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Global research landscape of cactus pear (*Opuntia ficus-indica*) in agricultural science

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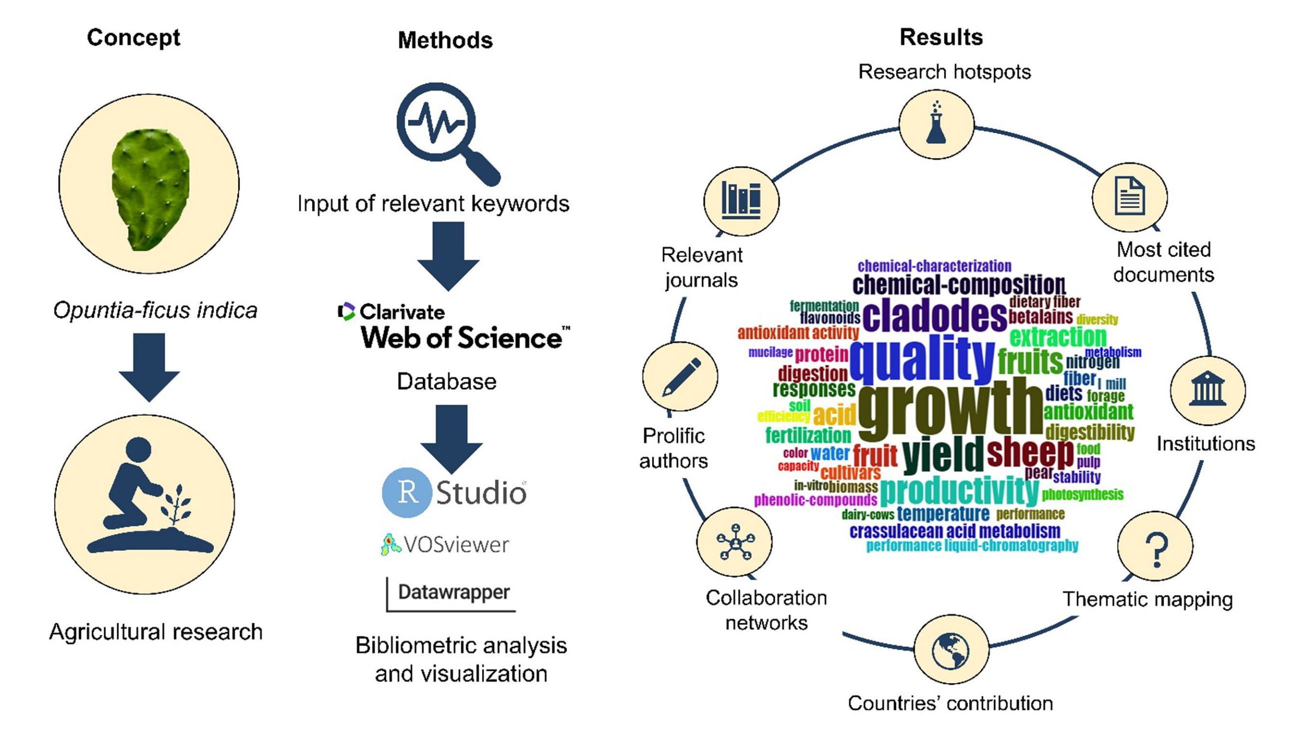
The cultivation of unconventional or underutilized crops, such as *Opuntia ficus-indica* (OFI), under a climate change scenario is an important subject and has been increasingly studied in agricultural research. Therefore, a scientometric study was conducted to identify research focal points, assess the milestones that have been attained (1990–2023), determine the extent of progress made, and outline possible directions in this field. Using the Web of Science database, the study identified 2,372 OFI documents that were refined into 518 research articles in English related to agriculture. The increase in publications showed a more pronounced acceleration after 2000. On average, each OFI research document had five co-authors, with 17.6% involving international collaboration among 1,835 authors. The analysis revealed that the OFI has gained prominence as an agronomic resource in regions characterized by a severe drought, which has prompted a surge in physiological investigations focused on cladodes aimed at comprehending its crassulacean acid metabolism capability, which contributes to reduced transpiration and higher water use efficiency than other conventional crops. Furthermore, there has been an increase in research on animal health and nutrition, pest and disease control, and climate-smart OFI characteristics. We would emphasize the importance of research on standardization of agronomic practices based on local climate, the role of OFI in climate change, biofuel, taxonomy, stress tolerance, cultivar selection, wildlife interference, animal health/nutrition, economic studies, soil quality, and pest control. By addressing the identified research gaps and pursuing the suggested paths, the rope can be strengthened in sustainable agriculture, food security, and environmental management.

KEYWORDS

Opuntia, climate change, multipurpose crop, productivity, VOSviewer



GRAPHICAL ABSTRACT

1 Introduction

The human population is rapidly expanding and is expected to exceed 9 billion by 2050 (UN, 2023). This increase, coupled with climate change, significantly impacts agricultural productivity, ecological services, and global food security. As a result, some countries are working on developing what are currently considered unconventional crops that can withstand climate-change-induced disasters and help preserve agricultural productivity. One example is *Opuntia ficus-indica* (OFI), commonly known as prickly pear, spineless cactus, fodder cactus, the Indian fig opuntia, green gold, and fig opuntia (Bakewell-Stone, 2023). OFI could be an important crop in agriculture for several reasons (Figure 1).

1.1 Diverse nutritional needs

OFI can supplement regular meals with essential nutrients, vitamins, and minerals, which are typically deficient (Hernández-Becerra et al., 2022). This diversification could help combat malnutrition and promote public health. OFI is valued for its rich nutritional profile, including dietary fiber, vitamins, and bioactive compounds that offer anti-inflammatory, hypoglycemic, and antimicrobial benefits (Silva et al., 2021). Both its fruit and cladodes are versatile ingredients used in various foods like flour, snacks, and juices, containing essential phytochemicals such as polyphenols and vitamins, suitable for commercial applications. The antioxidant potency is enhanced by compounds like ferulic acid, flavonoids, and betalain pigments, contributing to its health-promoting properties, while fermented OFI products have shown potential in regulating cytokine secretion (Barba et al., 2022).

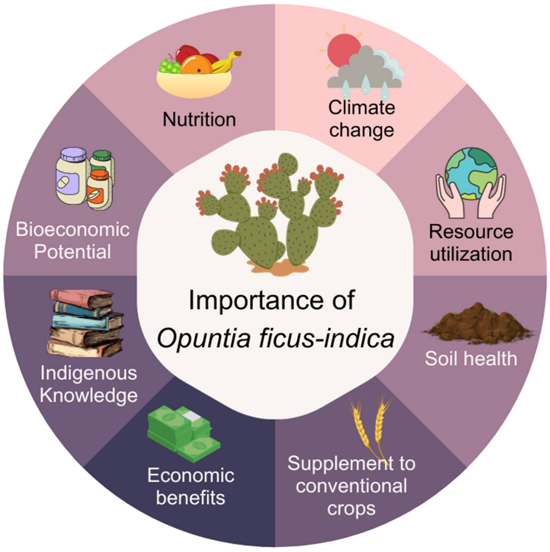


FIGURE 1
Importance of *Opuntia ficus-indica* in agriculture.

1.2 Climate resilience

Unlike traditional crops, OFI has demonstrated greater resilience to climatic conditions, such as arid and semi-arid soils (Konings, 2010), and may contribute to agricultural stability in the face of climate change. Its ability to thrive in arid conditions and poor soils makes it ideal for combating desertification and soil erosion (Jorge et al., 2023). Additionally, its versatility extends to its use as livestock fodder, which helps reduce water consumption and environmental impact in animal husbandry (Jorge et al., 2023). The nutritional and therapeutic properties of OFI, including its antioxidant and anti-diabetic effects, further enhance its value as a food source under a climate changing scenario (Prisa, 2021). Consequently, its cultivation has expanded globally, particularly in subtropical and Mediterranean regions (Prisa, 2021). This expansion highlights its potential to addressing both environmental and nutritional challenges in various climates.

1.3 Resource efficiency

Compared to OFI, conventional crops consume large amounts of water, fertilizer, and pesticides. Because of its adaptability to local conditions, OFI requires fewer resources (Alane et al., 2022), contributing to more sustainable farming practices. For example, OFI exhibits high transpiration-use efficiency, with values ranging from 2 to 6 times higher than traditional cereals (Kremer et al., 2021). Its water-use efficiency is particularly high, producing 7.87 kg of dry mass per hectare per millimeter of water used after 4 years of establishment (Snyman, 2013). OFI requires only 330 millimeter of water to yield 16,210 kg of dry matter per hectare (Consoli et al., 2013). Moreover, OFI demonstrates significant efficiency in water treatment applications. Both raw and dried forms of the plant can effectively remove turbidity, achieving removal rates of 76–91% and 54–87%, respectively (González Bermúdez et al., 2020). The symbiosis with arbuscular mycorrhizal fungi (AMF) further enhances OFI's drought tolerance by improving biomass production, photosynthesis, and WUE under water stress conditions (Kebede et al., 2023).

1.4 Soil health and biodiversity

Long-term monoculture of conventional crops can deteriorate soil quality, which can be improved by introducing OFI (Hassan et al., 2019), minimizing the need for chemical fertilizers, and improving ecosystem balance. Studies in Algeria and Morocco have demonstrated that OFI plantations significantly enhance soil organic matter, water content, and vegetation cover (Neffar et al., 2011; Yous et al., 2023). The age of the plantations is a critical factor, with older plantations showing greater improvements in soil properties and plant diversity (Neffar et al., 2011; Yous et al., 2023). OFI facilitates the colonization and development of herbaceous species by ameliorating harsh environmental conditions (Neffar et al., 2011). In northern Ethiopia, soil physical, chemical, and biological properties are considerably improved under OFI canopies compared to adjacent open areas, with increased soil organic carbon, nitrogen, phosphorus, moisture, and microbial content (Bariagabre et al., 2016).

1.5 Reduced pressure on conventional crops

Cultivating unconventional crops, such as OFI, can help relieve pressure on traditional staple crops. This diversification decreases the risk of crop failures and supply chain disruptions caused by pests, diseases, or severe weather events. Cactus pear is exceptionally well-suited to arid and semi-arid regions, where conventional crops often struggle to thrive. Its ability to grow in harsh conditions with minimal water makes it an ideal candidate for areas affected by water scarcity and climate change. By integrating cactus pear into farming systems, farmers can effectively utilize marginal lands that are unsuitable for traditional crops, thereby expanding agricultural productivity (Meena et al., 2022). Introducing cactus pear into agricultural systems allows farmers to diversify their crop portfolios. This diversification leads to a more resilient food supply, reducing the risks associated with dependency on a few staple crops. Cactus pear provides a nutritious fruit rich in vitamins and minerals, significantly contributing to food security and dietary diversity (Elouafi et al., 2020). Moreover, cactus pear pads can serve as a valuable source of fodder for livestock, particularly in dry regions where other forage crops are scarce. This reduces the dependency on traditional fodder crops, alleviating the pressure on agricultural systems to produce both feed and food crops simultaneously (Dubeux et al., 2022).

1.6 Economic opportunities

Cultivating unconventional crops, such as OFI, can provide new economic prospects for farmers and local communities. Andreu-Coll et al. (2020) explored the economic opportunities of OFI cultivation in Spain, revealing significant differences in production structures and costs among Spain, Mexico, and Italy. The production costs per hectare are markedly different, with Spain at €9453.77, Italy at €4055.10, and Mexico at €939.77. In Mexico, the OFI supported approximately 20,000 families (Gallegos-Vázquez et al., 2013; Timpanaro et al., 2015). The total cultivated area in Mexico spans 50,000–70,000 hectares, with an annual production of 300,000–500,000 tonnes, making OFI the fifth most important fruit crop in the country. In South Africa's Eastern Cape Province, Shackleton et al. (2011) demonstrated that OFI significantly contributes to household incomes in the Makana Municipality. These crops may have niche markets (if properly developed), high-value products, or distinguishing features (Mouas et al., 2021) that may contribute to higher income and rural development.

1.7 Preserving indigenous knowledge

Unconventional crops are culturally and historically significant in specific locations (Sinicropi et al., 2022). Indigenous knowledge and traditional farming practices can be preserved and appreciated by fostering OFI cultivation (Paz-Navarro et al., 2023). Different parts of the plant, including the cladodes, fruits, and flowers, have been utilized for their medicinal properties. Some traditional uses of OFI include treating wounds, stomach ailments, inflammation, and as a diuretic.

1.8 Bioeconomic potential

OFI is a beneficial source of bioactive chemicals, medicinal components, and industrial materials (Ramadan, 2021). Therefore, OFI offers various health benefits such as anti-inflammatory, hypoglycemic, antimicrobial, and antioxidant effects (Martins et al., 2023). These properties make it suitable for applications in the food, pharmaceutical, and cosmetic industries (Silva et al., 2021). Additionally, cactus leather, made from the prickly pear cactus, is gaining popularity as an eco-friendly and sustainable alternative to traditional leather (Black, 2023). Therefore, OFI can be an important contributor to the bioeconomy and support environmentally friendly industries.

Given these potential benefits, scientometric studies can be used to map the research landscape, identify research trends and gaps, assess impacts, promote research institutions, inform policymakers, guide collaboration, redefine terminologies, evaluate scientific progress, and validate research impacts. However, few authors have undertaken scientometric studies focusing on cacti. Guedes et al. (2023) published an OFI scientometric map of pharmacology, toxicology, and pharmaceutics and discussed the qualitative nutritional composition and bioactive components of OFI. Bravo-Vinaja and Méndez-Gallegos (2016) investigated cactus pear production and research trends in prominent journals. Their study included all species of Opuntia and covered a wide range of research areas. However, the study provided few results, and the discussions have been presented in a short manner. Through a scientometric analysis, De Andrade Vieira and Tribuzy De Magalhães Cordeiro (2023) studied the sources, composition, extraction techniques, and applications of cactus mucilage (generally used in baking, powdered products, and edible films). Chen et al. (2021) highlighted the research progress of *Opuntia milpa alta* in China. Zheng et al. (2023) conducted a scientometric study to understand the research on cactus polysaccharides, which could help in creating novel medications, nutraceutical products, and functional food items.

Although the use of OFI in agriculture has historical roots, research within the agricultural context is on the rise. Consequently, there is a growing need for a comprehensive scientometric study to gain insights into the evolving research landscape concerning OFI. The central goal of this study is to pinpoint research focal points, assess the milestones that have been attained, determine the extent of progress made, and outline possible directions in this field. Our study explores key sources, most prolific authors, affiliations, contributing countries, relevant documents, research hotspots, collaboration, and thematic mapping analysis to provide a comprehensive understanding of the research landscape.

2 Methodologies

2.1 Collection of databases

Adhering to the recommendations provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), our methodology adhered to a systematic process (Figure 2). Initially, we accessed the core collection of the Web of Science database and conducted a thorough search using the keywords "*Opuntia ficus-indica*" and "*Opuntia ficus indica*" on August 31, 2023.

2.2 Screening

Subsequently, we applied filters to narrow the search results by focusing on papers related to agriculture, after removing duplicates and retracted papers. Further refinement included restricting the results to only the research articles. Papers written in English were selected. The resulting refined collection of papers was exported as a plain-text file. Subsequently, we conducted a comprehensive scientometric study using RStudio in the *bibliometrix* package (Aria and Cuccurullo, 2017).

2.3 Data analysis

Using a scientometric analysis conducted within RStudio, we systematically examined the following:

The primary information encompassing dataset characteristics;

i annual scientific production; average number of citations per annum;
ii identification of the most influential sources;
iii a longitudinal assessment of sources' production;
iv the identification of preeminent authors;
v a similar assessment of author affiliations and their production trends; an evaluation of countries' scientific output;
vi recognition of the most frequently cited nations;
vii identification of the most globally cited documents;
viii the delineation of research hotspots based on keywords appearing more than five times within the database;
ix a comprehensive exploration of trending topics;
x the construction of thematic maps to highlight research clusters; and
xi an assessment of collaborative patterns among researchers in the field.

Two laws of scientometrics, Bradford's law and Lotka's law, were applied to provide insights into sources and author impact, respectively. According to Bradford's law, finding the core articles addressing a specific topic will help us understand the total literature collection (Heine, 1998). The journals were arranged in decreasing order of their productivity (articles) on OFI (agriculture) and grouped into three zones. Lotka's law describes the frequency of articles published with respect to the number of contributors to a specific topic (Lotka, 1926).

2.4 Thematic mapping analysis

Based on Callon's centrality and density rank, co-occurrence network clusters were presented as bubbles within a graph in the thematic mapping (Callon et al., 1991). The frequency of word occurrence within a cluster is shown as the size of the bubbles. The x-axis of the graph displays network cluster centrality, which measures the extent to which one cluster interacts with other clusters within the graph and denotes the importance of a specific study theme. On the other hand, the y-axis shows density, which is a measure of the internal cohesiveness and expansion of a cluster network (Cobo et al., 2011). We identified several categories by visually charting these themes: (i) motor themes, situated in the first quadrant at the top right, with high centrality and density, indicating their well-developed nature and crucial role in structuring the research subject; (ii) niche themes, positioned in the second quadrant at the top left, with high density but low centrality, indicating their limited relevance; and (iii)

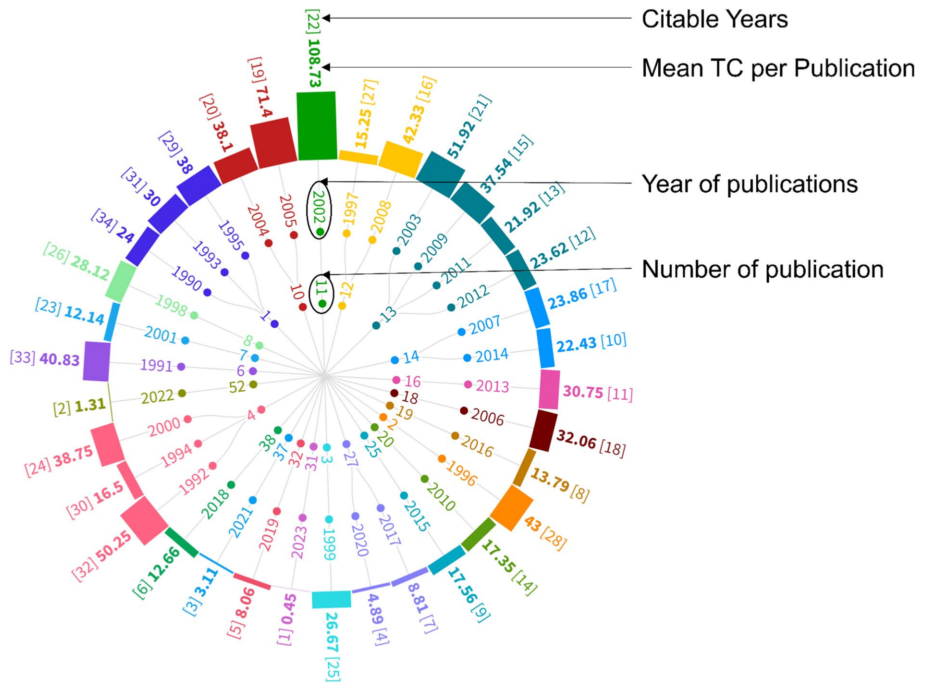


FIGURE 2
Flowchart of scientometric analysis in global *Opuntia ficus-indica* (**OFI) research within the agricultural domain. The data were collected from the core collection of Web of Science Database (*WoS) and further refined for scientometric analysis and visualization.

emerging or declining themes, placed in the bottom quadrant. In this representation, the trajectory of the themes is discerned by dividing time into segments. A line that gradually moves to the upper right denotes a growing trend for a particular theme, whereas a path that gradually moves to the lower left denotes a declining trend. These analytical techniques offer insightful information about the dynamics and development of OFI research within the agricultural domain.

2.5 Data visualization

In addition, we employed tools such as VOSviewer (Van Eck and Waltman, 2017) and Datawrapper (Lorenz et al., 2012) to create visualizations aimed at comprehending relationships and progress within the dataset. Following this systematic approach, we aimed to extract insights.

3 Results and discussion

3.1 Overview

After inputting the designated keywords into the Web of Science advanced search bar, a substantial corpus of 2,372 results was retrieved. A multi-step screening process was undertaken to ensure data integrity and relevance. Initially, two duplicate papers and one retracted article were identified and excluded from the dataset. Furthermore, 1,763 papers were excluded, as they were deemed to fall outside the predefined research domain of agriculture. This rigorous filtering process effectively refined the dataset to a more focused collection of 605 papers, which was reduced to a final count of 518 by retaining only the research articles authored in English. The selected papers spanned a timeframe from 1990 to 2023 and came from a diverse set of 109 distinct sources.

Agriculture-related OFI research has a long history. For instance, Garcia de Cortázar and Nobel (1990, 1991) made several efforts to determine global environmental productivity indices and OFI yields under conditions of elevated carbon dioxide and different plant spacings during the 1990s. Additionally, research on prickly pear (fruit) cultivation has led to various studies aimed at standardizing agronomic practices (Nerd et al., 1991). We identified several of the oldest significant studies in our database. Garcia de Cortázar and Nobel (1990) predicted that the minimal OFI green fodder output (without irrigation) would be 10 metric tonnes ha^{-1} year^{-1}. The prediction emphasized the OFI's excellent water use efficiency and potential to support future food security under several climate change scenarios. Garcia de Cortázar and Nobel (1991) demonstrated that the dry matter yield of OFI indica could attain 50 megagrams ha^{-1} year^{-1}, a level of productivity on par with other conventional high-biomass crops like sugarcane. Nerd et al. (1991) examined the impact of fertilization and drought on prickly pear productivity. Their study outlined several research avenues, including investigating the long-term implications of fertigation and drought on prickly pear yield, optimizing the timing and duration of fertigation to enhance fruit quality, and conducting trials with various cultivars to identify the most suitable ones.

3.2 Annual scientific production rate

Over the entire study period, the analysis of annual publication growth rates indicated a steady, albeit moderate, increase in research

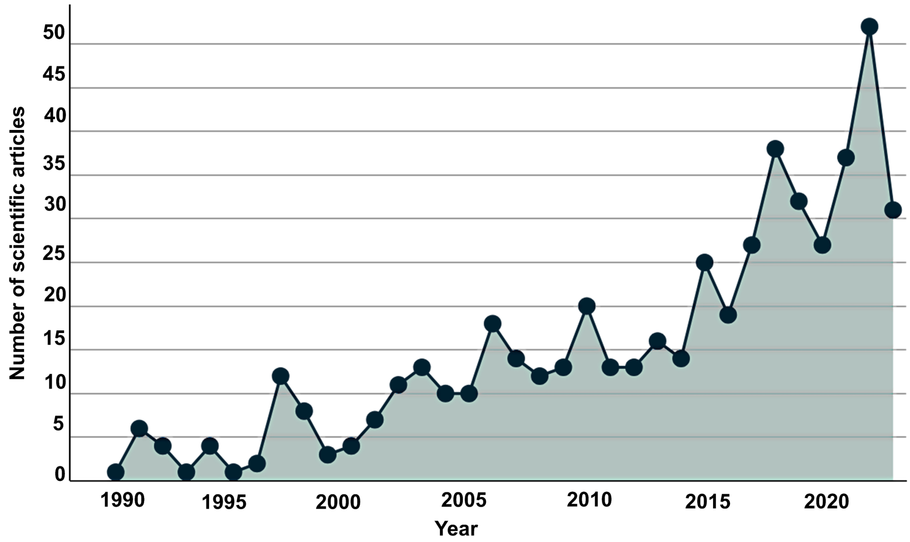


FIGURE 3
Annual scientific production of articles on *Opuntia ficus-indica* within the agricultural domain. Source: Database collected and refined from Web of Science.

output within this thematic area. However, this growth exhibited a more pronounced acceleration post-2000 (Figure 3), signifying a noteworthy upsurge in scholarly interest and contributions to OFI research. Remarkably, the calculated average citation rate per document was 19.39, indicating the significance and impact of research in this field. When dissected into distinct phases, the data revealed a higher average citation count for papers published in Phase II (2002–2023) compared to Phase I (1990–2001). However, the 1990s marked a period of significant expansion in OFI research, encompassing areas such as plant physiology, orchard management, and hybrid development, thus providing a robust scientific foundation to support international development initiatives (Felker and Inglese, 2003). Nevertheless, it emerged that while Phase II exhibited a higher average citation count, it also displayed a decreasing trend in citations over time, hinting at potential shifts in research focus or other contributing factors that deserve further investigation.

The observed increase in the average citation count for articles published in Phase II (2002–2023) compared to Phase I (1990–2001) indicates a growing interest in and recognition of the importance of OFI research in agriculture. However, the concurrent trend of falling citations during Phase II raises several factors that need to be considered. Early studies may have covered fundamental aspects of plant production, nutrition, and consumption, which could explain the saturation of research topics related to OFI. Phase II research may have focused on more specialized or narrow topics, leading to fewer citations because there was a smaller audience interested in these particular subfields. The introduction of alternative or more cutting-edge research areas and methodologies in agriculture during Phase II is another aspect to consider. Research interests may have shifted away from OFI studies and towards new problems and technology. Additionally, adjustments in funding priorities or alterations in the nature of international agricultural problems may have affected research patterns and the number of citations in OFI papers.

3.3 Most relevant sources

Out of the 109 journals that disseminate research on OFI in the agricultural domain, five stand out (Supplementary Figure S1). The Journal of the Professional Association for Cactus Development, published by the Professional Association for Cactus Development, has a distinctive role in OFI research, specializing in studies related to Cactaceae and its closely related species community since September 1996, with *Opuntia ficus-indica* frequently featured as a prominent keyword.

Because of their interdisciplinary nature, the Journal of Agricultural and Food Chemistry (American Chemical Society) and the Journal of the Science of Food and Agriculture (Wiley) are valuable journals for fundamental and applied OFI research. Scientia Horticulturae (Elsevier) also delves into the horticultural aspects of OFI, especially its fruit, cladodes, soil fertility, and agronomic management. Similarly, Industrial Crops and Products (Elsevier) published articles that contribute significantly to our understanding of the industrial aspects of OFI cultivation. These four journals represent Zone I, according to Bradford's Law, and collectively form a substantial body of literature on OFI, spanning specialized cactus research topics to broader agricultural and food science studies.

There are several reasons why some journals are more influential than others in publishing research on OFI; First, since the beginning of September 1996, the Journal of the Professional Association for Cactus Development has constantly concentrated on OFI research, making it a key resource for academics in this area. The journal's ongoing dedication to OFI research has strengthened its position as an essential resource for both basic and applied research. Second, journals such as the Journal of Agricultural and Food Chemistry and the Journal of the Science of Food and Agriculture are essential platforms for OFI research owing to their interdisciplinary nature. These periodicals efficiently bridge the gap between fundamental botanical research and agricultural applications by covering a wide range of aspects of agriculture and food science. The increase in OFI publications in journals such as Industrial Crops and

Products after 2011 points to a trend towards increased research activity, which may be prompted by shifting agricultural priorities, environmental concerns, or industrial applications. It is possible to connect the observed growth trends in these publications to the changing prominence of OFI in agricultural and scientific communities.

3.4 Most prolific authors

Within the dataset of 518 documents, 1,835 authors were identified as contributors to OFI-related research. Interestingly, this dataset includes eight authors who have singularly authored articles on OFI, indicating a diverse range of research participation. On average, each document in this dataset was authored by approximately 5.16 co-authors, highlighting a collaborative approach to OFI research. Furthermore, the analysis revealed that international co-authorship in the selected papers was substantial at 17.57%, suggesting a global collaboration in advancing knowledge in this area. Finally, the list of top authors who have made substantial contributions to the agricultural domain of OFI includes Inglese P., Donato S.L.R., Nobel P.S., Felker P., Guevara J.C., Valdez-Cepeda R.D., Zegbe J.A., Blanco-Macias F., Costa R.G. and Da Silva T.G.F (Supplementary Figure S2). According to Lotka's inverse relationship law, many authors have been grouped under those who have authored only a few documents. Specifically, 78.5% of authors have written only a single document, indicating that a significant proportion of authors are minimally prolific. Conversely, as the number of documents authored per author increases, the proportion of authors in higher categories decreases sharply. For instance, only 0.001% of the authors had authored 10 or more documents. This illustrates that there are relatively few highly productive authors, and most authors contribute minimally to the dataset (Supplementary Figure S2).

3.5 Affiliations and most prolific countries

The leading institutions producing the most articles on OFI within the agricultural field are:

I Federal Rural University of Pernambuco (Brazil);
II University of Palermo (Italy);
III Chapingo Autonomous University (Mexico);
IV Federal University of Paraiba (Brazil);
V Federal University of Ceara (Brazil).

These five institutions comprise 15% of all the affiliations in this domain. At the University of Palermo, OFI research gradually expanded, with an upswing from 1998 onward and the most significant surge from 2010 onward. The Federal University of Ceara experienced gradual growth and a marked expansion from 2016 onward. The Chapingo Autonomous University displayed steady growth from 2008 and a substantial increase after 2010. The Federal Rural University of Pernambuco witnessed gradual growth in 2010 and a significant upsurge in 2020, maintaining a consistent output of 50 articles in 2022 and 2023 (Figure 4).

In addition to this, the FAO-ICARDA International Technical Cooperation Network on Cactus (CactusNet) enhances collaboration through its General Coordinators, Research Theme Coordinators, and Regional Coordinators, who coordinate activities, share information, and foster cooperation within the cactus research community (CactusNet, 2024).[1] Paolo Inglese, Mounir Louhaichi, and Ali Nefzaoui are among the prominent researchers serving as advisors for CactusNet, contributing significantly to global cactus research. CactusNet covers locations including Sub-Saharan Africa, North America, South America, the Mediterranean, and Asia, and focuses on themes such as fruit production, post-harvest and agro-industries, biotic interactions, forage, bioenergy, rangeland, environmental protection, nopalitos/beles production, medicinal and cosmetic uses, and genetic resources and conservation. Furthermore, the CactusNet organizes a prestigious cactus congress every 3 to 4 years, bringing together experts, researchers, and enthusiasts from around the world to discuss advancements in cactus research and cultivation. The proceedings from these congresses are meticulously compiled and published by the International Society for Horticultural Science (ISHS) in Italy, ensuring that the latest findings and innovations are accessible to the global scientific community.

Understanding the importance of contributing institutions is essential for scientometric studies. It is particularly interesting that the top five universities that contribute the most significantly to this topic are all in Brazil. This alignment can be attributed to the extensive use and cultivation of OFI in the arid and semi-arid regions, where it is a crucial source of green fodder. Beyond the scope of academic research, this approach to agriculture considerably improves the lives of smallholder farmers in Brazil, demonstrating the real socioeconomic effects of OFI (Dubeux et al., 2006). The geographical distribution of these institutions highlights their specialized local knowledge and skills in this particular field, potentially resulting in more contextually relevant and significant research findings.

The scientometric study of OFI research revealed unique trends in country contributions. Mexico was the most prolific contributor. Brazil, Spain, Italy, and the United States are closely behind, indicating strong global interest (Figure 5). When this distribution is examined at the continental level, North America emerges as the leading contributor, accounting for 34% of all OFI publications. Europe is closely behind, accounting for 31% of the research output, indicating its significant position in the European academic landscape. South America also makes an important contribution, accounting for 20% of all the articles. On the other hand, while making major contributions, Asia has a somewhat lower proportion (13%), reflecting increasing interest in this continent.

Africa and Australia account for less than 2 and 1% of global OFI research, respectively. Italy had 1,918 citations and was therefore the leading country in terms of total citations. However, Tunisia stands out in terms of average citations per article, with an average of 38 citations per article. The top five countries with the most citations were Italy, Mexico, Tunisia, the United States, and Germany.

Korea and Germany had outstanding averages of 143.3 and 107.60 citations per paper, respectively. Interesting trends can be seen in the data on the output of research publications on OFI over time in different countries. The United States (USA) has maintained a significant research output on this subject, expanding slowly from two articles in 1990 to 69 publications in 2023, demonstrating gradual but consistent development. Italy has a more dynamic pattern, with a significant increase in research production, from two articles in 1992

1 https://www.cactusnetwork.org/about-us/

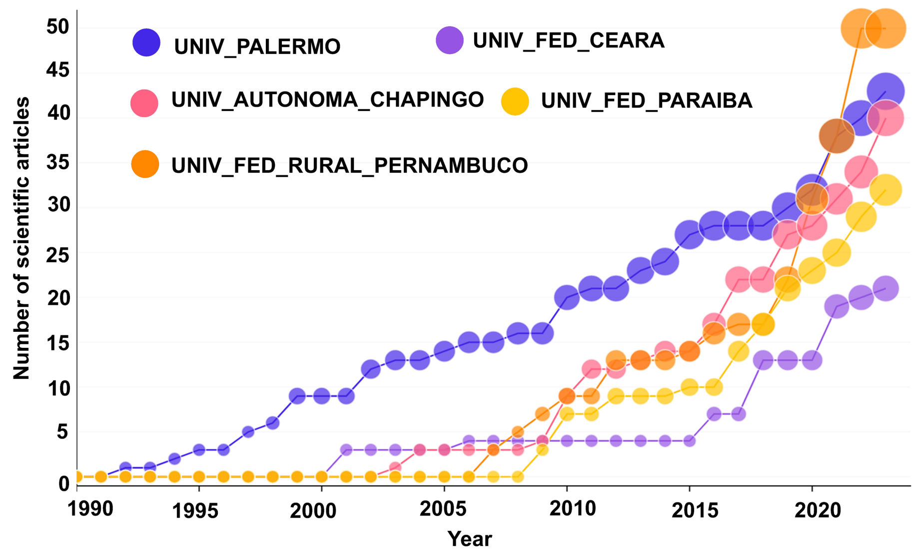


FIGURE 4
Top five institutions with the highest number of scientific articles on the *Opuntia ficus-indica* research within the agricultural domain. UNIV_FED_RURAL_PERNAMBUCO = Federal Rural University of Pernambuco; UNIV_PALERMO = University of Palermo; UNIV_AUTONOMA_CHAPINGO = Chapingo Autonomous University; UNIV_FED_PARAIBA = Federal University of Paraiba; UNIV_FED_CEARA = Federal University of Ceara. Source: Database collected and refined from Web of Science.

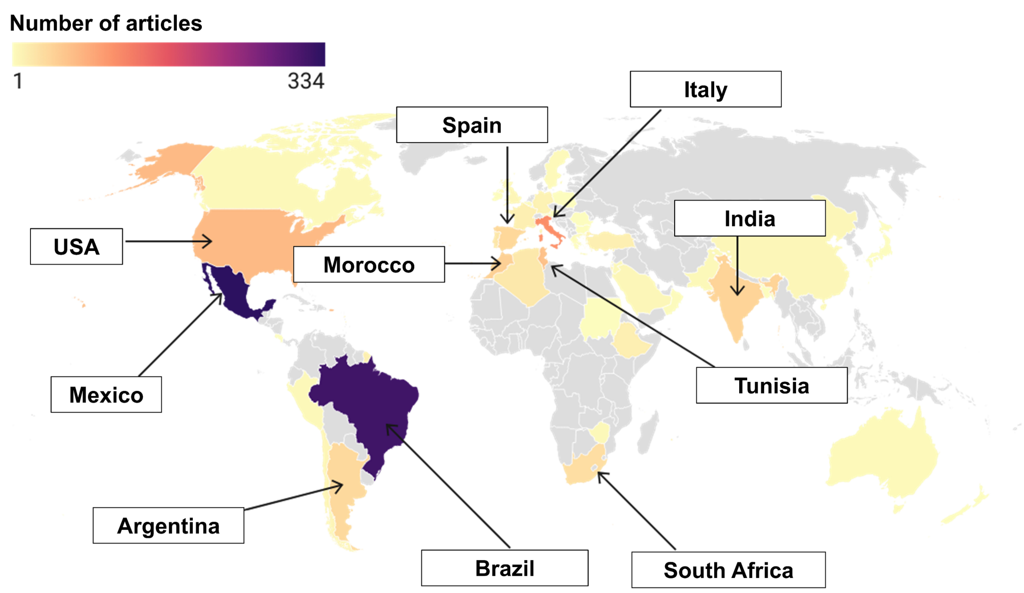


FIGURE 5
Top 10 countries that contribute the highest number of scientific articles on *Opuntia ficus-indica* within the agricultural domain. The intensity of the color depicts the number of scientific articles. Source: Database collected and refined from Web of Science.

to 111 publications in 2023. Mexico's research articles increased considerably from two in 1992 to 334 in 2,023, with a significant spike in OFI research output. Tunisia followed a similar pattern, beginning with an insignificant presence, and gradually expanding to 62 articles by 2023. Brazil, which had a low initial research output, has undergone exponential development, with 317 articles published in 2023, indicating a growing interest in OFI research.

Opuntias are historically vital subsistence crops globally, yet their fruit consumption is largely local with minimal export. Commercial production centers in Mexico, Italy, Chile, South Africa, and Argentina (Reyes-Agüero et al., 2013), benefiting from effective marketing. Mexico leads global production (45%), followed by Italy (12.2%) and South Africa (3.7%) (Andreu-Coll et al., 2020). Italy is the leading exporter, cultivating 7,000 to 8,300 hectares annually for 78,000 to

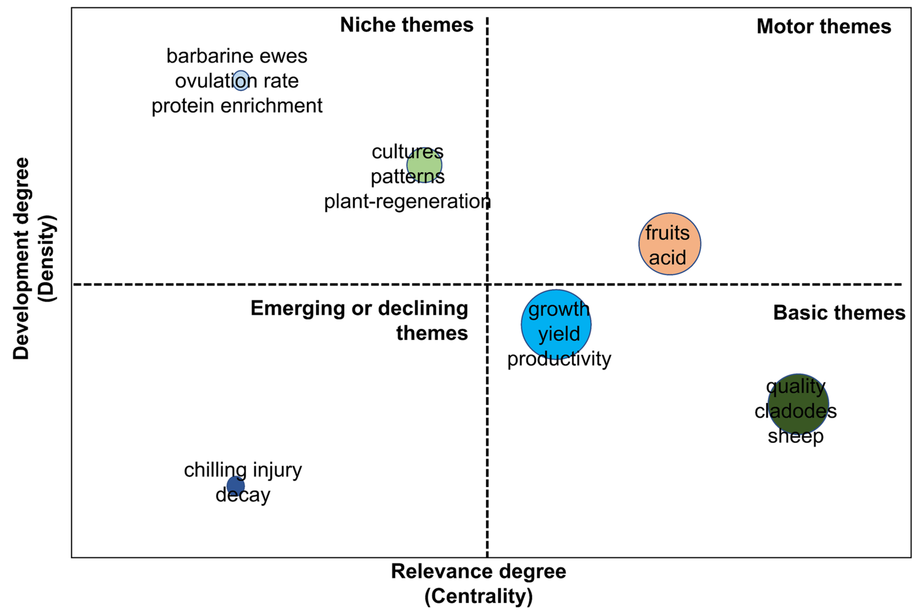


FIGURE 6
Citation dynamics of the total documents in *Opuntia ficus-indica* research (agriculture). Four parameters are highlighted: (i) year of publication, (ii) number of publications, (iii) mean total citations per publication, and (iv) citable years (number of years during which a scientific article is relevant to be cited by other researchers). Source: Database collected and refined from Web of Science.

87,000 tons (Timpanaro et al., 2015). Other significant producers include Chile, Argentina and the USA (Inglese et al., 2017). Additionally, Egypt, Bolivia, Pakistan, Israel, Tunisia, Brazil, Algeria, Morocco, Jordan, India, and Spain also cultivate cactus pear, highlighting its global agricultural importance (Inglese et al., 2017).

3.6 Citation numbers and dynamics

The persistent impact of a few foundational works is shown in the scientometric analysis of the total citations in OFI-related agricultural research. The contribution made by Stintzing et al. (2005) in the Journal of Agricultural and Food Chemistry was the foremost among these (Supplementary Figure S3). The highest total citation count was attained by this document, showing its continued scholarly attention and lasting value. The studies conducted by Butera et al. (2002) and Lee et al. (2002) also maintain significant positions within the total citation rankings. The studies represented by these publications stand the test of time and continue to influence and inform the current discussions. Papers published by Galati et al. (2003) and Castellar et al. (2003) garnered significant citations, further highlighting their applicability to the field of OFI research. Other documents also had a high number of citations (>150) (Stintzing et al., 2002; Castellanos-Santiago and Yahia, 2008).

The total citations per year shed light on contributions that have attracted significant interest in the field and offer valuable insights into emerging areas of OFI research. Articles with high citations were also shown to have high total citations per year (Figure 6). Volpe et al. (2018) stand out within this category due to its current relevance and the rapid rate at which it has influenced OFI research.

Among the twenty most-cited articles, a significant majority (12) were published in the Journal of Agricultural and Food Chemistry, a reputable journal under ACS Publications. The majority of these articles emphasize research related to prickly pear fruit, specifically focusing on various aspects of its quality, nutritional characteristics, chemical properties, color, biological effects, digestibility, and juice storage (Butera et al., 2002; Lee et al., 2002; Stintzing et al., 2002, 2005; Castellar et al., 2003; Galati et al., 2003; Castellanos-Santiago and Yahia, 2008; Volpe et al., 2018). This research direction aligns with the growing interest in understanding the potential benefits and applications of prickly pear in agriculture, food science, and nutrition. However, there was one article on the biochemical analysis of OFI cladodes (Ginestra et al., 2009).

The substantial amount of prickly pear research is one of the most likely causes for the prominence of highly cited articles in the Journal of Agricultural and Food Chemistry (Garcia de Cortázar and Nobel, 1990; Stintzing et al., 2002; Castellar et al., 2003; Galati et al., 2003; Castellanos-Santiago and Yahia, 2008; Ginestra et al., 2009; Volpe et al., 2018). Investigating the nutritional characteristics of OFI is crucial to optimizing its use in food, agriculture, and pharmaceuticals. Insights into its nutritional benefits, cultivar selection, and potential uses in health and environmental adaptation are also provided. This fruit holds an important place, spanning the lines of agriculture and food science, and is therefore a topic of great scientific interest. This finding emphasizes that there have been more studies on prickly pear fruits than on cladodes. This is a significant distinction, especially in light of the expanding significance of OFI as a drought-resistant fodder resource in arid and semi-arid areas (Naorem et al., 2022a). It is crucial to address this gap in the research on cladodes and fruits to exploit the full potential of this crop.

3.7 Keyword analysis

A comprehensive word-frequency analysis identified important recurrent elements in the literature (Figure 7). The word "growth" stands out as a recurring theme, indicating a strong scientific interest in the physiological maturity and development of OFI. The terms "quality" and "yield" are frequently used, highlighting the agricultural and economic importance of maximizing the quality and quantity of products derived from OFI. The term "cladodes" appears frequently, emphasizing its importance in OFI research, likely due to its prominent role as the primary photosynthetic organ and a good source of fodder. The word "sheep" appears frequently, indicating research on the use of OFI as a source of fodder. The repeated occurrence of "productivity" highlights the agricultural implications of OFI farming. The frequent use of words like "antioxidant," "chemical composition," and "extraction" highlights the growing interest in the bioactive substances produced by OFI and their prospective uses.

Keyword analysis revealed a structured grouping of the six distinct topic categories. Group I included keywords related to cladode physiological development, with a focus on keywords such as growth, productivity, photosynthesis, and carbon dioxide uptake. Group II is associated with the chemical makeup of prickly pear, with a focus on terms such as betalins, antioxidants, acidity, and color. Group III focused on cultivar selection and genetic diversity, denoted by keywords such as clones and genetic diversity. Group IV addresses post-harvest issues, including terminology, such as storage and decay.

Group V emphasized the nutritional aspects of cladodes, highlighting keywords, such as cladodes and protein content. Finally, Group VI centers on the use of OFI as livestock feed, denoted by keywords such as sheep, goat, neutral detergent fiber, dietary fiber, and feed intake. After 2008, most of these keywords gained momentum. Over the next 15 years, the OFI field has grown significantly (Supplementary Figure S4; Figure 8).

A comprehensive keyword analysis identified six hotspots; First, OFI has gained prominence as a valuable source of green fodder in regions characterized by arid and semi-arid conditions, and which has prompted a surge in physiological investigations focused on cladodes aimed at comprehending its crassulacean acid metabolism (CAM) capability (Nobel et al., 2002), which contributes to reduced transpiration and higher water use efficiency than other conventional crops. Concurrently, researchers have embarked on inquiries into the variations in the chemical composition of cladodes throughout their maturation process, seeking to pinpoint the optimal growth phase for harvest (Naorem et al., 2022a). It is imperative to gain insights into the photosynthetic activity of OFI, particularly in response to escalating environmental stressors such as elevated temperatures and increased carbon dioxide levels (Nobel and De Cortázar, 1991). These scientific endeavors have the potential to determine whether OFI can be classified as a climate-smart crop. Consequently, the exploration of CAM crops, including OFI, has

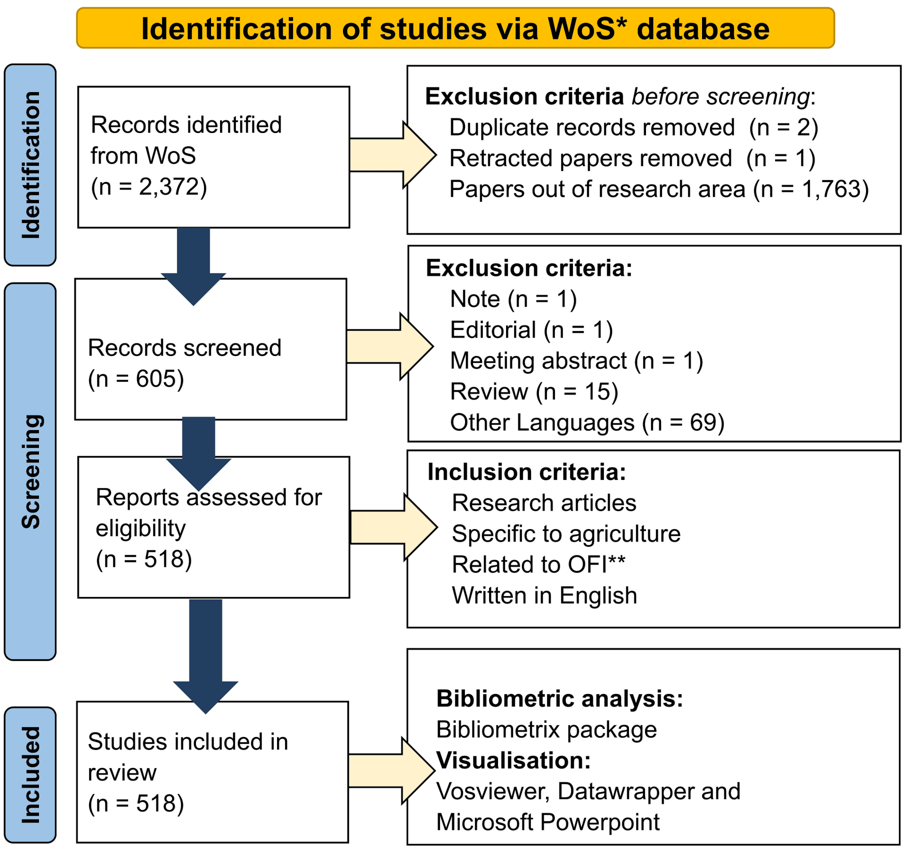


FIGURE 7
Keyword analysis. Based on 1,529 keywords generated from the database of the collection on *Opuntia ficus-indica* (agriculture). Source: Database collected and refined from Web of Science.

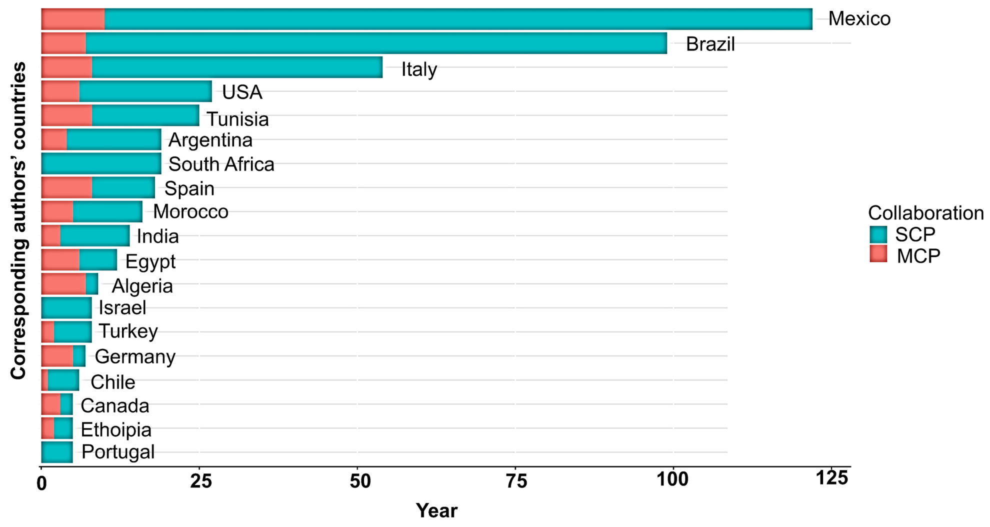


FIGURE 8
Trending topics in *Opuntia ficus-indica* agricultural articles (1990–2023). Source: Database collected and refined from Web of Science.

seen a considerable increase in scholarly attention, reflecting the growing importance of sustainable agriculture in a changing climate scenario.

Second, one of the primary cultivations of OFI centers around the fruit (prickly pear) (Ginestra et al., 2009). Prickly pear fruit is characterized by its succulent and sweet flesh encased in a spiky peel (glochids) that contains small, hard seeds (Castellanos-Santiago and Yahia, 2008). There has been a substantial increase in the production of prickly pear across many countries in recent years owing to its nutritional profile, with significant quantities of sugars, vitamin C, antioxidants, pigments, and essential minerals such as calcium, sodium, magnesium, manganese, zinc and iron (Galati et al., 2003).

Third, before disseminating planting materials to farmers, rigorous selection of appropriate cultivars tailored to local climatic conditions is crucial. Naorem et al. (2022b) conducted a study in which 62 spineless cactus accessions were subjected to comprehensive physiochemical analysis and yield trials. Five superior accessions were identified as the best for cultivation in the Kutch region of arid Gujarat, India. Similarly, Akroud et al. (2021, 2022) evaluated numerous OFI cultivars for their resistance to pest infestation. Some researchers have used molecular techniques to identify and select the most suitable accessions for cultivation (Wang et al., 1998; Zoghlami et al., 2012).

Fourth, since prickly pear and cladodes contain more than 80% water, storing these plant parts after harvesting is a concern (Hajji and Salmaoui, 2020). Several authors have studied the storage conditions and shelf life (Schirra et al., 1997a,b, 1999, 2002; Palma et al., 2018). Andreu-Coll et al. (2021) emphasized the optimal storage conditions for cactus pear fruit, suggesting that it can be adequately stored at 2°C and 90% relative humidity for up to 28 days. Alternatively, if a shorter storage period is required, it can be maintained at 20°C for 3 days. Furthermore, dos Santos et al. (1998) analyzed the effects of storage time on forage cactus, specifically its effect on the performance of lactating dairy cows. Their research found that lactating dairy cows may be fed with preserved fodder cactus, which can remain suitable for consumption for up to 16 days after harvesting, with no significant effects on performance. After storage at 5°C for 15 days, chilling injury and low level of decay in the stored produce were visible (Rodríguez-Félix and Villegas-Ochoa, 1997), but the use of edible coatings on the cladodes can lengthen shelf life (Villegas-Ochoa et al., 2007).

Fifth, another significant area of research has focused on the chemical composition of the cladodes (El Otmani et al., 2019). Lamia et al. (2022) found a range of chemical components, including total phenolics ranging from 10.75 to 1.80 mg of gallic acid equivalent per milligram of dry weight and total flavonoid contents from 7.99 to 1.31 mg of epicatechin/catechin equivalent per milligram of dry weight. Various compounds were identified, including kaempferol, epicatechin/catechin, quercetin (13%), myricetin (9%), vanillin, ascorbic acid (3%), nicotinamide (3%), tannic acid (0.4%), caffeine (0.1%), and cinnamic acid (0.1%). These findings indicate that OFI has potential as a natural antioxidant for food applications. However, macro- and micronutrient composition of the cladodes can be influenced by factors such as cultivar., maturity, and pruning season.

Sixth, an emerging area of investigation in OFI research is its use as an alternative source of fodder, particularly in drylands. Andrade-Montemayor et al. (2011) shed lights on the nutritional composition of OFI cladodes, revealing that they consist of approximately 8–15% dry matter and 5–7% crude protein (CP), wherein CP-ADF constitutes 10–30% of the total nitrogen content. The inclusion of OFI cladodes in the diet of goats reduced their drinking water consumption, presenting a multifaceted dimension to its potential as a fodder resource. Incorporating forage-neutral detergent fiber into diets improves ruminal function, digestibility, and consumption behavior in goats fed diets composed of OFI cladodes (Araújo et al., 1970). Most of these studies have been conducted on small ruminants, such as goats and sheep. Ben Salem et al. (2002) reported that a diet based on cactus, supplemented with *Atriplex nummularia*, a perennial halophyte species, elicited similar growth performance in sheep compared to conventional diets. A recurring issue of diarrhea among animals, especially young goats and sheep, has been documented in diets primarily consisting of cactus (Pereira et al., 2021). Multiple

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authors have attributed this phenomenon to factors such as the low content of neutral detergent fiber in the diet (Gebremariam et al., 2006) and the presence of oxalate in spineless cactus (Pinho et al., 2018).

3.8 International collaboration

If we compare countries based on the corresponding author, the most productive countries with multiple publications were Mexico, Brazil, Italy, the USA, Tunisia, and Argentina. Portugal had only single-country publications and no collaborations outside Portugal (Figure 9).

International network analysis was used to show the collaborative environment for OFI research (Supplementary Figure S5). The distinctive thematic clusters and measures of centrality shown by this network highlight on the importance of these countries in the field. The USA, Brazil, India, Argentina, Mexico, Italy, and Cluster 1 appear to be the major hubs in this research network. Mexico occupies one of the top positions, with the highest Betweenness and PageRank values, indicating its crucial contribution to international OFI research. This cluster is mostly focused on the concept of "fruits." Despite its smaller size, Turkey, which makes up Cluster 2, has emerged as a significant actor and suggests a distinct focus in Opuntia research. German-led Cluster 3 maintains a sizable presence, while having a slightly lower centrality. European and North African nations make up Cluster 4, with Tunisia, Morocco, Spain, and other nations making minor contributions to Opuntia research, especially in Mediterranean areas. In Cluster 5, Egypt was a significant collaborator in Opuntia research across the Middle East and North Africa, and in Cluster 6, Ethiopia collaborated extensively with Sweden.

3.9 Thematic mapping

Thematic mapping analysis led to six distinct thematic clusters derived from keyword occurrences. These clusters were subsequently categorized into four themes based on their contents (Figure 10). The analysis of the dataset revealed four broad themes: "cultures," "quality," "fruits," and "growth." These subjects cover a wide range of subtopics and are significant because they have high connectivity and centrality, emphasizing their significance within the dataset. There are two smaller clusters in addition to the main themes, "chilling injury" and "Barbarine ewes." Despite being smaller, these clusters illustrate the precise, narrowly concentrated themes of the dataset.

Cluster 1, centered around the theme of "fruits," encompasses words related to fruits such as "fruit," "acid," "extraction," and "antioxidant." This cluster displayed a significant degree of centrality, as evidenced by the high Betweenness and PageRank centrality values. This finding highlights the central and well-connected nature of the fruit themes within the dataset. Noteworthy subthemes within Cluster 1 include "chemical characterization" and "phenolic compounds." The "fruits" theme included several subtopics such as post-harvest handling and storage of prickly pear (Allegra et al., 2016; Shumye Adilu et al., 2020), molecular cytogenetics (Ahumada et al., 2020), optimization of cladode micronutrient content for better fruiting (Alatriste-Jiménez et al., 2021), effect of fertilization on quality and yield of prickly pear (Arba et al., 2017) and comparison of nutritional characteristics of fruits from OFI and wild cactus (Boudjouan et al., 2022).

Two clusters were identified within the niche themes. Cluster 2 focused on "Barbarine ewes," "ovulation rate," and "protein enrichment." Although smaller, this cluster has significant thematic relevance within its context. Cluster 3 was centered around the theme of "cultures," incorporating words such as "patterns," "plant regeneration," "selection," and "markers." The "cultures" theme indicated those studies related to

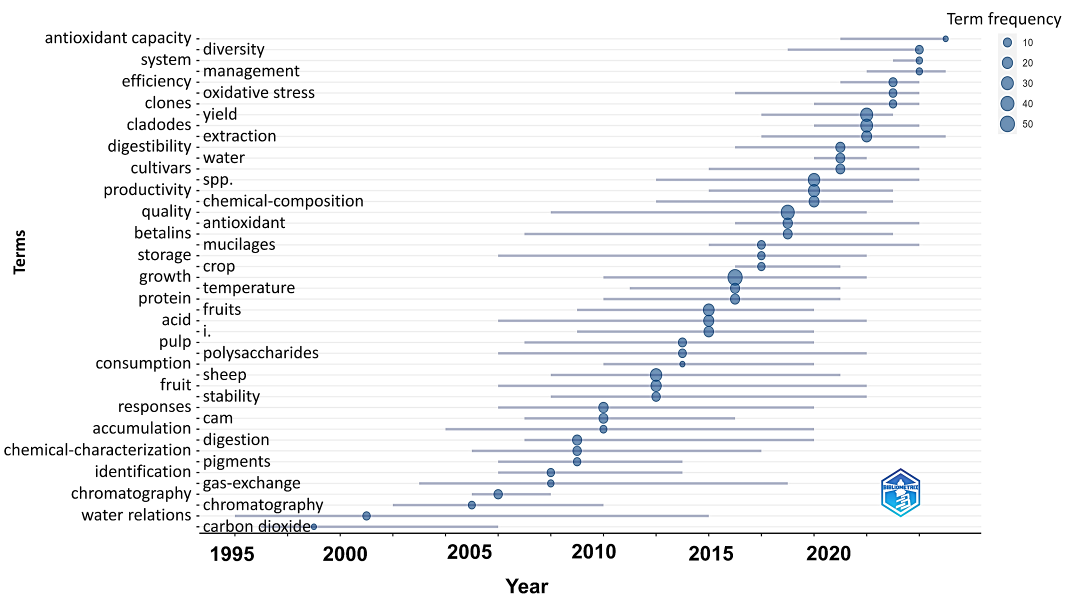

FIGURE 9
Number of single-country publications and multiple-country publications of *Opuntia ficus-indica* research in agriculture by country. SCP, single country publications; MCP, multiple country publications. Source: Database collected and refined from Web of Science.

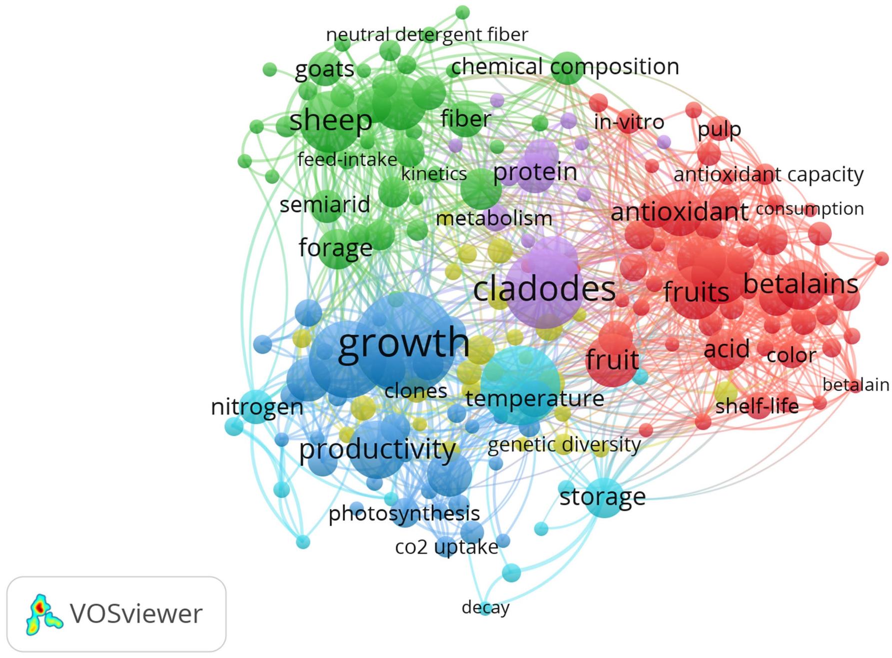

FIGURE 10
Thematic map in *Opuntia ficus-indica* research (agriculture) depicting the research areas in four different categories: motor, niche, emerging/declining, and basic themes. Source: Database collected and refined from Web of Science.

in-vitro micropropagation (Estrada-Luna et al., 2002), transformation of OFI callus cultures (Llamoca-Zárate et al., 1998; Felker et al., 2018), and control of pathogens during post-harvest handling of OFI (Moreno-Rodas et al., 2021). Centrality measures suggest that Cluster 3 holds a relatively central position within the dataset with high betweenness, closeness, and PageRank centrality values.

Cluster 4, which addresses "chilling injury and decay," was found within emerging or declining themes. Although this cluster is relatively smaller than others, it maintains a significant degree of centrality within its specific context. Cluster 5 demonstrated a high degree of centrality and encompasses themes related to "growth," "yield," and "productivity." The "growth" theme highlights those research topics that deal with the increased productivity of OFI. For example, de Cortazar et al. (2001) tested the response of OFI treated with biofertilizer and found a 13% increase in the number of cladodes per plant and 30% increase in photosynthetically active areas as compared to plots with no biofertilizer. de Farias Ramos et al. (2011) observed that above-ground biomass production per area was directly proportional to planting densities, with high biomass in the spacing of 1 × 0.5 m. However, the spacing may differ based on the reasons for cultivation, local climate, and cropping system. Other subtopics that fall under this cluster are the effect of irrigation on OFI productivity (Flores-Hernández et al., 2004), soil water dynamics of OFI (Freire da Silva et al., 2015), cladode-shading effects (La Mantia et al., 1997), and saline water tolerance (Nadaf et al., 2018; Dantas et al., 2023).

Meanwhile, Cluster 6 incorporated words related to various aspects of quality, including "diets," "digestion," "protein," and "performance." Cluster 6 exhibited particularly high PageRank centrality, indicating its vital role in connecting various themes within the dataset. The "quality" theme refers to the quality of livestock feed (cactus-based diets) and the performance of small ruminants. Ruminal fermentation studies have indicated that the nutritive value and gas production from fermentation are similar in both spiny (*Opuntia amyclae*) and spineless cactus (OFI) (Abidi et al., 2009a). In drylands where small ruminants are raised on low-quality roughages, OFI cladodes can supplement barley-based diets in lambs and kids with no substantial negative effects on digestion or growth (Abidi et al., 2009b). In diets for developing sheep, a mixture of saltbush and spineless cactus (1.7:1) can substitute 60% of the barley straw and 16% of the concentrate combination, reducing expenses without negatively impacting growth or health. Additionally, it meets 16% of the water requirements of Awassi lambs, making it suitable for desert areas (Alhanafi et al., 2019). However, animals do not readily ingest OFI when converted into silage, which could adversely affect intestinal health (Araújo et al., 1970).

4 Current research trends of OFI in other areas directly/indirectly related to agriculture

4.1 Climate change mitigation

OFI offers significant benefits in addressing climate change. OFI cultivation can enhance soil carbon sequestration, thereby contributing to environmental sustainability (Andreu-Coll et al., 2020). Its remarkable drought resistance makes OFI a suitable crop for drylands, requiring minimal water and reducing agricultural water consumption (Zegbe and Servín-Palestina, 2021). The high levels of proline, indicaxanthin, and betanin helps its adaptation to adverse conditions (Honorato-Salazar et al., 2021). Moreover, the resilience of OFI under harsh agro-climatic conditions and its potential to combat desertification indicates its role in sustainable agriculture and land management, vital for mitigating climate change impacts (Iqbal et al., 2020). Additionally, OFI provides a sustainable food source for both humans and livestock, offering economic opportunities beyond food production. This highlights its importance in building resilient, climate-smart food systems (Du Toit et al., 2020). Compared to other crops, OFI cultivation shows promising results in reducing greenhouse gas emissions and lowering carbon footprints. OFI fields maintain SOC content and recalcitrance index similar to forest soils, contributing to climate change mitigation (De León-González et al., 2018). In contrast, maize monoculture significantly reduces total organic carbon levels, leading to higher CO_2 emissions (De León-González et al., 2018). As a CAM plant, OFI utilizes 4–10 mmol CO_2 per mol H_2O compared to 1–3 mmol for C_3 and C_4 plants (Yahia, 2012). Moreover, a single cladode of OFI contains 36.2% carbon, equating to approximately 166 kg of CO_2 per adult plant, with an annual CO_2 fixation rate of 8.29 kg per plant (Gomez-Casanovas et al., 2007). De León-González et al. (2018) further demonstrates OFI's contribution to soil organic carbon accumulation.

4.2 Biofuel production

OFI has been extensively studied as a sustainable feedstock for biofuel production. For example, Blair et al. (2021) formulated a microbial consortium, particularly *Pectobacterium cacticida*, which effectively degrades OFI biomass to release fermentable sugars. Furthermore, Alencar et al. (2018) optimized enzymatic hydrolysis conditions for OFI, achieving high fermentation efficiencies. Jamai and Ettayebi (2021) demonstrated the production of bioethanol from OFI juice using thermoresistant yeast, achieving a high yield of 0.43 g/g. Honorato-Salazar et al. (2021) reviewed the potential of OFI as sustainable feedstocks for bioenergy and byproducts, highlighting their suitability for cultivation in marginal and dry lands. Yang et al. (2015) investigated the biomass characterization of OFI, along with its high water-use efficiency and suitability for expanding feedstock production into semi-arid marginal lands. In Tunisia, OFI waste has shown promise as a local biomass for a circular economy. Maaoui et al. (2023) reported the highest biochar yield at 500°C and 30 min, while higher temperatures and longer durations produced more liquid and gaseous products. However, because of low calorific value and high ash content, San Miguel et al. (2022) suggested densification is needed to improve usability as a solid biofuel.

Nori et al. (2024) produced bioethanol from OFI using *Saccharomyces cerevisiae* and Water Kefir following an autohydrolysis pretreatment. Owing to low fiber level, OFI cladodes could potentially generate a significant amount of methane (327 m3 CH_4 Mg^{-1} Volatile solids). OFI biomass competes favorably with other crops for biogas generation, showing a high methane production to biomass ratio of 57.12% (Ortiz-Laurel and Rössel-Kipping, 2014). To optimize biogas production and quality, mixing the OFI cladodes with manure, crop residues and beneficial microbes aids in balancing the C/N ratio for microbes in the digestate. Since OFI cladodes are typically acidic (3.5–5.5), the pH must be raised to neutral-alkaline levels to generate methane (Quiroz et al., 2021).

4.3 Taxonomy

The taxonomy of OFI remains a topic of debate. Molecular evidence indicates that OFI is closely related to cactus pears from central and southern Mexico, with its domestication likely centered in central Mexico (Griffith, 2004). There is also evidence suggesting that OFI may be polyphyletic, originating from multiple lineages (Griffith, 2004). Distinct from *O. amyclae*, *O. megacantha*, and *O. streptacantha*, OFI is a native species of Mexico known for its economic importance (Reyes-Agüero et al., 2005). OFI exhibits various ploidy levels and can reproduce both sexually and asexually, contributing to its adaptability and widespread cultivation (Reyes-Agüero et al., 2005).

4.4 Genetic improvement

Research on the genetic improvement of OFI has been centered on characterizing genetic diversity and developing strategies for conservation and breeding. In Morocco, studies have identified significant genetic differentiation between provenances, which can be leveraged for resource characterization and enhancement programs (El Finti et al., 2017). Similarly, genetic diversity assessments in Tunisia using molecular markers have demonstrated continuous variation among cultivars, independent of geographic origin (Bendhifi Zarroug et al., 2015). Additional research in Morocco, using both morphological traits and molecular markers, has revealed a high similarity between OFI and *O. megacantha* species (El Kharrassi et al., 2017).

5 Future research directions

5.1 Transfer and exchange of genetic resources

The Nagoya Protocol emphasizes the transfer and exchange of genetic resources, yet there are currently no clear guidelines on how to exchange cactus plant materials. This lack of regulation poses challenges for international collaboration and conservation efforts.

5.2 Lack of accurate data on cactus cultivation

No country has an exact figure on how many hectares are planted with cactus. This presents an interesting research topic that should be addressed using state-of-the-art technologies such as geoinformatics, remote sensing, and GPS to accurately map and monitor cactus cultivation areas.

5.3 Quantification of productivity

There is a critical need for the exact quantification of productivity (both cladodes and fruits) per unit area and per age of the plants. Accurate productivity metrics are essential for optimizing cultivation practices and maximizing yield.

5.4 Research on OFI as biofuel and fertilizer

More research is needed to assess the potential of OFI as a biofuel and fertilizer. Investigating its efficacy and feasibility in these applications could contribute significantly to sustainable agriculture and energy production.

5.5 Overcoming barriers to adoption

Despite its potential advantages, people in certain regions are reluctant to adopt OFI cultivation because they consider the cactus to be an invasive plant. Future research should focus on cultural, economic, and environmental variables as examines the challenges and causes of the slow adoption of OFI.

5.6 Economic assessment

There are currently few economic studies on OFI. Future research should examine the economic sustainability of growing OFI while considering the cost of production, market value, and prospective farmer's income.

5.7 Market expansion

The OFI encounters difficulties with marketing, particularly in developing nations such as India. To effectively promote OFI products, research should be undertaken to determine obstacles to market development and suggest solutions.

5.8 Resource-use efficiency

Although OFI is regarded as a low-input crop, comparative studies must be conducted to evaluate how effectively it uses water, fertilizer, labor, and land resources. Such investigations can shed light on their environmental impacts and long-term viability.

5.9 Stress tolerance and cultivar selection

The ability of OFI to withstand stress should be further studied, especially in challenging environments, such as saline soils, acidic soils, and high humidity. Its successful cultivation depends on identifying resilient cultivars that thrive in many environments.

5.10 Wildlife interference

It is critical to address the issue of biological interference by wild animals in order to protect OFI crops. Future studies should focus on understanding animal behavior and devising efficient crop damage mitigation techniques.

5.11 Animal health and nutrition

OFI consumption should be further studied in animals, notably in terms of diarrhea and high oxalate concentration. This would be helpful to developing feeding programs that maximize the nutritional benefits of OFI while minimizing health hazards.

5.12 Pest and disease management

Given the lack of focus on pests and diseases affecting OFI, more studies are needed to identify the prevalent risks and to create management measures to ensure crop health and productivity. The cactus cochineal (*Dactylopius opuntiae*), a sap-sucking insect, is spreading across many countries, causing severe damage to cactus crops by feeding on the plant's moisture and nutrients, leading to reduced productivity and, in severe cases, plant death. Effective management strategies are urgently required to mitigate this pest's impact and safeguard OFI cultivation.

5.13 Soil health and management

Although OFI is commonly regarded as a robust crop, research concerning its interaction with soil remains relatively scant and requires more extensive investigation. There are numerous inquiries, including the feasibility of employing OFI for soil reclamation in challenging or degraded soil conditions, and defining the boundaries of its applicability in such contexts.

5.14 Climate-smart agriculture

The OFI should be studied to determine whether it can be genuinely designated as a climate-smart crop. This includes examining climate change resistance and its possible contributions to climate adaptation and mitigation initiatives.

6 Conclusion

The scientometric analysis of *Opuntia ficus-indica* (OFI) research in the agricultural domain has provided significant insights into this evolving landscape. Through an analysis of authorship, collaboration, publication trends, and citation patterns, we developed a better understanding of the research networks and knowledge dissemination around the OFI. One of the most important findings was the widespread interest in OFI research, with Brazil, Mexico, Spain, Italy, and the United States emerging as the major contributors. The recognition of important milestones and focal areas in OFI research has been made possible by identifying top journals, prolific writers, and significant papers. Future research includes overcoming adoption obstacles in countries where OFI cultivation encounters resistance, conducting economic analyses to determine the sustainability of OFI production, addressing marketing issues, and investigating how to maximize this resource efficiently. While significant studies have been conducted in understanding and utilizing OFI for various purposes, including emerging trends like its use in fashion (e.g., leather for bags, jackets, etc.), critical research gaps persist. These include the urgent need for robust pest management strategies, clearer protocols for genetic resource exchange under the Nagoya Protocol, and advanced methodologies to quantify cultivation extent and productivity accurately. Addressing these priorities will not only safeguard OFI crops from threats like the cactus cochineal but also promote sustainable utilization and innovation in OFI-based industries worldwide. This scientometric analysis is a starting point for researchers, policymakers, and agricultural practitioners interested in expanding their understanding and cultivation of OFI. By addressing the identified research gaps and pursuing the suggested paths, the OFI's rope can be strengthened in sustainable agriculture, food security, and environmental management. As OFI grows in prominence in the global arena, a collaborative and multidisciplinary approach will be the most effective for realizing its full potential and resolving the problems that lie ahead.

Author contributions

AN: Conceptualization, Investigation, Methodology, Software, Visualization, Writing – original draft. AP: Visualization, Writing – review & editing. SH: Funding acquisition, Supervision, Writing – review & editing. ML: Funding acquisition, Supervision, Writing – review & editing. SJ: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1354395/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Most relevant journals publishing articles on *Opuntia ficus-indica* research within the agricultural domain. PACD: Journal of the Professional Association for Cactus Development; A&FC: Journal of Agricultural and Food Chemistry (American Chemical Society); SF&A: Journal of the Science of Food and Agriculture; SH: Scientia Horticulturae; IC&P: Industrial Crops and Products. Source: Database collected and refined from Web of Science.

SUPPLEMENTARY FIGURE S2
Most prolific authors in *Opuntia ficus-indica* (OFI) research. Note: Left: number of scientific articles based on OFI, middle: year of publication, right: total citations (TC) per year. Legend shows the top 10 authors with highest number of articles under OFI research. Source: Database collected and refined from Web of Science.

SUPPLEMENTARY FIGURE S3
Top 10 documents in *Opuntia ficus-indica* research (agriculture). Note: Citations are sorted by total citation count, average citation rate (calculated by dividing total citations by the number of years), and normalized total citations (the total number of citations an article had received, normalizing it in comparison to other articles in the refined database). Source: Database collected and refined from Web of Science.

SUPPLEMENTARY FIGURE S4
Timeline of the keywords used in *Opuntia ficus-indica* agricultural articles. Source: Database collected and refined from Web of Science.

SUPPLEMENTARY FIGURE S5
Network analysis of countries collaborating in research based on *Opuntia ficus-indica* in agriculture. Source: Database collected and refined from Web of Science.

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