improving low-buffering-capacity soils.
Rodas-Gaitán et al. (2019) [33]	Evaluate the effect of biodynamic preparations (BD) in the composting of cladodes and moringa.	Field experiment with a 2 × 2 factorial design.	Static pile composting with passive aeration using cladodes/moringa and manure for 1 year.	Not applicable. Focused on the composting process and product stability.	Final compost C:N ratio ranged from 12–14.	Using cladodes residues as a substrate produces high-quality compost.
González-Torres et al. (2024) [34]	Investigate the effect of raw cladodes and goat manure on soil and crops.	Field experiment with randomized block design.	Direct application to the soil of raw cladodes residues and goat manure. Duration: N/A.	Applied to tomato and carrot crops, compared with control and residue combinations.	Increased carrot yields up to 3.3 times and tomato yields up to 3.9 kg/plant.	Adding Opuntia components to the soil is a viable alternative that enhances horticultural crop production.
Alvarado-Raya et al. (2016) [35]	Compare compost, fresh manure, and synthetic fertilizer in Opuntia cultivation.	Comparative field trial.	Composting on concrete beds with manual turning using manure, cladodes residues, and garden waste for 3 months.	Applied to Opuntia crop, compared with fresh manure and synthetic fertilizer.	No significant differences in yield among treatments. Compost influenced the firmness and shelf life of the cladodes. Final compost had a C:N ratio of 25.5.	Manure compost is an adequate substitute in vegetable Opuntia fertilization without negatively affecting yield.

Collectively, these designs cover the spectrum from process standardization to field performance, offering enough variation to distill operational levers (C/N balancing, aeration regimes, and co-substrate choices) with direct relevance for producers.

Table 6 summarizes the key physicochemical properties of the different residue valorization products identified in the Mexican case studies. It highlights how compost and biofertilizers vary according to the process used. This comparative overview provides a baseline to evaluate the agronomic potential and quality standards of products derived from cladodes residues.

Table 6. Physicochemical Characteristics of Valorization Products.

Product	C/N Ratio	pH	Moisture	Organic Matter	Electrical Conductivity (EC)	Main Nutrients
Aerobic Composting with Manual Turning	25.5:1	7.8–9.0 (slightly alkaline)	N/A	High (exact% not provided)	N/A	Assumed N, P, K, Ca, Mg from cattle manure [35,36]
Standardized Compost (120 days)	26.5:1	8.6	40%	32.9%	2.89 mS/cm	N: 1120 mg/L, P: 355 mg/L, K: 990 mg/L, Ca: 335 mg/L, Mg: 187 mg/L, Zn: 8.6 mg/L, Fe: 15.1 mg/L [31,37–40]
Biodynamic Static Compost (1 year)	12:1–14:1	7.8–9.0 (alkaline)	N/A	Higher in prickly pear (exact% not reported)	N/A	Increased P, Ca, Mg, Fe, Zn, Mn (exact values not provided) [33,40,41]
Liquid Biofertilizer (Anaerobic Fermentation)	N/A	5.9 (acidic)	N/A	1.8% (total organic carbon)	3.83 mS/cm	K: 5568 mg/L, N: 1120 mg/L, P: 355 mg/L, Fe: 15.1 mg/L, Ca, Mg, Zn [32,37,39]

This data reveals important contrasts between valorization strategies and their resulting products. Aerobic composting, even under non standardized manual turning,

generates alkaline materials with moderate to high organic matter and balanced macronutrients. Long-duration biodynamic composting produces more mature material (lower C/N ratios between 12:1 and 14:1) and enriched mineral profiles, supporting its potential for improving soil fertility and structure. In contrast, anaerobic fermentation yields liquid biofertilizers with acidic pH and high electrical conductivity, indicating concentrated nutrients readily available to plants, particularly potassium and nitrogen.

Importantly, several of the reported values meet or approach Mexican compost quality standards (NMX-AA-180-SCFI-2018; NADF-020-AMBT-2011), supporting their use for sustainable smallholder systems [37,38]. However, gaps remain in the systematic reporting of some parameters which limit direct comparability and standardization.

4. Discussion

4.1. Global Landscape and Regional Gaps

The global analysis of *Opuntia* spp. research between 2014 and 2024 shows a rapidly expanding and thematically diversified field. Publication output has grown at an annual rate of 16.8%, and collaboration networks reveal active hubs in Africa, the Mediterranean, and Latin America. Yet this expansion is not evenly distributed. Distinct regional agendas have emerged: African groups focus on drought resilience and nutritional use of cladodes; European and Mediterranean teams, particularly in Italy, emphasize high-value bioactive compounds and industrial applications; while Latin American efforts, including Brazil and Mexico, remain strongly agronomic and production-oriented.

The temporal evolution of keywords indicates a clear global shift after 2020: earlier work focused on descriptive aspects—pigments, mucilage, basic agronomy—whereas recent research increasingly emphasizes sustainability, circular economy, and bioactive compounds. This transition reflects a maturing field seeking to move beyond simple characterization toward integrated systems that convert residues into high-value products and sustainable inputs [15–18].

In contrast, Mexican research has remained largely focused on compost, organic amendments, soil improvement, and fertilization. This emphasis reveals a strong orientation toward technical feasibility and localized agronomic performance but shows limited engagement with the nutraceutical, bio industrial, policy, and sustainability-driven perspectives that shape the global conversation. As a result, the relatively weak presence of Mexican studies within clusters linked to industrial applications represents a missed opportunity to move *Opuntia* spp. research beyond farm-level soil enhancement toward higher-value innovation pathways [14].

This gap is particularly striking given Mexico's historical and biological leadership as the center of Opuntia domestication. Although bibliometric results confirm that Mexico leads in the total number of publications, they also reveal a lag in diversification and thematic integration. Collaboration networks further highlight this imbalance: Mexican authors are strongly connected within Latin America and North America but maintain limited links with Mediterranean and African research groups where advances in circular economy practices and value-added products are progressing most dynamically.

4.2. Valorization Processes of Cladodes Residues

The analysis of the five studies revealed three distinct strategies for the valorization of cladodes residues: aerobic composting, anaerobic fermentation, and direct soil application.

The most common strategy was aerobic composting, tested in three studies, though with different system designs and operational scales. Alvarado-Raya et al. [35] and Escamilla-García et al. (2025) [31] applied windrow systems with manual turning but varied in design, duration, and complementary materials. For instance, Alvarado-Raya et al. [35]

combined cattle manure, pruned cladodes, and garden waste, producing compost with a C:N ratio of 25.5 after three months, while Escamilla-García et al. (2025) [31] incorporated regional grasses and extended the process to 120 days, obtaining a mature product and a nutrient-rich leachate proposed as a liquid fertilizer. By contrast, Rodas-Gaitán et al. (2019) [33] implemented static piles with passive aeration and biodynamic preparations, achieving greater mineralization and microbial activity after a one-year process. This methodological variety underscores both the adaptability of Opuntia as a composting substrate and the trade-offs between labor intensity, process duration, and final product quality.

Anaerobic fermentation was tested by Cruz-Méndez et al. (2021) [32], who developed a liquid biofertilizer from cladodes and rabbit manure. Conducted in batch reactors for 50 days, this process yielded improvements in water retention and phosphorus availability when applied to tomatillo crops, offering a complementary pathway for soils with low buffering capacity.

Finally, González-Torres et al. (2024) [34] explored the direct incorporation of raw cladodes into the soil, combined with goat manure. Results showed significant yield increases—up to 3.3 times for carrot and 3.9 kg per tomato plant—demonstrating that even minimally processed residues can improve soil fertility and crop productivity.

Taken together, the three strategies [31–35] delineate a practical menu of options with distinct cost–labor profiles. Aerobic windrows are accessible and adaptable but labor-intensive; passive static piles reduce labor at the expense of longer maturation; and anaerobic fermentation generates complementary liquid inputs suited to alkaline soils. Direct soil incorporation, while the least processed, can deliver yield gains when integrated with manures. Across strategies, three operational levers consistently emerge: (i) targeting balanced C/N ratios through locally available co-substrates; (ii) choosing aeration regimes aligned with labor and time constraints; and (iii) valorizing process by-products (e.g., leachates) to improve overall nutrient circularity [31–35].

4.3. Quality and Properties of the Products

The physicochemical properties reported in the analyzed Mexican studies reveal considerable variation depending on processing method, treatment duration, and the composition of the mixtures. These parameters are critical because they determine both the stability of the product and its suitability for agricultural use. Using Mexican regulatory standards such as NMX-AA-180-SCFI-2018 and NADF-020-AMBT-2011 provides a useful benchmark for assessing the compliance and potential applicability of these bio-inputs in local production systems [37,38]. Interpreting product quality against NMX-AA-180-SCFI-2018 and NADF-020-AMBT-2011 offers not only a compliance lens but also a decision framework for producers—e.g., maturity indicators (C/N) to time field application, pH/EC thresholds to manage salinity risks, and nutrient panels to align product use with specific crop stages [37,38].

In the study by Alvarado-Raya et al. (2016) [35], compost produced through three months of windrow composting with weekly turning reached a C/N ratio of 25.5:1. This value slightly exceeds the maximum threshold of 20:1 established by NADF-020-AMBT-2011, suggesting that additional maturation may be necessary before direct application to crops such as Opuntia [37,38] The pH was slightly alkaline (7.8–9.0), a property that can be beneficial in correcting acidic soils but requires caution when applied to already alkaline soils [37]. The compost was also characterized by its high organic matter content, derived from a mixture of fresh manure, cladodes residues, and grasses, which contributes to soil health by enhancing water retention and gradual nutrient release [37]. Although macronutrients and micronutrients were not directly quantified, the presence of nitrogen

(N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) from cattle manure is assumed.

Escamilla-García et al. (2025) obtained standardized compost after 120 days, with a C/N ratio of 26.5:1 and 32.9% organic matter [31]. Despite the C/N ratio being marginally above recommended limits, the compost displayed favorable stability and nutrient richness [37,38,41]. The measured pH (8.6) and electrical conductivity (2.89 mS/cm) suggested a low risk of salinization. Importantly, the process also generated a nutrient-rich leachate, with high concentrations of nitrogen, phosphorus, and potassium, which was proposed as a liquid biofertilizer. This dual output (solid compost and liquid leachate) demonstrates a circular approach that enhances the value of cladodes residues for integrated nutrient management [31,37–40].

In contrast, Rodas-Gaitán et al. (2019) reported highly stable compost from static piles with passive aeration over one year [33]. The final product exhibited a C/N ratio between 12:1 and 14:1, indicating advanced mineralization and compost maturity, which is ideal for use in perennial crops like Opuntia [36,37,41]. The pH was alkaline (estimated between 7.8 and 9.0), and the nutrient profile showed increased concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), and manganese (Mn), though nitrogen (N), potassium (K), and copper (Cu) showed slight decreases. This compost is highly stable and suitable for direct application in crops like Opuntia, though further quantitative data on organic matter and electrical conductivity (EC) would be useful for complete regulatory compliance [40,41].

The anaerobic fermentation process studied by Cruz-Méndez et al. (2021) generated a liquid biofertilizer with distinct properties [32]. With a slightly acidic pH (5.9), this product could be useful in correcting alkaline soils or improving phosphorus solubility [36,41]. Its electrical conductivity (3.83 mS/cm) fell within acceptable ranges, and the total organic carbon content was reported at 1.8%. The biofertilizer was particularly rich in potassium (5568 mg/L), alongside nitrogen, phosphorus, and iron, making it a promising input for foliar applications during critical growth stages such as flowering and fruiting [32,38,40,41].

In practical terms, two quality-by-design implications follow from the Mexican cases: (i) when C/N remains >20 at curing, either extend maturation or apply to non-sensitive crops/soils to avoid transient N immobilization; and (ii) leverage liquid fractions (leachates/biofertilizers) in phenological windows where K and readily available N/P are most effective (e.g., flowering, fruit set), particularly in alkaline soils where mildly acidic inputs aid P availability.

Taking together, these findings demonstrate that cladodes residues can be transformed into high-quality composts and biofertilizers that meet or approach regulatory standards [31–35,37,38]. The key properties—C/N ratio, pH, organic matter, and nutrient content—not only validate their technical feasibility but also highlight their potential to reduce dependence on synthetic fertilizers, improve soil health, and increase crop productivity [31–35,37,38]. These results are particularly relevant for smallholder farmers in Mexico, who often face limited access to external inputs. By valorizing locally available residues, these practices foster economic self-sufficiency and align with circular economy principles, turning waste management challenges into opportunities for sustainable agricultural development.

4.4. Why Mexican Research Lags Behind

The gap between Mexico's potential leadership [6] and its current focus on small-scale feasibility studies stems from interconnected structural and institutional barriers.

Funding limitations remain a primary constraint. Most agri-environmental research in Mexico is financed through short-term, project-based schemes. These are adequate for ex-

ploratory composting experiments—such as the five Mexican studies analyzed [31–35]—which typically assessed process parameters and immediate soil or yield effects but seldom support multi-year field validation or the development of scalable, standardized protocols. In contrast, countries like Italy and South Africa maintain long-term research programs that integrate agronomy, chemistry, and industrial valorization, allowing the generation of robust and replicable results [1,16].

Weak policy incentives further limit adoption and technological refinement. Although national strategies mention sustainable agriculture and organic production, there is no dedicated policy framework to promote residue-based bio-inputs for Opuntia [34]. Economic incentives, certification schemes, or subsidies that would make compost and biofertilizer production competitive against synthetic fertilizers are lacking. This absence of support discourages farmers and private actors from investing in valorization technologies beyond the experimental stage.

Technology transfer gaps also contribute to the lag. The reviewed Mexican studies yielded technically promising results, yet these outputs largely remain within academic settings [31–35]. Extension services and farmer training networks are underdeveloped, leading to limited dissemination and adoption of protocols that could otherwise be cost-effective and locally adapted.

Finally, fragmented research agendas hinder the creation of synergies. Much of the existing work is driven by isolated initiatives rather than coordinated, multi-institutional programs. In the absence of national or regional strategies that link agronomic research, policy frameworks, and producer networks, innovations remain scattered and difficult to scale.

Addressing these systemic barriers would help align Mexican research with global momentum toward circular economy and sustainable value chains. Coordinated funding schemes, policy-driven incentives for compost and biofertilizer use, and stronger researcher–farmer interactions could accelerate technology adoption, reduce the environmental footprint of *Opuntia* spp. production, and enhance the resilience of smallholder systems.

5. Conclusions

This study offers an integrated perspective on international *Opuntia* spp. research and the emerging practices of residue valorization in Mexico. The findings reveal a rapidly expanding and diversified international research field increasingly focused on sustainability, bioactive compounds, and circular economy strategies. By contrast, Mexican research remains concentrated on small-scale agronomic feasibility studies and shows limited integration into global innovation networks.

Bridging this gap will require long-term funding, stronger policy incentives, and improved technology transfer mechanisms to scale up low-cost residue-based bio-inputs. Expanding research efforts beyond localized feasibility studies toward standardized protocols and diversified applications could position Mexico as a leader in sustainable *Opuntia* spp. value chains.

This work has certain limitations, including the small number of empirical studies available for analysis and the absence of long-term field validations, which limit the generalizability of current findings.

Future research should focus on developing and testing scalable models for the valorization of cladodes residues, as well as stepwise approaches to ensure adoption. Interdisciplinary studies are also needed to address socio-economic barriers, identify enabling incentives, and inform policies that foster circular economy practices and cross-regional knowledge exchange.

Overall, residue valorization emerges as a practical and socially acceptable strategy to reduce waste, improve soil health, and increase the resilience and profitability of smallholder systems. Strengthening the linkages between research, policy, and producer networks is essential to fully realize the sustainability potential of Opuntia cultivation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15102311/s1, Table S1, dataset of the global research analysis (789 records); and Table S2, dataset of the empirical evidence screening (721 records).

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