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Original Article

Analysis of the potential for utilization of pineapple crop residues in Colombia

Análisis de la potencial utilización de los residuos del cultivo de piña en Colombia

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Abstract

Introduction: pineapple cultivation generates large amounts of residual biomass. Consequently, the expansion of the cultivated area in Colombia requires valorization alternatives based on circular bioeconomy strategies to mitigate the environmental and health impacts associated with conventional crop residues management practices.
Objective: to analyze the potential for utilizing pineapple crop residues in Colombia, particularly leaves, from three complementary perspectives: biomass availability, technological opportunities and the market potential of pineapple leaf fibre (PALF).
Methodology: the theoretical availability of residual biomass was estimated using crop residue generation coefficients, cultivated area, and production statistics for the main pineapple-producing departments in Colombia. A bibliometric analysis using the Scopus database permitted the characterizing of PALF market potential using international trade statistics and sectoral market reports. Finally, the information was integrated into a SWOT analysis, and a conceptual PALF value chain was proposed.
Results: Colombia was estimated to generate between 5.9 and 7.1 million tons of theoretical residual biomass in 2024. The technological review showed that vegetal fibre production for polymer composites, textiles and paper represents the most promising technical and economic valorization pathway. Market analysis identified growing opportunities associated with increasing demand for sustainable materials, while also challenges related to production costs, technical standardization, access to international markets, and limited articulation of PALF value chain in Colombia.
Conclusion: pineapple crop residues in Colombia represent a valuable resource for PALF production within a circular bioeconomy framework. This study provides technical, technological, and market evidence, together with conceptual guidance for the development of the PALF value chain.

Keywords: Agricultural Waste Valorization; Biorefinery; Circular Bioeconomy; Pineapple Leaf Fiber; Sustainable Agriculture.

Resumen

Introducción: el cultivo de piña es intensivo en la generación de biomasa residual, por eso el crecimiento de la superficie sembrada en Colombia exige alternativas de valorización acordes con la bioeconomía circular para mitigar los impactos ambientales y sanitarios provocados por las prácticas convencionales de manejo.
Objetivo: analizar el potencial de utilización de los residuos del cultivo de piña en Colombia, específicamente las hojas, desde tres perspectivas complementarias: disponibilidad de biomasa, oportunidades tecnológicas y potencial de mercado de la fibra de hoja de piña (PALF).
Metodología: se estimó la biomasa residual a partir de estadísticas departamentales de producción y área cultivada según los coeficientes de generación de residuos del cultivo. Se realizó una revisión bibliométrica usando la base de datos Scopus para identificar tendencias y aplicaciones tecnológicas, y se caracterizó el mercado de fibras naturales mediante estadísticas internacionales y reportes sectoriales, integrando la información en un análisis FODA y en una propuesta conceptual de cadena de valor para PALF.
Resultados: en Colombia se generaron entre 5,9 y 7,1 millones de toneladas de biomasa residual en el 2024. La revisión tecnológica evidencia que la producción de fibras vegetales para compuestos poliméricos, textiles y papel representa la ruta con mayor potencial técnico y económico, mientras que el mercado de fibras naturales ofrece oportunidades asociadas a la demanda de materiales sostenibles, aunque persisten limitantes asociados a los costos, estandarización y acceso a mercados internacionales.
Conclusiones: los residuos del cultivo de piña en Colombia poseen un alto potencial para ser valorizados como PALF en esquemas de bioeconomía circular. Este estudio proporciona evidencia técnica, tecnológica y de mercado, al igual que una guía conceptual para el desarrollo de una cadena de valor para PALF.

Palabras clave: Valorización de Residuos Agrícolas; Biorrefinería; Bioeconomía Circular; Fibra de Hoja de Piña; Agricultura Sostenible

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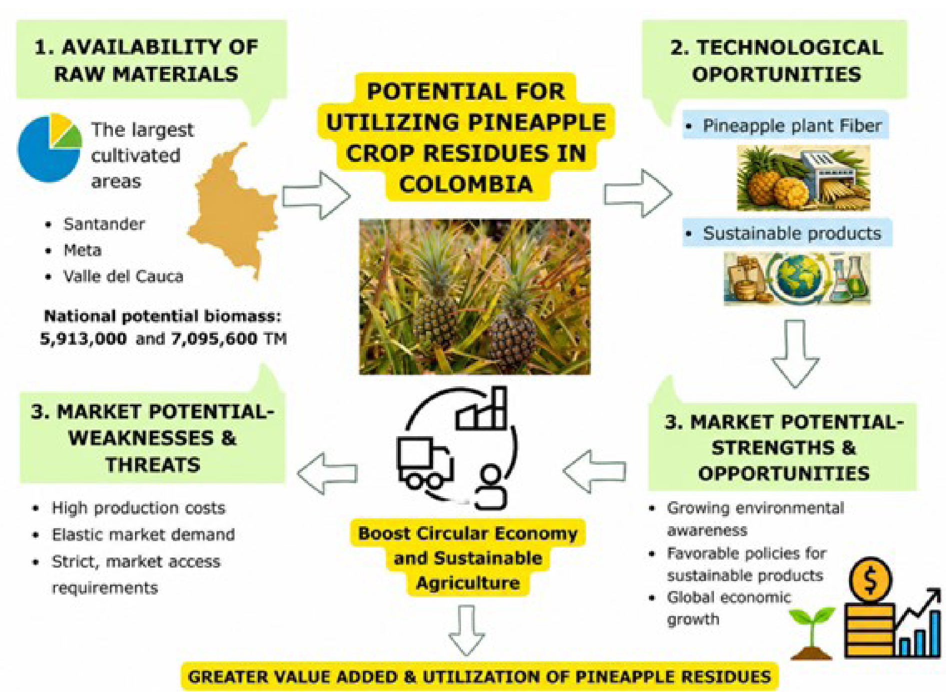
Why was the study conducted?
This study was conducted in response to the need to identify sustainable management alternatives for the residual biomass generated by pineapple cultivation, particularly considering the expansion of the cultivated area in Colombian with special emphasis on the Valle del Cauca department. The study explored technological opportunities for pineapple residue valorization through a comprehensive review of scientific literature and evaluate the market potential for Pineapple Leaf Fibre (PALF) in order to contribute with the development of a PALF value chain and a long-term sustainability of the pineapple production system in Colombia.

What were the key findings?
The key findings of this study are as follows: i) Estimation of a theoretical residual biomass potential between 5.9-7.1 million of tons based on the Colombian cultivated area in 2024 with the highest concentration in the departments of Santander, Meta and Valle del Cauca. ii) Regarding the technological perspective, bibliometric analysis revealed a sustained increase in scientific research on pineapple biomass valorization, identifying plant fibre for polymer composites, textile and paper production as the alternatives with greatest technical and economic potential. iii) From a market perspective, increasing environmental awareness, rising consumer purchasing power and public policies promoting sustainable materials represent important opportunities for PALF-based products. However, significant challenges remain, including high production costs, market demand fluctuations, absence of specific technical standards, barriers to international market entry, and the incipient and poorly articulated commercial capacity in Colombia represent limitations for the development of the PALF value chain.

What do these findings contribute to?
Our findings provide an integrated assessment of the agricultural, technological and market dimensions associated with the valorization of pineapple leaves as a feedstock for PALF within bioeconomic circular strategies in Colombia. From a scientific perspective, the study consolidates and synthesizes the available knowledge on the potential uses of the pineapple residues, identifies the most extensively investigated application areas and existing research gaps, and proposes a conceptual PALF value chain as a prospective framework for future development. From a practical and public perspective, this study highlights the need to move beyond pilot scale initiatives toward scalable business models. Achieving this transition will require technical standardization, stronger coordination among value chain actors, efficient logistics and target investment. Furthermore, the findings emphasize the importance of future research on biomass availability, integrated biorefinery approaches, techno-economic feasibility and governance mechanisms for agriculture residues-based chains.

Graphical Abstract



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Introduction

The expansion of agriculture to food production for the growing global population has a critical challenge associated with the generation of biomass. In this context, agricultural production systems must be equipped with practices to management of crop residues more sustainable, particularly in crops intensive in residual biomass production (1,2). In the case of pineapple cultivation, one of the most significant fruit-growing activities in tropical regions, it is estimated that up to 80% (3,4) of the plant's biomass including leaves, crowns, peels, and stems is discarded during harvesting and processing.

In Colombia, 2024 data from FAOSTAT indicates a production of 910,265 tons (t) of pineapple over 23,652 hectares (ha), accounting for 3.1% and 2.2% of global totals, respectively. This production generates high volume of residual biomass that due to their high fiber content and slow degradation, are often managed through traditional practices: a) chemical desiccation followed by burning, or b) plowing remnants into the soil (5–7). The most used method—cutting and burning—is preferred for its low cost and speed, in this regard, (8) highlight worrying consequences, including soil carbon and nutrient loss, damage to soil biota, increased erosion, reduced water infiltration, and air pollution. The severity of which depends on soil quality and climatic conditions. However, these residues, historically underutilized and associated with environmental degradation due to methane emissions, have a great technical and economic potential owing to their richness in lignocellulosic fibers, sugars, and bioactive compounds such as bromelain and polyphenols in different economic sector (4,9–11).

Due to the growing pineapple production in Colombia and the increasing international interest in finding bioeconomic models to reincorporating agricultural residues into the economic cycle (12) as either end-use by-products or inputs for other production systems, this manuscript explores the potential use of pineapple crop residues from three perspectives. First, it identifies residue production centers by analyzing the availability of biomass by department. Second, it identifies technological opportunities by reviewing the scientific literature to find advancements and alternatives for valorizing residual pineapple leaves. Third, it characterizes the market potential of textile fibers to find opportunities for commercializing by-products derived from pineapple leaves. The aim is to provide information and indicators that contribute to develop the pineapple fiber value chain in Colombia and strengthening the long-term sustainability of pineapple production.

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Materials and methods

Availability of raw materials

Generation of pineapple crop residues is dependent on its production, data from FAOSTAT and Agronet on cultivated areas and yield at both national and departmental levels from 2000 to 2024 were reviewed. These data were analyzed in Excel to identify production trends across different departments. The 2024 statistics were visualized on a map generated using ArcMap 10.3.1 in order to identify the major production niches. Therefore, potential biomass production was calculated as the product of the cultivated area (ha) and the residue generation factor (t ha^{-1}), where this factor corresponds to volumes reported in the literature.

Identification of technological opportunities

To explore, retrieve, and analyze data that facilitate the identification of trends in the scientific literature regarding alternatives for managing pineapple crop residues for valorization, bibliometric tools were employed through three steps: i) mapping the research question to guide the information search; ii) defining the search equation and conducting a search in Scopus and iii) reviewing and analyzing results using Excel and VosViewer. To identify potential uses for pineapple leaves as residual biomass from pineapple cultivation, the following research questions were formulated: What management alternatives for residual pineapple leaves have been explored to utilize and valorize them? Which fields lead research on pineapple waste valorization?

Using the keywords derived from these guiding questions, the search aimed to locate them, non-simultaneously, in the titles, abstracts, or keywords of academic documents. The search equation was defined as follows: TITLE-ABS-KEY: pineapple AND leaves AND waste OR residues. No time period was chosen to retrieve the literature, since the intention of the present study is to explore the available documents on advertising in the Scopus database up to 17 January 2026.

Using descriptive statistics and pivot tables in Excel, following the methodology proposed by (13) retrieved abstracts were reviewed and organized by disciplinary fields and potential industries for pineapple leaf residue utilization. Additionally, the Scopus database was analyzed using VoSviewer©, as per the instructions of (14), to create a bibliographic map Keyword co-occurrence, the final graphical results were analyzed and interpreted.

Characterization of market potential

Due to the potential diversity of pineapple waste, the market analysis prioritized the product with the greatest technical and economic potential: pineapple leaf fiber (PALF) for industrial

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use. To confirm the market's global expansion, international statistics on the production, export, and import of natural, plant-based fibers were analyzed using sources such as FAOSTAT, Trademap, and the Discover Natural Fibers Initiative (DNFI).

To analyze international trade in plant-based fibers, export and import statistics from Section XI of the Harmonized System were reviewed, specifically focusing on Chapters 52 and 53 (Headings 01, 02, 03, 04, 05). As proxy variables for synthetic fibers were included Chapters 54 and 55, while yarns and fabrics were excluded to focus on raw or processed PALF. Data was supplemented by sources such as Indiamart, Made-in-China, and Markets and Markets. Although robust markets currently exist in the Philippines and Taiwan, the rise of eco-conscious consumers presents a promising opportunity for other producers, such as Colombia.

The analysis of the above aspects was integrated into a SWOT matrix to identify the Strengths, Weaknesses, Opportunities and Threats associated with the product in both the national and international markets. Strengths and Weaknesses refer to internal factors that can either positively or negatively affect the market for the evaluated product. Opportunities and Threats refer to external factors that can either enhance or hinder the market for the product considered. In this context, SWOT analysis was developed based on the combination of sources, including scientific literature, official statistics and market reports, as well as authors´ experience and primary information collected through workshops involving pineapple growers and an artisanal PALF startup. This approach allowed the results to be aligned with the conditions and perceptions of a real production environment. Finally, a structure for the PALF value chain is proposed as a conceptual and prospective framework derived from the integration of three principal sources of information: (i) a review of the literature on the cotton fiber value chain, (ii) an analysis of the pineapple production context in Colombia, and (iii) information obtained from workshops involving pineapple growers and a startup currently engaged in PALF extraction in Colombia.

Results and discussion

Availability of raw materials

The potential amount of residual biomass was determined by the cultivated area, planting density, cultivar, and using the parameter that each plant producing 25 to 40 leaves (15,16). According to FAOSTAT (2026), Colombia's production has shown an upward trend since 2000 with a recent drop of 19.8% in 2019 and a 1.7% in 2020 due to the pandemic. Those were followed by a 10.7% recovery in 2021 reaching 920,000 t, with a slight decrease in 2023, explained mainly by extreme weather events in the most productive departments, and with production improvements in 2024 as shown in Figure 1. At the same time, data showed that pineapple cultivation has been a consistent activity rather than a response to

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short-term market fluctuations. In addition, although Colombia represents only 2.25% of the global area and 0.3% of production, the highest potential for residue generation lies in Nigeria, India, China, the Philippines, and Brazil, which together account for 48.3% of the global area and 38% of production. Notably, Costa Rica (11%) and Indonesia (9%) are among the top five producers due to high yield, then in Latin America, Brazil (5.4%) and Costa Rica (5.0%) lead in cultivated area.

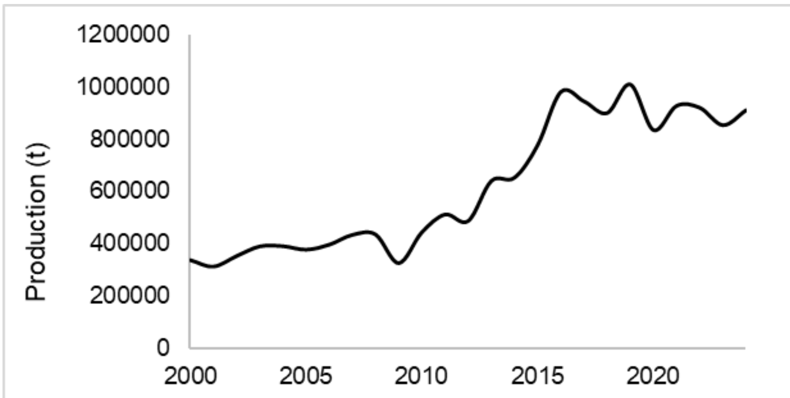

Figure 1. Pineapple production in Colombia between 2000 – 2024. Source: Own elaboration

According to the distribution by department, as illustrated in Figure 2, national production in 2024 was led by Santander, Meta, and Valle del Cauca, which also accounted for the largest cultivated areas: Santander (42%), Meta (12%), and Valle del Cauca (9.4%). The department of Cauca is also notable for its proximity to Valle del Cauca, home of the National Pineapple Council (17). Based on this information, the total residual biomass was estimated by using the residue generation coefficients reported in the literature, ranging from 250 metric tons (MT) (18) and 300 MT (15). Thus, potential biomass production for Colombia’s 23,652 ha of cultivated pineapple in 2024 was estimated to generate between 5,913,000 and 7,095,600 MT of potential biomass.

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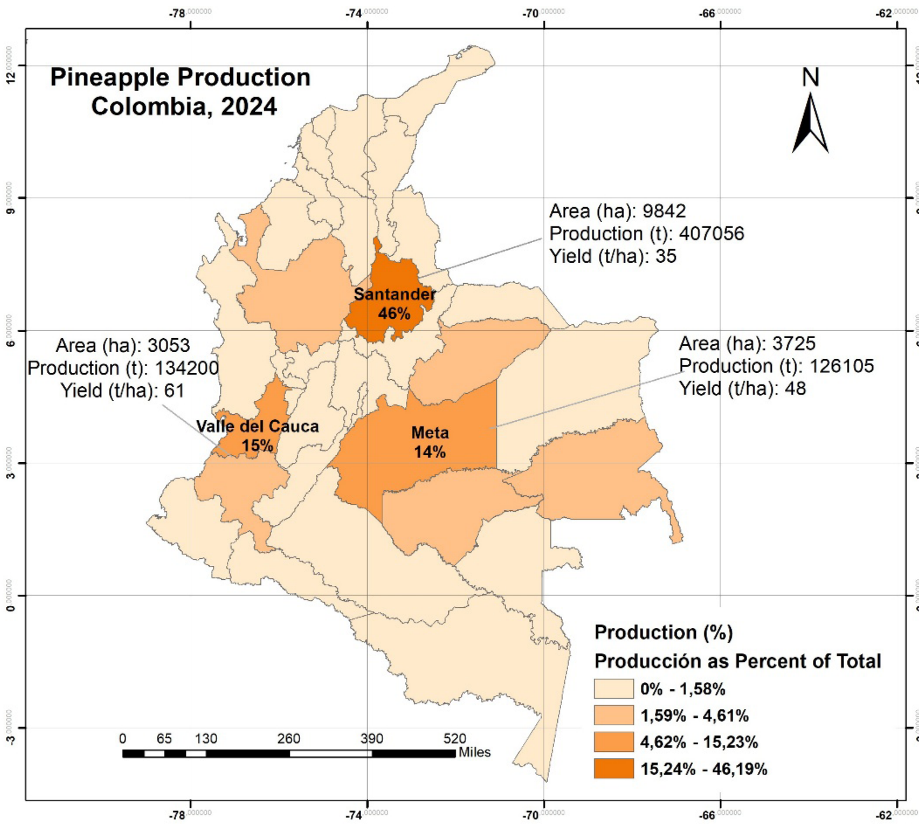

Figure 2 National production of pineapple in 2024. Source D.-Y. Mora.

Considering that the PALF biomass estimated in this study represents a theoretical potential based on total residue generation, future research focuses on quantification of the proportion of biomass that can be effectively recovery and utilized for fiber extraction under commercial conditions. This assessment should consider the fraction of leaves suitable for PALF production, alternative uses for crop residues, collection and transportation efficiencies, post-harvest losses, and the operational difficulties associated with different pineapple production systems.

Identification of technological opportunities

This section presents the main findings on research related to the management of pineapple crop residues (specifically leaves) based on the literature search conducted in Scopus.
In total, 616 documents have been published in the field, 68% Articles, 18% Conference papers, the remainder corresponds to another type of manuscript. The evolution of scientific production from 1968 to 2010 on pineapple residue management showed that the overall production remained relatively low (fewer than 10 manuscripts per year), but a noticeable and sustained increase has been observed since 2018. The annual average rose from 2 documents per year during the 1980–2010 period to 37 documents per year between 2011 and 2025. This trend reflects a growing concern and awareness about the need to valorize pineapple residues.

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The scientific journals with the most publications on the topic since 1980 are: Industrial Crops and Products (12) that is JCR-Q1; Biomass Conversion and Biorefinery (10) classified as JCR-Q2; Chemical Engineering Transactions (10) with classification JCR-T3 and Heliyon (8) positioned as JCR-Q1. According to the Scopus results analysis, 17.4% of the manuscripts are produced in the field of Materials Science; 14.1% in Engineering, 12.2% in Environmental Sciences and 11% in Agricultural and Biological Sciences with the remaining percentage coming from other research areas. The highest scientific productivity is concentrated in Malaysia (149) and India (116), in Lantin America, the leader is Brazil (40). The five authors with the highest scientific output in the field are Taweechai Amornsakchai (17 documents and 603 citations), Osumanu Haruna Ahmed (15 documents and 326 citations), Phung Le Thi Kim (11 documents and 325 citations), Ahmad Husni Mohd Hanif (11 documents and 114 citations) and Nga H.N. Do (10 documents and 316 citations). The most citated paper is "A review on pineapple leaves fibre and its composites" by (19) with 504 citations.

To determine the research trend in the management of pineapple (leaf) residues, a co-occurrence map of keywords was generated using VoSviewer©. A total of 4,859 keywords present in abstracts, titles or keywords sections were processed, with a minimum threshold of 10 occurrences. A total of 122 keywords met the defined threshold. The terms "article" and "priority journal" were excluded as keywords. By calculating the number of occurrences and the total strength of the correlations with other keywords, VoSviewer© grouped the terms into 4 clusters, each represented by a different color, as shown in Figure 3.

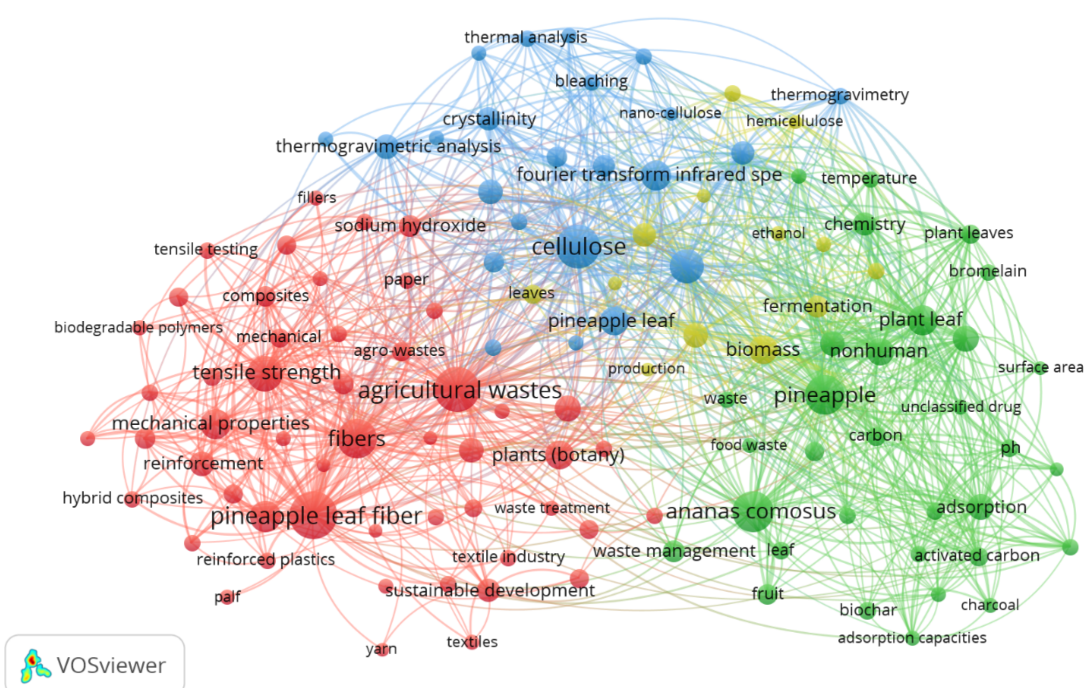

Figure 3 Bibliometric map of keyword co-occurrence "Pineapple leaves waste OR residues" using VoSviewer©. Source: D-Y Mora.

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The first cluster (Red), consisting of fifty-two terms, is associated with properties from pineapple fiber-reinforced composite materials for the textile and automotive industries, as an alternative for synthetic materials. Key terms include pineapple leaf fiber (113), agricultural waste (99), fibers (78), tensile strength (61), mechanical properties (44). The second cluster (Green), contains thirty-two terms, focuses for circular economy applications in environmental remediation, the principal terms of this group are Ananas comosus (85), pineapple (78), plant leaf (44) and nonhuman (37). The third cluster (Blue) consists of twenty-three terms associated with processes to pineapple leaf cellulose extraction to optimize their use of it in valorization alternatives, with cellulose (93) being the most frequently co-occurring term. Finally, the fourth cluster (Yellow) is limited to thirteen elements, linked to Integrate pineapple waste management for biofuel production, the terms more cited are biomass (42) and agricultural waste (32). 'Pineapple leaf fiber' has a linker role between clusters, with an emphasis on mechanical and biodegradable properties. Literature review evidence a growing interest regarding pineapple waste valorization, as a strategy to integrate agricultural sustainability with regional development, also suggest a maturation of bioeconomic applications, with significant potential for circular models within the agribusiness sector.

Until 2014, research focused primarily on evaluating the physicochemical properties of pineapple leaf fiber and the initial extraction techniques used to obtain it. This is why materials engineering dominates research on PALF valorization, particularly in fiber reinforcement for composites and textiles. Environmental Sciences is in second place, exploring applications in remediation. More recently, areas such as energy and biotechnology have emerged, as evidenced by studies on biorefineries and assisted enzymatic hydrolysis. The potential applications were classified into six categories according to the frequency with which keywords, titles, and abstracts: Composites (47%), Environmental (18%), Energy (15%), Pharmaceutical and food (10%), Textile (7%) and others (3%).

Initial studies in the composites sector (19,20) evidenced that pineapple leaf waste is an effective reinforcement in polymeric composites, that make it an ideal substitute for synthetic fibers. More recent research and applications demonstrated a growing interest in sustainable materials focusing on biocomposite films, household utensils, and cement mixtures (21,22). Environmental applications have primarily investigated the use of pineapple leaf biomass for remediation (23–29) but there are challenges such as the compositional variability of leaves, activation costs, competition among contaminants, and the need to regenerate for reuse. In energy applications, the main focus has been on producing biofuels, such as ethanol and biogas, from agricultural residues as renewable

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energy sources to improve efficiency. While these studies confirm the viability of using pineapple leaves as an input, challenges arise in terms of pretreatments needed to improve their digestibility (30–33). At the same time, studies in the food and pharmaceutical sectors emphasize the high content of bioactive compounds, such as polyphenols, tannins, and bromelain, and their functional properties. Key challenges include optimizing extraction technologies and addressing breakdowns in the value chain (3,4,34–36). In addition, researchers have focused their textile studies on evaluating the properties of extracted fibers from leaves and crowns. These fibers are notable for their versatility, which enables the development of biodegradable textiles (37).

Global and commercial initiatives have been developed in identified sectors. Global Supply Solutions in Kenya, which uses the leaves and other non-edible parts of the pineapple to produce biomass briquettes. Life Pack in Colombia, which utilizes pineapple crowns to manufacture biodegradable plates. Ananas Anam in the United Kingdom, which manufactures and sells natural leather from pineapple leaves (Piñatex®), a breakthrough in the textile industry for sustainable materials. In Indonesia, Bromelain Enzyme (BE) focuses on refining products from bromelain extracted from pineapple stems, providing health-related products from an otherwise discarded resource. Circular Systems™ in the United States, which transforms pineapple leaves into fibers, threads, and textiles for the fashion industry (38). Additionally, according to (39), the Hozen brand in the United States or the Aulive brand in India contribute to the growing demand for sustainable fashion and innovative to substitute traditional materials. Thus, among the technological alternatives for utilizing pineapple residues, the production of plant fibers (such as polymer composites reinforcement, textiles and paper) emerges as the most economically promising, followed by the production of environmental adsorbents to bioremediation, biofuel, and inputs for the pharmaceutical, food, and cosmetic industries (3,7,12,15,40–45).

These cases highlight the global potential for transition toward circular bioeconomy models in pineapple agro-industrial, repositioned its residues not merely as environmental challenges, but as strategic reserves of high-value biological resources.

Characterization of market potential

Considering that greatest potential for the production of plant fibers as biological and renewable input to produce paper, textiles and polymer composites reinforcement, the analysis of the potential market was focused in natural fibers, that can be Bast fibers (jute, flax, hemp, ramie, and kenaf), Leaf fibers (abacá, fique, and pineapple), Seed fibers (coconut, cotton, and kapok), Stalk fibers (wheat, corn, and rice) and other types of fibers (wood and roots) (46). In some cases, the production of fiber is the primary goal of commercial-scale cultivation, as with cotton, jute, hemp, kenaf, and fique. However, in other cases, fiber is a

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byproduct of a crop whose main objective differs from the fiber itself. This is the case with pineapple, palm oil, and coconut fibers. Therefore, the production of these fibers becomes a valorization alternative and an opportunity to reintegrate the residues into the production cycle, providing a potential business avenue for generating additional income for fruit producers.

Since 2020, the production of natural fibers has shown a growing trend. However, in 2021, crop yields and total production were limited due to weather conditions in various production zones. Additionally, supply chain disruptions caused significant economic losses due to high shipping costs and delivery delays. In 2022, natural fiber reached 30% (32.6 million tons) of global fiber production. This growth can be attributed to higher natural fiber prices (both animal- and plant-based), which have driven an increase in cultivated areas (47,48). Moreover, data estimated in 2019 showed that approximately 40 million households worldwide participated in the production of natural fibers derived from primary crops. Of those households, 29 million worked with cotton; 6 million worked with jute, kenaf, and related fibers; 5 million worked with wool; 1 million worked with coconuts; and 1 million worked with other natural fibers, such as abacá, hemp, sisal, and silk. Considering all links in the value chain, total employment could account for between 2% and 3% of the global population (49).

UN Resolution 78/169 (2023) highlights the importance of natural fibers for sustainable development due to their renewable and biodegradable nature, as well as their lower environmental impact compared to synthetic fibers. Furthermore, producing and processing natural fibers can improve the poverty and food security conditions of farmers and rural communities (50). According to the statistics reported in FAOSTAT and Trademap for custom tariff Chapters 52 and 53 (Items 01, 02, 03, 04, 05), the main countries producing, importing, and exporting plant fibers with independent reports are listed in Table 1. PALF is included under the category related to coconut fiber and others. FAOSTAT only reports primary crops, meaning that the statistics for fibers produced as byproducts of other crops are not included. Global production of crops other than cotton dedicated to fiber extraction collectively represents only 22.5% of the production level of cotton fiber, which is the most important non-food agricultural product, primarily used for industrial-scale textile production. Following cotton, the most produced natural plant fibers worldwide are jute and flax, although with fluctuating trends. In contrast, crops like agave, hemp, kenaf, sisal, and other fibers have shown relatively more stable production patterns.

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Table 1. Producers, importers, and exporters of plant fibers worldwide. Source: Own elaboration.

Variable	Cotton	Linen	Hemp	Jute	Coconut and others
Producers	China USA Brazil	France Belgium	France China	India Bangladesh	Sri Lanka Brazil Vietnam
Exporters	China USA India Brazil	France Belgium Italy	Netherlands Italy Luxembourg	Bangladesh India	India Sri Lanka Kenya Brazil
Importers	China Bangladesh Vietnam Turkish	China Belgium India Lithuanian France	Germany Czech-Republic U.K. Luxembourg China	India Pakistan Nepal	China USA U.K. Philippines

Imports of plant-based textile fibers average 9.5% of those for cotton and 6% of synthetic fibers. Since 2018, these natural fibers have grown by 7%, outpacing cotton (5.3%) and synthetics (3.4%). Despite higher sensitivity to external fluctuations, between 2019-2020 dropped by 22%, while for cotton decreased by 16.4% and for synthetics by 18.9%. Natural fibers showed a stronger recovery between 2021-2022 with a 21.6% increase, surpassing the 18.5% growth of synthetic fibers. This shift highlights a rising demand for eco-friendly materials and a reassessment of non-renewable resources. This shift also reflects volatile oil prices, which encourages a reconsideration of production systems based on non-renewable resources, such as synthetic fibers. On the other hand, natural plant fiber exports are growing, although their market value remains a small fraction (8.1% to 9.8%) compared to cotton and synthetics. Currently, cotton dominates the industry, with an export value representing 63.9% to 68.4% of that of synthetic fibers. Despite the rise of natural alternatives, such as PALF, petroleum-derived fibers still dominate the global market. In 2019, the production of these fibers reached 69 million tons (49).

Initially PALF was classified as a coarse material for rustic articles, but various studies have demonstrated that possess textile properties suitable for commercial use and sustainable biocomposite fabrication. According to (16), its length, strength, and spinnability make it comparable to or superior to other natural fibers. Its mechanical properties also allow for reduced chemical use during bleaching compared to fibers like bagasse or juteAncient peoples in the Philippines, Europe, and North America used PALF for fine garments before it was displaced by cotton in the 19th century due to cost. However, it is now seeing a resurgence in eco-conscious markets. Beyond textiles, it serves as a renewable substitute

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for wood fibers in the pulp and paper industry (51). Despite the challenge of ensuring a sufficient industrial supply, PALF remains a high-value resource produced primarily in the Philippines, Taiwan, Brazil, Hawaii, Indonesia, the West Indies, and India.

According to Indiamart, the price of raw natural pineapple fiber is approximately 750 INR per kilogram, which converts to about USD $9 per kilogram (at an exchange rate of 0.012 USD/INR). The extraction process, which can be manual or mechanical (52) involves five stages: extraction from green leaves, washing, drying, chemical or enzymatic treatment, and bleaching/dyeing. Due to its ecological nature and the use of by-products, it is considered a relatively expensive luxury item. Consequently, its target market consists of middle and elite classes, with potential focused on medium-scale manufacturing industries emphasizing exclusivity and innovation, unlike synthetic fibers or cotton which rely on large-scale economies.

In contrast, the synthetic leather industry, widely used in footwear and automotive sectors, faces criticism for its reliance on petrochemicals like PU and PVC, leading to stricter regulations in the EU and North America (53). Major players in this market include Kuraray Co., Ltd., San Fang Chemical Industry, and Teijin Limited. In this context, bio-based alternatives, such as pineapple leaf leather, are emerging. While the global synthetic leather market was valued at USD 68.7 billion in 2023 with a CAGR of 5.1%, the bio-based leather market is projected to grow at a CAGR of 15.0% by 2028 (from USD 107 million to USD 216 million) CAGR (54). Demand is highest in fashion centers like Italy, Germany, and Spain, though adoption is limited by elastic demand in emerging markets.

Consumers’ income levels and environmental awareness are key determinants in the bio-based leather market because bio-based leather has higher production costs than conventional leather. This is due to the fact that novel, sustainable production methods require extensive research and development and specialized equipment. Thus, consumers are confronted with a trade-off between price and sustainability. Leading companies in this market include Natural Fiber Welding, Inc. (USA), Ananas Anam Ltd. (UK), MycoWorks Inc. (USA), Bolt Threads Inc. (USA), Modern Meadow (USA), Adriano di Marti (Mexico), Ultrafabrics Holdings Co., Ltd. (USA), Beyond Leather Materials (Denmark), Fruitleather Rotterdam (Netherlands), and VEGEA (Italy).

Global economic growth has driven consumer spending and altered lifestyles, resulting in increasing demand in the global market for sustainable, environmentally friendly products that are also biodegradable and biocompatible. In this context, natural fibers, in contrast to their synthetic counterparts, hold significant potential for the development of clothing and fashion items, curtains, and decorative materials. Additionally, the growing concern

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for environmentally sustainable consumption has compelled producers to reconsider the methods and materials used in their production and distribution processes. Furthermore, improved living conditions—reflected in higher disposable income among consumers—have increasingly fueled the market for natural plant fibers.

Taking into account the methodology explained previously, a SWOT matrix for the potential market of pineapple fiber was generated (Table 2). This matrix can serve as a foundation for proposing strategies for development, promotion, and investment in the natural fiber sector, with a particular emphasis on PALF.

Table 2. SWOT matrix for the potential market of PALF

Strengths	**Weaknesses**
● High quality (durability, texture, and appearance) of pineapple leaf fiber. ● Increased demand for vegan, cruelty-free, and biodegradable products. ● Diversity of uses (fashion, automotive, and furniture industries). ● Potential for utilizing by-products. ● Global regulations regarding the use of animal-derived and petrochemical raw materials. ● Environmental impact of utilizing harvest residues.	● Dependence on markets where pineapple is produced as fruit and difficulty in ensuring the supply of leaves required by the fiber industry. ● High production costs leading to high selling prices. ● Market demand is highly sensitive to small price changes. ● Compliance with regulations for commercialization in European and North American markets (USDA, PETA, and REACH).
Opportunities	**Threats**
● Growing demand in markets in Asia, Europe, and South America. ● Market segment of consumers with medium-high income levels. ● Reorientation of the textile industry towards higher sustainability standards. ● Global market growth rate of 15%. ● Development of innovations to improve current technology.	● Price competition with synthetic fibers produced in large-scale economies. ● Climatic conditions that may affect pineapple production and, consequently, the raw material supply. ● High price sensitivity among consumers. ● Fluctuation in oil prices. ● Lack of integration of natural fiber processing and trade into the social and environmental contexts of the producing regions.

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To propose a structure for the PALF supply chain for textile use in Colombia, and considering the supply chain as the articulation of economic actors who perform activities that add value to the production of a good or service, an analysis of the gathered information revealed that the textile and apparel chain comprises several links that contribute value to the sector based on their areas of expertise. In this regard, and by comparing PALF to the world's most widely used natural fiber (cotton), a supply chain structure is proposed. The conceptual design of the value chain is presented in Figure 4, in which the key actors, raw material flows, intermedia products and potential integration points with end-user industries are identified. This framework should be understood as a prospective and conceptual exercise rather than an exhaustive analysis of a fully established supply chain. We acknowledge that a comprehensive value chain assessment would require detailed quantitative analysis of logistics, costs, operational performance and market dynamics. Therefore, future research should focus on evaluating the technical, economic and financial feasibility of the proposed value chain, as well as identifying the conditions necessary for its successful implementation and scaling within the Colombian context.

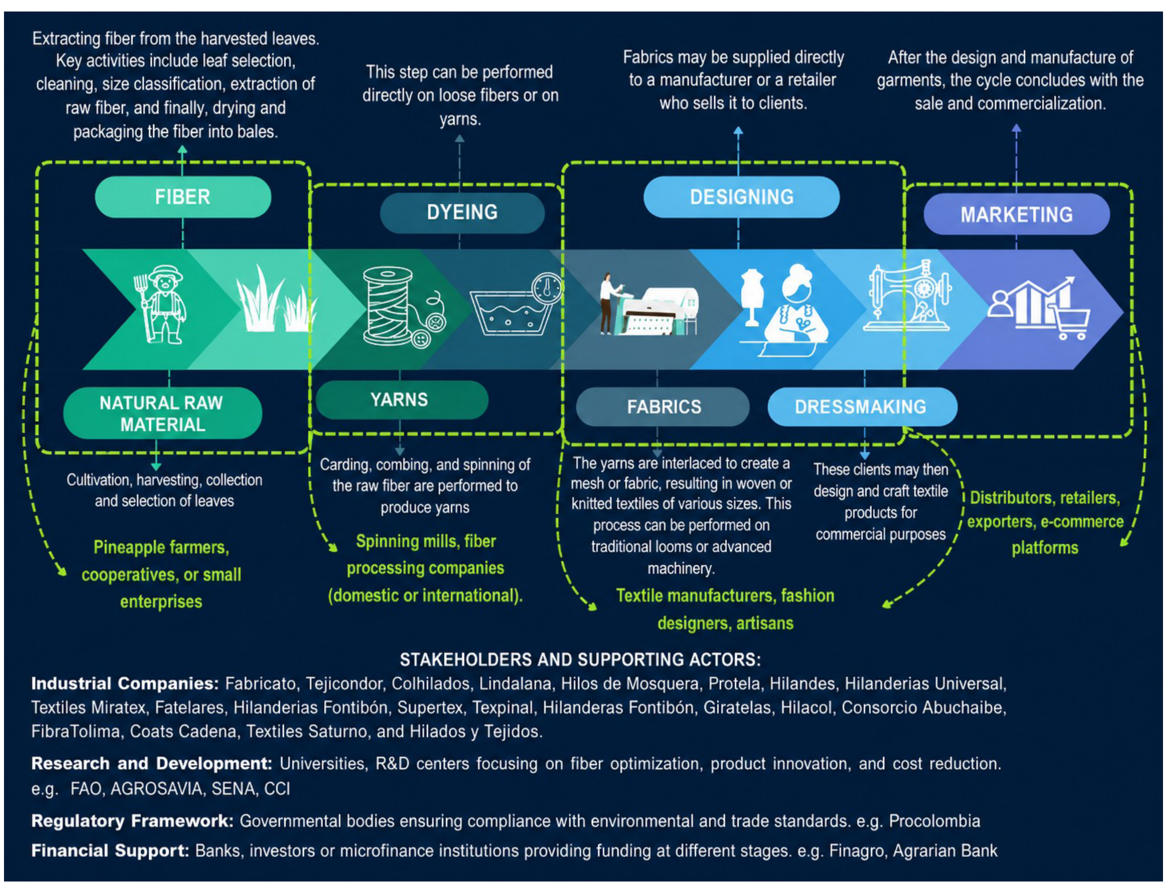

Figure 4 Proposed structure of the PALF value chain for textile use in Colombia, based on the cotton-textile sector value chain..

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Conclusions

The promotion of residual biomass utilization from pineapple crops intended for fruit production is essential for achieving more economically, socially, and environmentally sustainable agriculture. In line with the results of this study, which reveal both the significant technical potential for PALF and the technological and market barriers that currently limit its large scale adoption, we emphasize the crucial role of academic research in supporting technological innovations to reduce production costs, improving efficiency and enable economies of scale, while fostering awareness and collaboration among stakeholders. This collaboration should drive production systems within industries such as fashion, automotive, and furniture that can integrate PALF as a sustainable input. However, in the case of Colombia, initiatives from various governmental, public, and private sectors to promote the advantages of PALF remain incipient. Consequently, the current landscape is predominantly an emerging innovation ecosystem composed of pilot-scale and exploratory initiatives, rather than a consolidated value chain.

Although there has been progress in raising collective awareness to produce and consume environmentally friendly goods/services, even acknowledging that they may entail higher prices, statistics show that the progress made is still minimal compared to the size of the market. This is largely explained by the development of economies of scale in the synthetic fiber sector, which captures nearly 70% of the global fiber market. As reported by the DFNI, of the nearly 10 million tons produced in 2022, only 32.6 million tons correspond to natural fibers (animal and plant-based).

The greater economic growth, and the higher per capita income globally, is driving the increasing consumer demand for products derived from processes that address both ethical and ecological concerns. Similarly, producers are transforming production practices and replacing materials in pursuit of carbon neutrality, material recycling, sustainable and alternative resources, management of chemical-origin products, more sustainable production practices, and animal welfare. These conditions collectively promote the global expansion of PALF usage in various potential industries.

Limitations

In Colombia, the commercial use of pineapple leaves as a source of fibre faces significant constraints on both the supply and demand sides. In terms of supply, the diverse production crop systems in the country require standardized protocols for fibre mechanical extraction process adapted to local conditions. This situation leads to high transaction costs or highly variable product quality at the farm level, while the continuous provision of residual biomass is conditioned by the harvested area. Additionally, there is currently

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no organized scheme for the collection and storage of crop residues, and the high inland transport costs force to carry out fibre extraction close to the source of raw material in order to support economic viability even at small scale. In addition, there has been progress regarding the technical feasibility of transforming PALF into textile inputs or biocomposites but the commercial-scale capacity remains incipient, and for now there is very limited coordination among producers, processors, user industries and R&D centers. From a public policy perspective, although there are advances in supporting biorefinery initiatives, there are still no specific financing mechanisms for value chains based on agricultural residues, which increases the perception of risk and limits the entry of new actors, so that the potential of PALF in Colombia remains largely at the pilot-project stage and has not yet been consolidated commercially as a competitor to segments of the traditional natural or synthetic fibres.

On the demand side, the potential of PALF is constrained because the industries involved (textile, packaging, biocomposites) still regard it as an experimental input, with limited information on its technical performance, consistent availability and prices. This is compounded by the lack of technical standards and certifications related to quality, traceability and environmental attributes, which are key to promoting PALF in national and international markets.

Perspectives and Future Research

To advance towards the development of a PALF value chain in Colombia, it is necessary to expand its characterization for the various end uses, including blending strategies with other fibres, performance tests and life cycle studies compared with conventional materials. Likewise, it is necessary to move towards multidimensional assessments that integrate agronomic, technological, economic and environmental aspects, with the objective of moving from pilot experiences to scalable business models. In this regard, priority should be given to research aimed at quantifying the spatial and temporal availability of residual biomass under different production systems and the possibility to integrate cultivars present in the different regions of Colombia, as well as extraction, processing and logistics models that reduce costs and enable greater traceability and standardization of fibre quality. Similarly, the development of integrated biorefinery models could enable the simultaneous use of fibres, bioactive compounds and lignocellulosic biomass, thus maximizing the economic value of pineapple residues within circular bioeconomy frameworks. Finally, future lines of research should address governance and financing mechanisms for chains based on agricultural residues, the design of public policy instruments and technical standards that reduce perceived risk, as well as exploratory studies on consumer acceptance and the creation of national and international market niches for products that incorporate PALF wholly or partially.

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These efforts can contribute not only to reducing the environmental impact associated with agricultural residues, but also to generating new rural employment opportunities, promoting income diversification for farmers and supporting sustainable industrial development.

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