

Article

A Prospective Study of Bioeconomy-Based Strategies in the Corn Sector Using a 2035 Time Horizon and the Delphi Method, S-Curves and Patent–Publication Matrices

Catalina Gómez Hoyos ^{1,*}, Jhon Wilder Zartha Sossa ², Luis Horacio Botero Montoya ^{3,*},
Jorge Andrés Velásquez Cock ¹, Nicolás Montoya Escobar ¹ and Juan Carlos Botero Morales ⁴

¹ School of Engineering, Faculty of Engineering in Nanotechnology, Universidad Pontificia Bolivariana, Medellín 050031, Colombia; jorgeandres.velasquez@upb.edu.co (J.A.V.C.); nicolas.montoya@upb.edu.co (N.M.E.)

² School of Engineering, Faculty of Agroindustrial Engineering, Universidad Pontificia Bolivariana, Medellín 050031, Colombia; jhon.zartha@upb.edu.co

³ School of Economics, Administration and Business, Faculty of Business Administration, Universidad Pontificia Bolivariana, Medellín 050031, Colombia

⁴ School of Economics, Administration and Business, Faculty of Economy, Universidad Pontificia Bolivariana, Medellín 050031, Colombia

* Correspondence: catalina.gomezh@upb.edu.co (C.G.H.); luishoracio.botero@upb.edu.co (L.H.B.M.)

Abstract

This article presents a prospective analysis of the corn agro-industrial chain in Colombia up until 2035, using a mixed-methods approach that integrates technological surveillance, two rounds of the Delphi method, S-curve analysis, and patent–publication matrices and quadrants. Text-mining analysis was conducted using VantagePoint® v15.1 software, enabling the generation of multiple analytical outputs, including cluster maps, co-occurrence networks, and relational matrices. The study examines the dynamics of scientific and technological production related to the utilization of corn by-products and residues over the period 2003–2025. A total of 30 Delphi responses were collected from experts representing academia, industry, and government institutions in Argentina, Ecuador, Portugal, and Colombia. Based on expert consensus, the Delphi process identified 23 priority topics and 40 additional topics for discussion. Six priority themes were highlighted: (i) antioxidant and antimicrobial packaging derived from bioactive compounds extracted from corn by-products; (ii) bioethanol production; (iii) biodegradable straw manufactured from basket fibers; (iv) bioactive extracts for application in anti-aging cosmetic formulations; (v) modified biochar for the adsorption of ammonium and phosphate ions from aqueous systems; and (vi) the use of corn stover to enhance soil nitrogen content and grain yield. Finally, patent-based S-curve analysis and patent–publication matrices revealed notable asymmetries between scientific knowledge production and patenting activity, underscoring structural gaps in the translation of research into technological innovation within the corn agro-industrial sector.

Keywords: prospective analysis; Delphi method; S-curve analysis; patent–publication matrix; technological surveillance; corn; bioeconomy

Academic Editor: Teodor Rusu

Received: 9 December 2025

Revised: 31 January 2026

Accepted: 3 February 2026

Published: 5 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The transition toward sustainable agro-industrial systems requires robust methodological instruments that integrate scientific analysis, technological intelligence, and expert consensus. In this context, the present study applies a mixed-methods foresight approach to anticipate innovation pathways and sustainability scenarios in the Latin American corn agro-industrial chain until 2035. To address this objective, a systematic review of articles published in specialized journals was conducted as part of a technological surveillance process, and the Delphi method (DM) was applied to achieve expert consensus on technological priorities under conditions of uncertainty [1]. Complementarily, patent-based S-curve analysis was employed to identify technology maturation stages and potential windows of disruption [2], while the patent–publication matrix enabled the detection of imbalances between scientific knowledge generation and technological appropriation [3,4]. In parallel, a bioeconomy-oriented perspective was adopted to frame strategies for biomass and waste valorization, fostering sustainability and value creation within the agro-industrial system [5].

This research focuses on the corn agro-industrial value chain, one of the most extensively cultivated and consumed cereal systems worldwide, with particular emphasis on by-products derived directly from the plant—collectively referred to as corn stover and comprising stalks, leaves, husks, cobs, and silks—rather than residues generated during downstream industrial processing. In the 2024/25 agricultural cycle, global cereal production approached 2.9 billion tons, with corn accounting for approximately 40% of total output, positioning it as the world’s leading cereal crop by production share. Corn plays a central role not only in human nutrition but also as a key input for livestock feed, biofuel production, and a wide range of industrial applications. Global corn utilization in the 2025/26 cycle is projected to exceed 2.9 billion tons, reflecting sustained growth in both feed use and direct human consumption, driven by population growth and evolving dietary patterns [6].

From an international trade perspective, corn represents a strategic commodity in global markets. In 2024, the United States led global corn exports with an estimated export value of USD 14.3 billion, followed by Brazil with approximately USD 8.2 billion and Argentina with around USD 6.6 billion, together accounting for a substantial share of total global exports. In terms of shipment volume, the United States exported approximately 62.6 million tons (31.4% of global exports), Brazil 39.8 million tons (20%), and Argentina 32.1 million tons (16.1%), highlighting their critical roles in global supply chains. These patterns underscore the economic, agricultural, and geopolitical relevance of corn as a staple crop, making it a focal point for studies on production systems, market integration, and food security dynamics [7].

Despite its global importance, the corn sector faces significant challenges arising from climate change, environmental degradation, and increasing pressures from international markets [8]. Adaptation to drought, pest outbreaks, and resource constraints requires integrated innovation, governance, and technological strategies. Additionally, the increasing cultivation of corn has led to a growing volume of corn stover, which represents approximately 0.65 of the total plant biomass on a dry weight basis. The management and valorization of these underutilized by-products pose both a challenge and an opportunity for sustainable development. By transforming corn stover within a circular bioeconomy framework, this research directly contributes to Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) through waste reduction and resource efficiency, and to SDG 9 (Industry, Innovation, and Infrastructure) by promoting value-added agro-industrial chains. Moreover, improvements in crop resilience and yield stability support SDG 2 (Zero Hunger) by strengthening food security.

Accordingly, the integrated analysis of the corn agro-industrial chain through the combined application of technological surveillance, foresight methods, and expert consultation—within a bioeconomy-based perspective and a 2035 time horizon—enables the identification of strategic windows of opportunity for the development of resilient, competitive, and sustainable agro-industrial systems. These insights are aligned with the United Nations Sustainable Development Goals [9] and respond to evolving global consumer demands and sustainability expectations [10].

2. Theoretical Framework

2.1. The Corn Marking

Corn, together with wheat and rice, ranks among the most important staple grains worldwide. Globally, approximately 208 million hectares are devoted to corn cultivation, with major production areas located in sub-Saharan Africa, Asia, and Latin America. The largest shares of cultivated area are concentrated in the Americas and Asia, each accounting for more than one-third of total global corn acreage, followed by Africa and Europe, which contribute approximately 20% and 10%, respectively.

In terms of production, the United States and China dominate global corn output, with annual production volumes of approximately 361 million tons and 259 million tons, respectively. Combined, these two countries accounted for more than half of global corn production (54.5%) in 2019. Corn exhibits greater versatility in these economies compared to many other crops, largely due to its broad range of applications, particularly its strategic role in bioenergy production. In Latin America, Brazil and Argentina are the leading producers, with outputs of approximately 110 million tons and 57 million tons, respectively. By contrast, corn production in Colombia remains comparatively low; in 2019, the country ranked 57th out of 168 producing nations, with a total production of 1.4 million tons. This positioning reflects both a production gap and structural challenges in consolidating corn as a strategic crop at the national level [11–19].

From a consumption perspective, corn's relevance becomes even more pronounced. Global consumption reached approximately 1387 million tons, with the United States, China, and Brazil as the largest consumers, at 298, 283, and 66 million tons, respectively. In this context, Colombia ranks 23rd among 168 countries, underscoring the importance of corn within its national food and production systems. With respect to international trade, global corn imports amounted to USD 52,403.4 million in 2024. Mexico emerged as the leading importer (USD 5392.1 million), followed by Japan (USD 3941.7 million), China (USD 3785.8 million), and Vietnam, South Korea, and Spain, each with imports of approximately USD 2000 million. Colombia is also a significant importer, ranking ninth globally with imports valued at USD 1579.1 million. Import dynamics in Latin America are particularly notable: while the global corn import growth rate is close to 3%, Colombia's imports have increased at an annual rate of approximately 13%. Similarly, Colombia, Mexico, and Peru exhibit declining supply indices, increasing their dependence on international markets to satisfy domestic demand [18–20].

In response to this dependency, several government initiatives have been implemented to strengthen the corn production chain. In Colombia, the Corn Chain Productive Management Plan seeks to consolidate regions with high productive potential and specialization, improve yields, and increase the share of domestic consumption supplied by nationally produced raw materials. The plan also emphasizes productivity gains through improvements in cultivated area, yield performance, and production indicators, alongside reductions and optimizations of unit costs. Collectively, these measures are intended to enhance producer income and improve the competitiveness of the entire value chain [18].

Strengthening the corn production chain will inevitably lead to an increase in the generation of agricultural residues and by-products during cultivation and harvesting,

underscoring the need for efficient resource use within a sustainable economic framework. Consequently, corn agricultural by-products must be processed in ways that minimize environmental impacts while enabling their valorization as sources of proteins, carbohydrates, dietary fiber, and nutrients for human consumption, as well as for value-added applications in food, agriculture, and biotechnology sectors [21,22]. The utilization of corn by-products reinforces the integration of circular bioeconomy principles within the production chain, facilitating a transition from linear production models toward integrated systems in which agro-industrial residues are reincorporated as inputs for bioproducts and functional compounds.

In conventional terminology, corn by-products typically refer to materials generated during industrial processing, such as starch or oil extraction. However, the by-products considered in this study are those obtained directly from the corn plant—namely husks, cobs, stalks, silks, and leaves—collectively referred to as corn stover. These are distinct from industrial by-products such as corn gluten meal, corn steep liquor, dried distillers grains with solubles (DDGS), or condensed distillers solubles. At the local level, corn stover is primarily used for animal feed or is incinerated by farmers; nevertheless, these materials are rich in bioactive compounds and fibers, offering significant potential for value-added applications in food, agriculture, and biotechnology, particularly within sustainability-oriented and circular economy frameworks [21].

To address this challenge, a range of technologies has been promoted to reduce corn residues and enhance their value through transformation into dietary fibers, bioactive compounds, functional foods, or microbial enzymes that support biofuel production. Advanced extraction and fractionation techniques, such as microwave-assisted extraction (MAE) and ultrasound-assisted extraction (UAE), have been widely applied to recover high-value biomolecules with improved yields and reduced energy consumption. These physical methods enhance mass transfer and disrupt cell walls more efficiently than conventional techniques while minimizing solvent use and processing time [20,21].

Despite the availability of diverse processing technologies and the well-documented presence of valuable biomolecules in corn stover, there remains limited strategic clarity regarding the most appropriate end-use applications for these materials. In this context, the Delphi survey results presented in this study aim to identify priority applications for corn by-products and to inform decision-making within corn chain management plans. By doing so, the study seeks to address the lack of specificity that often characterizes existing public policies and development strategies in this domain [23–25].

2.2. The Corn Market in Colombia

In Colombia, official data indicate that national corn production has experienced sustained growth in recent years. In 2018, total production reached 1.33 million tons, increasing to an estimated 1.6 million tons in 2024, according to USDA reports. Nevertheless, exports remain marginal. In 2019, exports of cornmeal amounted to 31,857 tons, equivalent to USD 26.6 million, while in 2023 total corn exports were valued at only USD 2.41 million, as reported in [8]. These figures reflect a strong dependence on the domestic market and highlight the need to develop higher value-added niches within a bioeconomy framework.

Figure 1 illustrates corn production trends in Colombia for the period 2018–2024, while Figure 2 presents the value of corn exports. Figure 3 shows corn yield performance (tons per hectare) since 2015, with projections to the 2025/26 cycle. Table 1 summarizes key indicators related to corn production, supply, and distribution in Colombia [24].

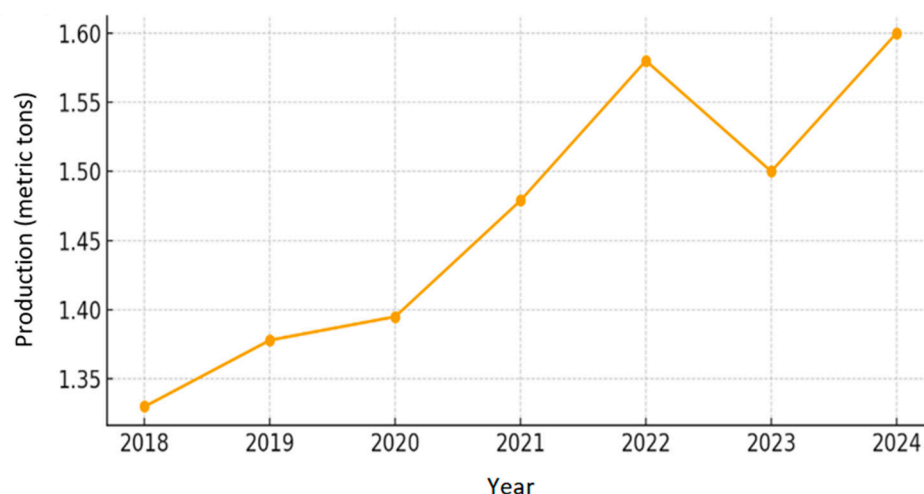


Figure 1. Corn production in Colombia, 2018–2024. Source: [24].

Figure 1 illustrates the evolution of total corn production in Colombia over the period 2018–2024, highlighting year-to-year variations in output levels and revealing underlying trends of expansion, contraction, or relative stability. Fluctuations in production may be associated with multiple factors, including climatic variability, changes in cultivated area, access to agricultural inputs, price incentives, and the adoption of improved technologies. These dynamics are particularly relevant for assessing the capacity of the national production system to meet domestic demand and for evaluating the extent to which Colombia depends on imports or, alternatively, is able to generate production surpluses for export.

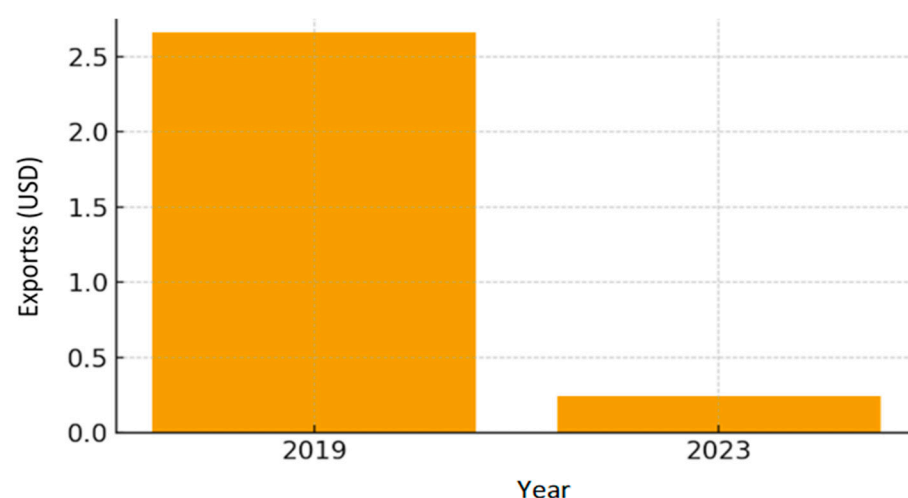


Figure 2. Value of corn exports in Colombia. Source: [24].

Figure 2 depicts the evolution of the monetary value of Colombia's corn exports over the study period, highlighting the economic significance of corn within the national trade structure. This figure facilitates an assessment of the sensitivity of export revenues to fluctuations in international prices and traded volumes. Comparing trends in export value with production levels provides insights into whether variations in export revenues are primarily driven by changes in domestic production, shifts in global market conditions, or exchange-rate movements. Consequently, the figure supports a more nuanced analysis of the relationship between agricultural performance and trade outcomes in the Colombian corn sector.

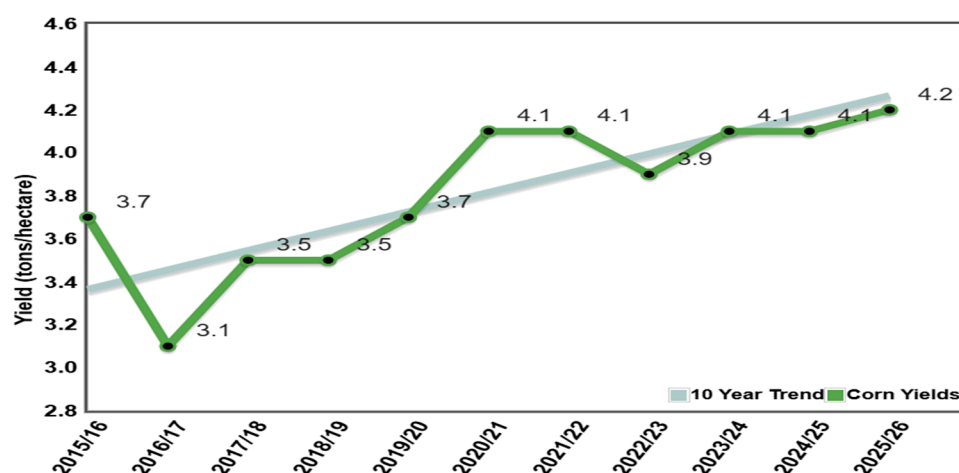


Figure 3. Yield ton/hectare of corn in Colombia, 2015–2025/26. Source: [24].

Figure 3 illustrates the historical trends and projected trajectory of average corn yields in Colombia, expressed in tons per hectare, from 2015 through 2025/26. Unlike total production figures, yield indicators isolate the effects of technological efficiency and agronomic management from variations in cultivated area. Rising yield trends suggest improvements in seed quality, fertilization practices, irrigation, mechanization, or extension services, whereas stagnating or declining yields may indicate constraints related to climate variability, soil degradation, or limited adoption of technology. The inclusion of projections provides a foundation for analyzing potential future productivity scenarios and the feasibility of expanding domestic supply without increasing land use.

Table 1. Production, supply and distribution of corn in Colombia.

Market Year	Area (1000 Ha)	Production (1000 Tons)	Yield (T/Ha)
2015/2016	401	1471	3.67
2016/2017	421	1295	3.08
2017/2018	380	1330	3.50
2018/2019	394	1378	3.50
2019/2020	373	1395	3.74
2020/2021	364	1479	4.06
2021/2022	390	1580	4.05
2022/2023	380	1500	3.95
2023/2024	390	1600	4.10
2024/2025	370	1500	4.05
2025/2026	370	1550	4.19
5-year Average 2020/21–2024/25	379	1532	4.04
Percent Change From 5 Year Average (%)	–2	1	4
Record	421	1600	4.10
Record Year	2016/2017	2023/2024	2023/2024

Source: [24].

This table summarizes key indicators of corn production, cultivated area, and yield in Colombia from 2015 to 2025/26. Over the period, fluctuations in cultivated area and yields reflect changes in agronomic practices, technology adoption, and environmental conditions. The five-year average from 2020/21 to 2024/25 highlights the stabilization of production around 1.53 million tons, with yield improvements of approximately 4% relative to this average. Record values for area, production, and yield are also noted,

providing benchmarks for evaluating trends and potential productivity gains within the national corn sector.

Table 1 summarizes the principal quantitative components of the corn supply–demand balance in Colombia, including national production, imports, exports, total supply, domestic consumption (both for human and industrial/feed use), and stocks or inventories. This information enables a rigorous assessment of the sector’s self-sufficiency, the magnitude of dependence on international markets, and the internal demand structure. Consequently, the table serves as a key analytical tool for discussions related to food security, market organization, pricing policies, and the strategic planning of agricultural production systems.

2.3. Bioeconomy and the SDGs

In the context of corn stover management, the bioeconomy has emerged as a central paradigm for aligning economic development with environmental sustainability and social inclusion, positioning biological resources, processes, and innovations at the core of production systems. By promoting the efficient and circular use of biomass, biotechnologies, and ecosystem services, the bioeconomy provides systemic solutions to global challenges, including climate change, biodiversity loss, food insecurity, and resource scarcity.

The contribution of the bioeconomy to the Sustainable Development Goals is particularly notable in SDG 2 (Zero Hunger), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Through sustainable agricultural practices, bio-based value chains, and nature-based solutions, the bioeconomy enhances food security, fosters inclusive industrialization, and minimizes environmental footprints across production systems. Moreover, bio-based innovations support climate mitigation and adaptation by promoting low-carbon technologies, renewable biological resources, and ecosystem restoration.

From a socio-economic perspective, the bioeconomy contributes to SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities) by generating employment opportunities, particularly in rural and resource-dependent regions. The development of bio-based industries stimulates local economies, increases value addition in primary sectors, and fosters territorial cohesion [25,26]. When underpinned by inclusive governance frameworks, capacity-building initiatives, and equitable benefit-sharing mechanisms, the bioeconomy can strengthen socio-economic resilience and justice.

Additionally, the bioeconomy is intrinsically linked to SDG 14 (Life Below Water) and SDG 15 (Life on Land) through its emphasis on sustainable ecosystem management, biodiversity conservation, and the restoration of degraded landscapes and marine environments. By integrating ecological principles into production systems, the bioeconomy advances the transition from extractive to regenerative models of development, supporting planetary boundaries while maintaining economic viability [27,28].

2.4. Circular Economy and Value Chain for the Corn Agro-Industry in Colombia

The circular economy complements the bioeconomy by emphasizing resource efficiency, waste reduction, and the reintegration of biological by-products into productive cycles. In Colombian agro-food and agro-industrial systems, circular economy principles have been applied to optimize biomass flows, enhance residue valorization, and promote sustainable management practices. For example, transdisciplinary research on cacao value chains demonstrates how circular strategies—such as composting and resource recycling—improve system efficiency and reduce environmental impacts. These practices foster closed-loop systems, in which waste streams become inputs for new products, thereby enhancing overall sustainability within value chains [13].

Value chain theory provides the structural framework to analyze how value is created, distributed, and upgraded across actors and stages within Colombian agro-industrial systems. In the context of bioeconomy and circular economy approaches, value chain analysis yields critical insights into governance mechanisms, coordination structures, market linkages, and opportunities for upgrading. Colombian research on bioeconomy and regional development has employed input–output analyses to map sectoral linkages, demonstrating how bio-based industrial activities contribute to the broader economy while interacting with upstream and downstream nodes of the production system. This theoretical lens facilitates the identification of technological opportunities and governance challenges, guiding the transition of corn and other bio-based products toward sustainable and competitive value chains [28].

3. Materials and Methods

3.1. Technological Surveillance

A systematic literature review was conducted to identify emerging themes, innovations, applications, and trends in the utilization of corn by-products. The search strategy in the Scopus database used the following query:

(TITLE-ABS-KEY ((corn OR maize) AND byproducts) AND TITLE-ABS-KEY ((cob OR husk OR leaves OR silk)) AND ALL (food AND application))

The search encompassed the last 20 years. In addition, patent databases, including Espacenet and The Lens, were consulted to capture technological developments beyond academic publications. Identified articles and patents were organized into thematic affinity groups, generating clusters that informed the prioritization of technological opportunities in the subsequent Delphi rounds.

3.2. Delphi Method

3.2.1. First Round

The first round of the Delphi study was structured based on the themes and sub-themes identified through technological surveillance. A structured questionnaire was distributed to selected experts, who were asked to evaluate and prioritize each topic with a foresight horizon of 2035. A Likert scale from 0 to 5 was employed, where 0 represented the lowest priority and 5 the highest. Respondents were also given the options “I don’t know” (NS) and “No answer” (NA) to account for cases where they lacked sufficient information on a specific topic.

3.2.2. Expert Profile

Participants in the Delphi process were required to meet the following criteria:

- Possession of an advanced academic degree in disciplines such as Agronomy, Economics, or Bioeconomy.
- Professional experience within the corn value chain, agricultural policy, or related research fields.
- Peer-reviewed publications or leadership of technical projects related to agricultural foresight, circular economy, or bioeconomy.
- Strategic decision-making positions in government agencies, academic institutions, or private-sector organizations.

For the first round, 31 experts from Argentina, Ecuador, Portugal, and Colombia were invited, with 30 valid responses obtained. Participants represented diverse sectors associated with the corn value chain, including agro-industrial companies, universities, and governmental organizations.

3.2.3. Structured and Anonymous Consultations

The Delphi consultations were structured, anonymous, and iterative, allowing experts to provide informed judgments on bioeconomy-based strategies for the corn sector by 2035. The questionnaire aimed to prioritize topics within each thematic cluster derived from technological surveillance. Responses from 30 valid participants were analyzed statistically, while the collective results were presented schematically to inform the second round of consensus-building.

Tables 2 and 3 summarize the participating institutions and countries of origin of the experts involved in the Delphi process, illustrating the diversity and representativeness of the panel.

Structured, anonymous, and iterative consultations were conducted with national and international experts to evaluate bioeconomy-based strategies in the corn sector, with a foresight horizon to 2035. The questionnaire was designed to prioritize a set of topics corresponding to each thematic cluster identified through technological surveillance. Of the 31 experts invited, 30 valid responses were received and included in the statistical analysis.

Table 2 presents the participating institutions, representing a diverse set of organizations from four countries (see Table 3 for detailed affiliations). This first Delphi round was exploratory and not conclusive; therefore, the results are presented schematically to inform the second round of expert consensus, ensuring iterative refinement and validation of priority topics.

Table 2. Participating institutions.

Pontifical Bolivarian University
National Open and Distance University
University of Cartagena
Polytechnic Institute of Bragança
Salesian Polytechnic University
Center for Agroindustrial Technological Development, Technological University of Pereira
Luis Amigó Catholic University
IPF S.A.S
CIDCA (UNLP-CONICET) Argentina
Azimuth Energy/Concrete
Agritech Seeds SAS
SENA—Quindío Agroindustrial Center

Source: own elaboration (2025).

3.3. Definition of Priority Groups

Priority topics were defined based on the percentage of expert consensus per topic and the average consensus per thematic cluster (grouper). A topic was considered a priority if it met both of the following criteria:

1. Its consensus percentage exceeded the average for its respective cluster.
2. It had a modal rating value ≥ 4 , where the modal value represents the most frequently selected score among the experts.

Conversely, topics with a modal rating ≤ 2 , even if their consensus percentage exceeded the cluster average, were classified as non-priority. All other topics that did not satisfy either of these criteria were designated as topics under discussion to be reconsidered in subsequent Delphi rounds.

This approach ensured that prioritization reflected both agreement among experts and the perceived importance of each topic, providing a robust foundation for strategy development in the corn bioeconomy sector.

3.4. S-Curves

The results from technological surveillance were mapped onto S-curves, a graphical model that describes the adoption, growth, and maturation of a technology, product, or process. In prospective studies, S-curves are particularly valuable for:

- Identifying the current life-cycle stage of a technology.
- Anticipating technological transitions before existing solutions reach saturation.
- Highlighting potential windows for innovation and disruption.

In the context of the corn agro-industrial chain, S-curves facilitate the visualization of the evolution of agricultural practices, biotechnologies, transformation processes, and bioeconomy applications, including biofuels, bioplastics, and bioinputs. By mapping these technologies onto S-curves, stakeholders can identify opportunities for strategic intervention, optimize research and development priorities, and align investment with emerging market and sustainability trends.

Figure 4 illustrates the S-curve methodology across different phases of technological development, including introduction, growth, maturity, and saturation.

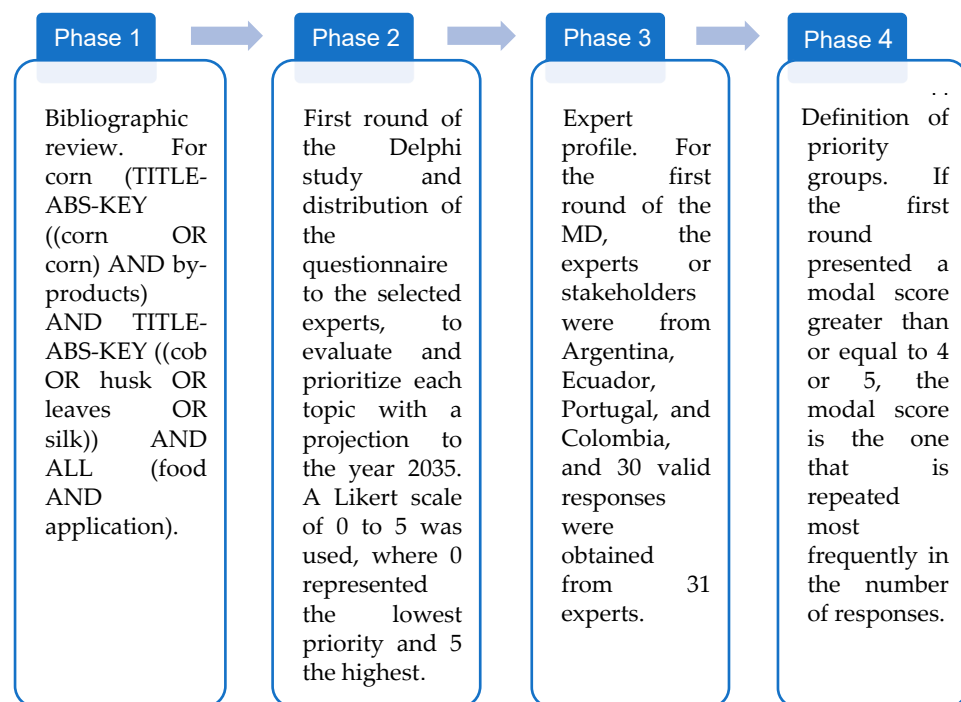


Figure 4. Phases of the methodology. Source: own elaboration (2025).

4. Results

4.1. Results of Technological Surveillance Analysis

In recent years, research on the utilization of corn by-products has exhibited consistent growth, reflecting increasing interest in sustainable valorization pathways. The literature can be categorized into distinct sectors, with food applications accounting for the largest share of publications, followed by materials, and then medicine and biology, among others. Each sector corresponds to specific applications of corn by-products, highlighting the diverse potential of these residues across industrial, agricultural, and biotechnological domains. Figure 5 illustrates the distribution of publications by sector, providing a clear overview of current research trends and thematic concentrations.

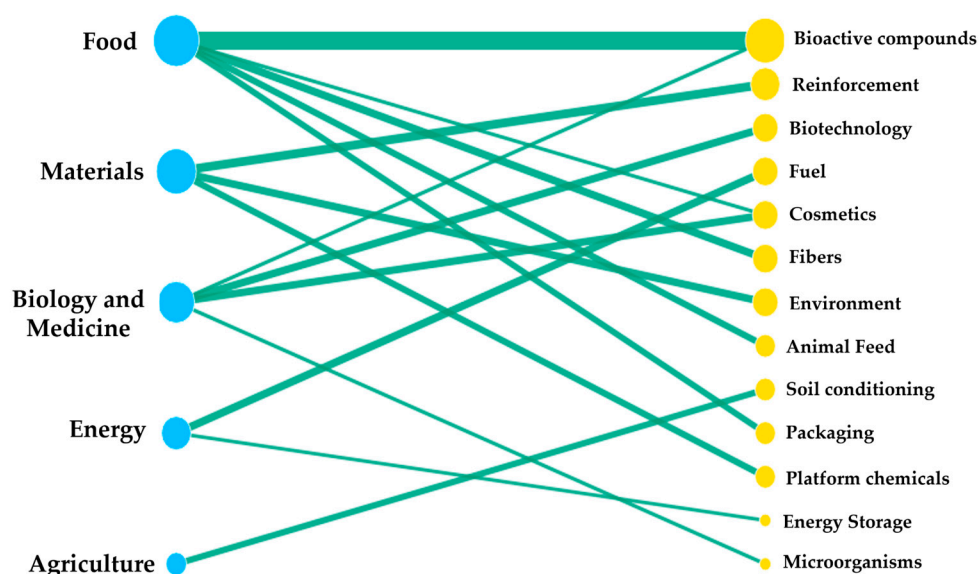


Figure 5. Industry-specific applications for the targeted items. Source: own elaboration (2025), based on Vantage point software v15.1.

Each application can be directly associated with specific corn by-products (Figure 6). The cob, husk, stalk, and leaves share numerous applications across sectors, whereas silk is more specialized, with applications largely overlapping only with the cob. Within these applications, several studies have focused on the optimization of bioactive compound recovery. For instance, the effects of two solvent extraction methods—solid–liquid extraction and hot water extraction—on the recovery of phenolic compounds from corn residues were evaluated to maximize total phenolic content (TPC). Methanol (50%) was identified as the most effective solvent for extracting phenolic compounds with the highest DPPH antioxidant activity, underscoring the potential use of these compounds in cosmetics and functional foods [22].

In the food sector, research has also explored the recovery of high-value intermediates, such as xylitol, which can serve as a sugar substitute or as a precursor for various chemical products. Corn biomass residues, including stalks, husks, and cobs, have demonstrated promising potential as feedstocks for xylitol production [26].

Beyond food applications, corn by-products have been investigated for energy storage, soil conditioning, reinforcement materials, microbial production, and biofuel generation [26,27,29–31]. Specifically, innovative applications in energy storage technologies have gained attention, including the use of corn stalks for lithium-ion battery anodes, the synthesis of porous electrodes for supercapacitors, and the development of battery binders derived from corn cobs [27,31–33]. These studies highlight the versatility of corn residues as functional and value-added materials, contributing to the circular bioeconomy and sustainable technology development.

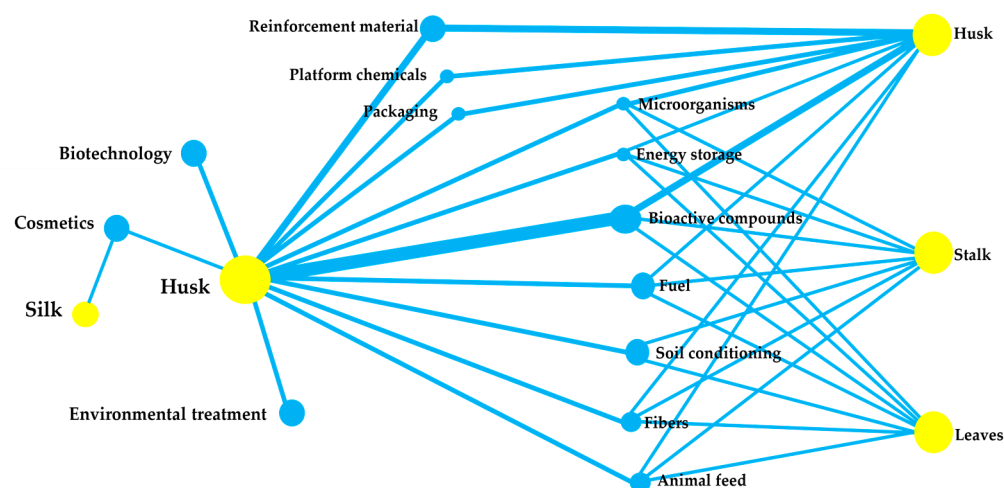


Figure 6. Applications by by-product. Source: own elaboration (2025), based on VantagePoint® v15.1 software.

Fuel production represents another sector with high potential for corn by-products. At an industrial level, these residues have been implemented as substrates for dark fermentation (DF), where microbial consortia or specific microorganisms produce hydrogen (H_2) that can subsequently be converted into energy or electricity. Additionally, corn by-products can undergo pyrolysis pre-treatment to release fermentable glucose, which is essential for bioethanol production. Certain microorganisms, such as *Thermoanaerobacterium saccharolyticum* HG8 and *Clostridium acetobutylicum*, are capable of fermenting glucose and xylose present in these residues, producing ethanol and butanol, respectively [30,34–36].

These findings indicate a growing trend in the valorization of corn by-products, aiming to strengthen the production chain while reducing the environmental impact of agro-industrial activities. Technological surveillance shows that applications in the food sector dominate, leveraging the bioactive compounds in agro-industrial waste. However, other sectors, particularly energy and advanced materials, are rapidly innovating, utilizing corn stover for fuel production or as fibers for reinforcement in composite materials.

Despite these advances, most applications remain at the laboratory or pilot scale, and commercial implementation is still limited. Furthermore, national agricultural plans often fail to integrate corn stover into bio-based economy strategies. For example, in Colombia, the Corn Chain Productive Management Plan does not explicitly provide structured pathways for the management or valorization of corn residues [18]. This gap hampers the adoption of corn stover for agro-industrial or environmental applications, indicating that technical and economic barriers must still be overcome before large-scale commercialization can be realized [37].

4.2. Results of the First Delphi Round for Corn

Following the statistical analyses conducted in accordance with the Delphi method (DM), 23 priority themes were identified, with no non-priority issues and 40 topics under discussion. Five comments provided by the experts were consolidated and incorporated into the second-round Delphi questionnaire. Figure 7 presents the word cloud and the graphs generated using Python (version 3.12.12) and the Natural Language Toolkit (NLTK) version 3.9.1 for natural language processing.

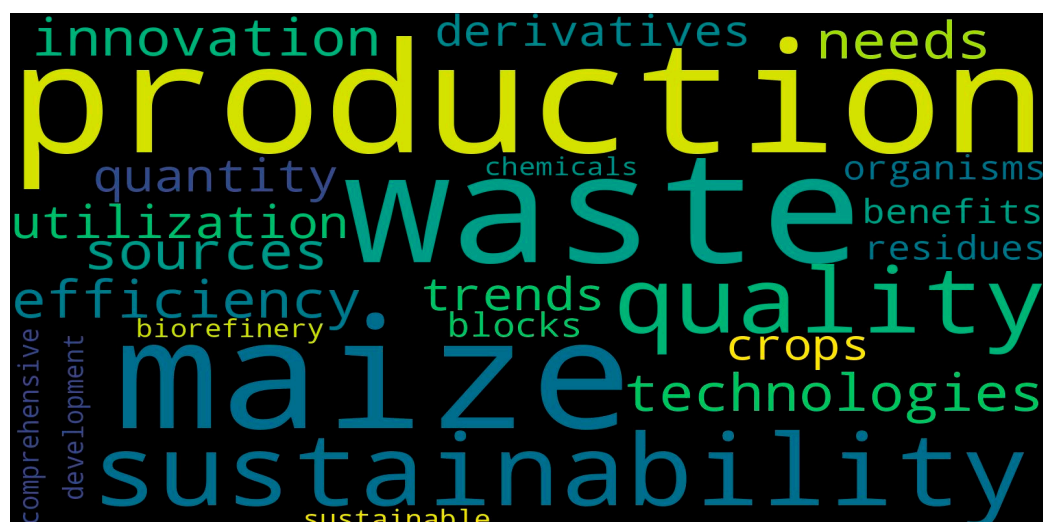


Figure 7. Word Cloud. Source: prepared by Wordcloud library—Python.

The results of the first Delphi round by grouper are presented below:

Table 3. Results DM.

Corn By-Products Have Been Widely Used as Functional Ingredients Due to Their Bioactive Compound Content. Prioritize the Functional Ingredient Uses Below:	First Round Decision Delphi	Second Round Decision Delphi
Xylooligosaccharides with prebiotic effects that stimulate the growth of several probiotic strains	Discussion	Priority
Xylitol extracted and used as a sugar substitute in beverages	Discussion	Priority
Food Fortification of Anthocyanins Extracted from Purple Corn	Priority	Discussion
Foods rich in polyphenols extracted from corn	Priority	Discussion
The meal from the by-products of corn is used in animal feed for different species, shown below. Prioritize the applications for use in this sector:		
Nutrition of worms that will be used as a source of protein	Discussion	Priority
Dairy cow and sheep nutrition for the promotion of gut development	Discussion	Priority
Nutrition for pig farming and appetite stimulation	Priority	Discussion
Nutrition of laying hens	Priority	Discussion
Nutrition in geese for the reduction in the proportion of <i>Escherichia coli</i> in the intestine	Discussion	Discussion
The by-products of corn have been used for fiber extraction. Prioritize your different uses for this activity:		
Lignin extraction	Discussion	Priority
Obtaining microcrystalline cellulose	Discussion	Priority
Obtaining cellulose fibres	Discussion	Priority
Obtaining cellulose nanowhiskers	Priority	Discussion
Nanometric dietary fiber powder	Discussion	Priority
Prioritize corn by-product applications in packaging or food contact material		
Packaging with antioxidant and antimicrobial activity thanks to bioactive compounds extracted from by-products	Discussion	Priority
Use of its extracts as a reinforcer in food barrier films	Priority	Discussion
Straws (straw) biodegradable using basket fibers	Priority	Priority
In bakery products, flour from corn by-products has been used in the applications shown below. Prioritize each of them.		
Use of flour to generate products with a satiating effect	Priority	Priority
Fiber enrichment and nutritional value of muffins	Priority	Discussion

Using Flour for Fat Reduction in Feed Formulation	Priority	Priority
Increased ferulic acid content in the product	Discussion	Priority
Prioritize cosmetic applications of corn by-products, where their bioactive compounds and extracts have been harnessed.		
Extracts with application in lightening creams through tyrosinase inhibition	Discussion	Discussion
Use of Extracted Xylitol as a Natural Moisturizer	Priority	Discussion
Formulation in facial creams for their inhibitory effect with the bacterium <i>S. epidermidis</i>	Discussion	Priority
Extracts with application for anti-aging creams	Discussion	Priority
Prioritize applications of corn by-products in obtaining enzymes, fungi, and microorganisms		
Obtaining the fungus <i>Rhizopus oryzae</i> for use in the production of lactic acid	Discussion	Priority
Obtaining Endoglucanase β -glucosidase (used in the biosynthesis of oligosaccharides) through solid-state fermentation	Priority	Discussion
Obtaining Cellulase and Xylanase with the bacterium <i>Phanerochate chrysosporium</i>	Discussion	Discussion
Prioritize applications of corn by-products used as substrate for the growth of microorganisms and fungi		
Immobilization of enzymes (lipase, peroxidase, trypsin, amylase)	Discussion	Priority
Substrate for the preparation of heat and acid-resistant glucose oxidase by solid-state fermentation	Discussion	Priority
Substrate for the fermentation of the bacterium <i>Bacillus subtilis</i> , whose action is the stability of the intestinal microbiota	Discussion	Priority
Using Flours from By-Products as a Mushroom Culture Medium Assistant	Priority	Discussion
Substrate for the growth of the fungus <i>Beauveria bassiana</i> for pest control	Discussion	Priority
Prioritize applications of corn flour and by-product extracts in the area of biotechnology		
Xylan extracted and modified with gallic acid with therapeutic use for oxidative stress	Discussion	Discussion
Inhibition against <i>C. acnes</i> and <i>S. epidermidis</i> bacteria	Discussion	Priority
Prioritize corn by-product applications in water treatment		
Biochar Modified for Adsorption of Ammonium and Phosphate Ions from Water	Discussion	Priority
Corn cob-based adsorbent for textile wastewater treatment	P Priority	Discussion
From corn by-products it is possible to obtain products used at an industrial level such as those shown below. Prioritize each of these material production applications.		
Production of furfural from corn cob	Discussion	Priority
Production of formic acid from corn sheath	Discussion	Discussion
Production of Succinic Acid from Corn stover	Discussion	Priority
Obtaining fumaric acid from corn stover	Discussion	Discussion
Levulinic acid production	Discussion	Priority
Production of polymalic acid using corn slings	Discussion	Discussion
Production of dihydrous alcohol and low molecular weight polyalcohol from corn basket	Priority	Discussion
The fibers of corn by-products, especially those of the basket, are used as a reinforcer in civil works materials. Prioritize the applications in this area shown below.		
Supplementary material for ordinary Portland cement (OPC) and geopolymers concrete	Discussion	Priority

Partial or total replacement of aggregate in concrete using cob ash	Priority	Discussion
Alternative aggregate material in concrete from corn cob ash	Priority	Discussion
Prioritize the use of corn by-products for soil conditioning applications		
Corn stover to increase nitrogen levels and grain yield	Discussion	Priority
Combining corn stover with phosphate fertilizers	Priority	Discussion
Prioritize Corn By-product Applications for Energy Storage in Batteries and Capacitors		
Nanosheets obtained from corn stover for use in lithium-ion battery anodes	Discussion	Priority
Cellulosic Stem Materials Used in Lithium Battery Anode	Priority	Discussion
Porous electrode for supercapacitors from corn stover	Discussion	Discussion
Binder in lithium-ion batteries, taking advantage of the corn cob	Discussion	Priority
Corn by-product protein as an electrocatalyst in redox flow batteries	Priority	Priority
The applications shown in this section correspond to applications of extracts of corn by-products for the treatment of plants. Give each of these a level of prioritization.		
Extracts for improving plant resistance to stress	Priority	Discussion
Extracts for the enhancement of the activity of defensive enzymes	Discussion	Discussion
Harnessing bioactive compounds to reduce the content of toxic substances in cells	Discussion	Priority
Corn silk extract that promotes nutrient accumulation	Discussion	Priority
Bioactive compounds to increase chlorophyll levels	Priority	Discussion
Corn stover is widely used to obtain biofuel. Prioritize the applications presented below this topic.		
Corn stover as a substrate for dark fermentation (FD) for the production of hydrogen (H ₂) and its subsequent conversion into energy or electricity	Priority	Discussion
Production of bioethanol by pre-pyrolysis corn stover to obtain fermentable glucose	Discussion	Priority
Production of ethanol from the fermentation of glucose and xylose by the bacterium <i>Thermoanaerobacterium saccharolyticum</i> HG8	Discussion	Priority
Butanol production by <i>Clostridium acetobutylicum</i>	Discussion	Discussion

Source: own elaboration (2025).

Table 3 presents the priority and discussion topics/technologies identified across the two Delphi rounds. The selection criteria for priority items were based primarily on their priority ratings in both rounds, as well as on topics that were under discussion in the first round but were classified as priority items in the second round. In a complementary analysis, and considering the highest consensus percentages, the top six topics/technologies with consensus levels exceeding 50% are listed below (Figure 8).

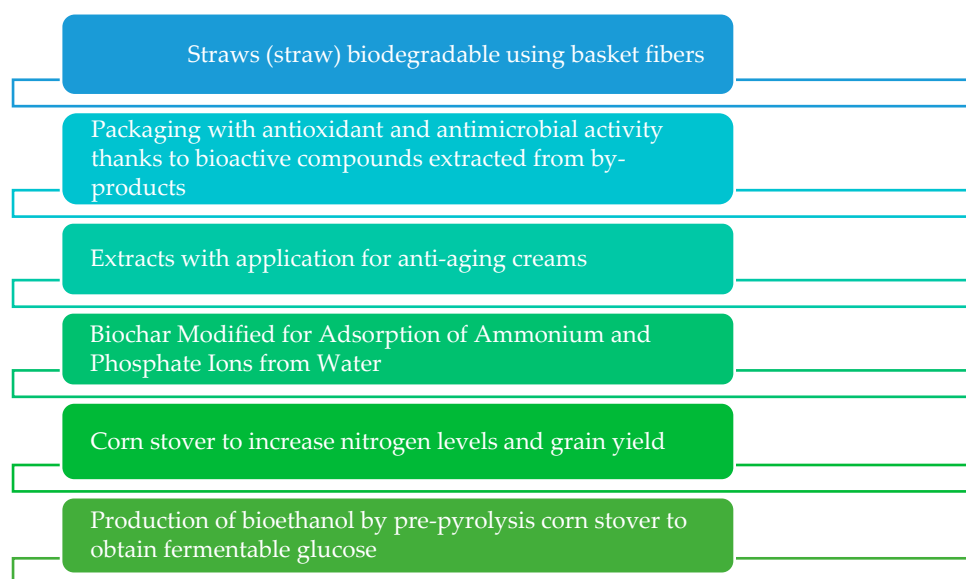


Figure 8. Top 6 priority topics/technologies according to a consensus percentage greater than or equal to 50%. Source: elaboration own (2025).

5. Discussion

5.1. Prospective to 2035

The prospective analysis to 2035 constitutes a key instrument for anticipating the behavior of the corn agro-industrial chain under scenarios of climate change, digital transformation, and transition toward circular production models. The results obtained through the Delphi method (DM) indicate a high level of consensus regarding the need to promote bioproducts, renewable energy, and bioinputs that reduce dependence on chemical inputs and contribute to the mitigation of greenhouse gas (GHG) emissions. According to [1], Delphi exercises enable the construction of innovation agendas under conditions of uncertainty by involving experts from different sectors and countries.

In this research, the prospective analysis to 2035 made it possible to identify high-impact scenarios for the corn value chain in Colombia, including the diversification of markets toward higher value-added products, the integration of biorefineries in producing regions, and the digitalization of traceability processes. These scenarios aim not only to increase the competitiveness of the value chain but also to strengthen its resilience to extreme events such as droughts and pests [8]. Likewise, the results suggest that by 2035, a circular economy model will be consolidated, in which corn by-products will find applications in biofuels, bioplastics, construction materials, and animal feed additives [35,38–42].

Prospective analysis also provides a tool to align the development objectives of the value chain with the Sustainable Development Goals (SDGs), which is consistent with the bioeconomy framework and value chain theory discussed in Sections 2.3 and 2.4. These frameworks offer a coherent conceptual basis for interpreting the 23 priority themes identified through the Delphi process, as they operationalize the bioeconomy by translating its sustainability objectives—food security, industrial innovation, responsible production, and climate action—into concrete technological and organizational pathways within the corn agro-industrial value chain. Specifically, the prioritization of functional ingredients, bio-based materials, bioenergy, biotechnology, water treatment, and soil conditioning applications reflects a systemic alignment with SDGs 2, 9, 12, and 13 while also reinforcing SDGs 8 and 15 through value addition, rural development, and ecosystem stewardship. Furthermore, the utilization of corn stover as a biofuel feedstock and its application in dark fermentation for hydrogen production, highlighted in the prospective analysis,

directly contribute to SDG 7 (Affordable and Clean Energy) [9]. This alignment enables the articulation of public policy, private investment, and scientific research around shared objectives, thereby maximizing the impact of innovative strategies.

From a circular economy and value chain perspective, the 23 prioritized applications represent strategic upgrading trajectories—including process, product, and functional upgrading—that enable the reintegration of corn by-products into higher-value uses across multiple industrial domains. This demonstrates that circularity is not merely a waste management strategy, but rather a governance and innovation mechanism that restructures value chains toward closed-loop and regenerative models. Consequently, the Delphi results empirically substantiate the theoretical connection between bioeconomy principles, circular economy logic, and value chain transformation, strengthening the discussion by illustrating how sustainability frameworks are translated into concrete, prioritized innovation pathways within the Colombian corn agro-industry.

5.2. Technology Surveillance

Technology Surveillance, understood as a systematic process of monitoring, analysis, and synthesis of scientific and technological information, enabled the identification of major trends in the use of corn by-products and in the development of new technologies. The bibliometric analysis of publications and patents conducted using databases such as Scopus, Espacenet, and The Lens revealed a sustained increase in scientific production in areas such as biorefineries, biopolymers, biogas, and wastewater treatment using bioadsorbents derived from corn cobs. This finding is consistent with previous work [3], which highlights the usefulness of patent studies for determining Technology Readiness Levels (TRLs) and guiding investments in R+D+i.

In this study, technology surveillance made it possible to prioritize highly relevant topics, such as bioethanol production from corn stover, the development of biodegradable packaging, and the extraction of bioactive compounds for the food and cosmetics industries. In addition, windows of opportunity were identified in emerging technologies, including nanocellulose and applications of corn fibers in the construction sector, which could scale toward technological maturity over the next decade and have been highlighted in multiple scientific studies [43–57].

The surveillance process also served as an input for structuring the Delphi questionnaires, facilitating the construction of informed and evidence-based consensus. This integrated approach ensures that technology prioritization decisions are not based solely on expert perception but are supported by global scientific and technological trends.

5.3. S-Curves and Matrix/Quadrants Patents—Papers

S-curves represent an analytical model that describes the life cycle of a technology, from its introduction to maturity and eventual obsolescence. In the present study, their application allowed the positioning of the technologies identified through technology surveillance within their respective stages of development. This information is critical for guiding innovation investments, as it supports decisions on when to scale emerging technologies, when to sustain those in maturity, and when to diversify into new alternatives prior to decline.

The search equation used for constructing S-curves for papers and patents was “(TITLE-ABS-KEY ((corn OR maize) AND byproducts) AND TITLE-ABS-KEY ((cob OR husk OR leaves OR silk)) AND ALL (food AND application)) AND PUBYEAR > 2003 AND PUBYEAR < 2025,” yielding accumulated time series of publications and patents. These results served as input for calculating technological inflection points through non-linear regression models using Python techniques (Figures 9 and 10).

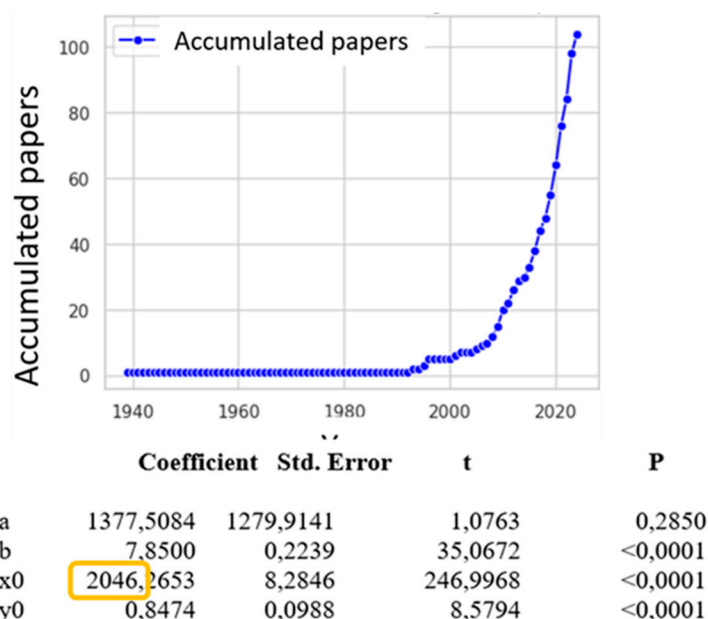


Figure 9. Paper inflection points. Source: elaboration own (2025). Yellow box corresponds to the inflection points. This observation is fulfilled in the name of Figure 9.

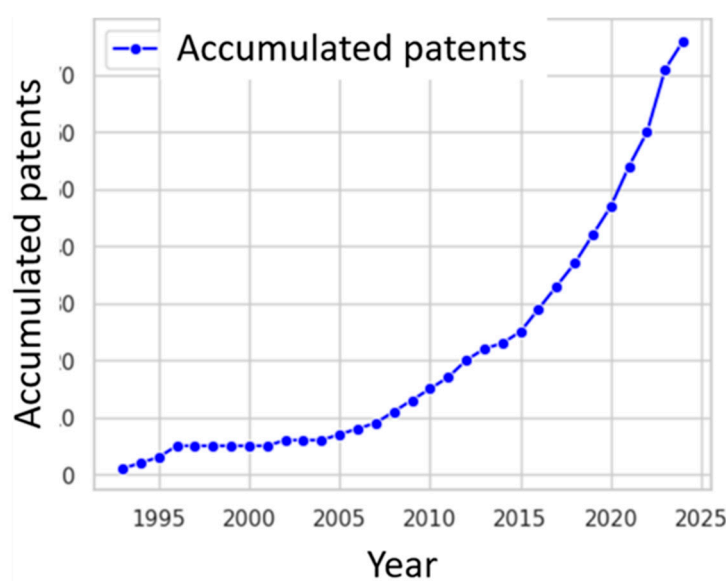


Figure 10. Patents inflection points. Source: elaboration own (2025). The yellow box shows the year of the turning point.

The inflection point years were validated using the T and *p* values, which must meet the following criteria: a T value greater than 2 or less than −2, and a *p* value lower than 0.005. In this case, the inflection points identified for papers and patents correspond to the years 2046 and 2120; however, the associated T and *p* values do not fall within the required thresholds. Therefore, although the estimated inflection points are located in the future, it cannot be established with statistical significance that these specific years represent the true inflection points of the analyzed trends.

The Durbin–Watson statistics obtained were substantially distant from the reference value of 2, indicating the presence of positive autocorrelation in the residuals. This behavior is inherent to bibliometric time series and is consistent with cumulative growth processes in scientific knowledge. In other words, the expansion of scientific production follows a structural and cumulative dynamic rather than a random one. Consequently, the presence of residual autocorrelation does not invalidate the model; instead, it confirms that scientific output evolves according to time-dependent patterns associated with processes of knowledge maturation and diffusion.

In addition, a complementary analysis was conducted through the application of the patent–paper matrix (quadrants) approach [58]. To determine the quadrant in which the topics and technologies of the corn agro-industrial chain are positioned—based on the critical monitoring factors defined in the search equation—the resulting patent–paper quadrant matrix was constructed as follows:

According to Figure 11, corn and its by-products—including cobs, husks, leaves, and silk—within the corn agro-industrial chain are positioned in the upper-right quadrant. This quadrant has the following interpretation and associated recommendations.

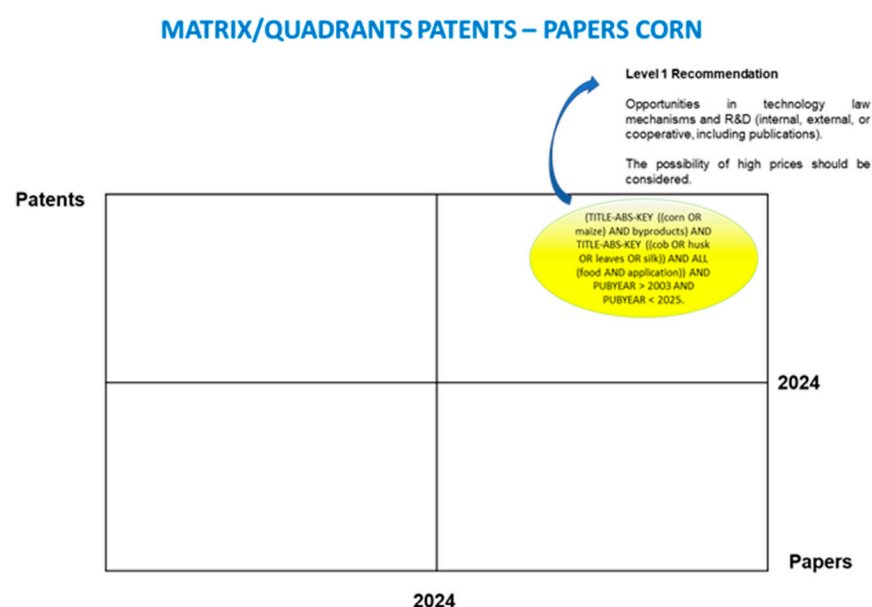


Figure 11. Patent–paper matrix/quadrants. Source: elaboration own (2025). The search query used in Scopus shows the position of the results in the upper-right quadrant with future inflection points in papers and patents.

This quadrant corresponds to Technological Surveillance and Future Investments and represents an emerging or future-oriented area in science and technology, where the tipping point has not yet been reached in either scientific publications or patents.

Interpretation: These technologies represent the technologies of tomorrow, as neither scientific development nor commercial application has yet reached its inflection point [52,53].

Strategic Recommendations:

- Project approach: Technological surveillance and exploratory research.
- Project management: Implementation of small-scale pilot projects and feasibility studies.
- R&D&I: Emphasis on basic research and collaboration with universities to remain at the forefront of technological development [53].

6. Conclusions

The prospective analysis of the corn agro-industrial chain with a time horizon of 2035 allows us to conclude that this sector is undergoing a profound transformation, in which by-products will no longer be regarded as waste but rather as strategic resources for the development of high-value-added bioproducts. The application of methodological tools such as the Delphi method (DM), technology surveillance, and S-curve analysis made it possible not only to identify priority research topics but also to project the most relevant technological trajectories and position innovations according to their respective stages of maturity.

The study also highlights the importance of digitalization and the integration of precision agriculture practices as key factors for increasing resource-use efficiency, reducing environmental impacts, and improving product traceability. The transition toward sustainable production systems further requires stronger articulation among value chain actors—including producers, agribusinesses, academia, and government entities—in order to design long-term policies that facilitate the adoption of advanced technologies and promote continuous innovation.

The corn value chain has the potential to become a driver of economic and social development by generating qualified employment, fostering technological innovation, and promoting more resilient and competitive rural territories within the global context. Achieving this scenario requires inter-institutional commitment, sustained investment in research and development, and a shared vision that prioritizes sustainability and the well-being of rural communities.

The projections indicate that the corn chain will not only continue to play a central role in food security and livestock supply but will also emerge as a key platform for the national bioeconomy. The recovery and valorization of agricultural residues will enable the production of bioplastics, second-generation biofuels, animal feed additives, biofertilizers, and construction materials with sustainable properties. This comprehensive utilization will strengthen the circular economy, reduce the environmental footprint of the chain, and open new business opportunities for producers and industries.

7. Recommendations

Based on the findings obtained, it is recommended to implement a comprehensive strategy that integrates technological, economic, environmental, and social dimensions. Strengthening research and development related to biorefineries, biomass conversion technologies, and the production of innovative bioproducts should be prioritized.

The establishment of open innovation platforms and technology clusters is recommended as a mechanism to accelerate the scaling of solutions that are currently in early stages of development, facilitating their progression toward technological maturity and large-scale industrial adoption.

It is essential to implement training and technical assistance programs for small and medium-sized producers in order to support the adoption of precision agriculture practices, integrated pest management, efficient water use, and adaptation to climate variability scenarios. These initiatives should be complemented by financial incentives that promote the adoption of clean technologies and reduce barriers to entry into specialized, higher-value-added markets.

At the institutional level, it is recommended to strengthen cooperation networks among universities, research centers, companies, and government agencies, with the objective of promoting joint innovation and technology transfer projects. In addition, the establishment of public policies that encourage investment in sustainable infrastructure, green financing, and international cooperation is necessary to position corn-derived bioproducts within global value chains.

The implementation of robust sustainability monitoring systems—capable of measuring environmental, economic, and social impact indicators—is also proposed. These systems will support strategic decision-making and continuous improvement of production processes. This roadmap will enable the corn agro-industrial chain to evolve toward a resilient and competitive model aligned with the principles of the circular economy and sustainable development by 2035.

The implementation of these recommendations will allow the corn value chain not only to enhance its competitiveness but also to actively contribute to the transition toward sustainable and resilient food systems, in line with global market demands and the environmental commitments of producing countries.

For future Delphi studies in this and other agro-industrial chains, it is recommended to include experts from Brazil and other countries with recognized research, academic, and policy expertise in the agro-industrial sectors analyzed.

8. Limitations

From the perspective of future research, this study focused on the application of the Delphi method due to its emphasis on technology, innovation, and potential new business models. Consequently, the analysis could be complemented by scenario-based approaches that consider not only possible futures but also probable and desirable scenarios, thereby providing additional context for decision-making in organizations, universities with academic and research commitments, and other stakeholders within the analyzed agro-industrial sector.

Although complementary methodologies—such as inflection point calculations using S-curves and the patent–paper quadrant matrix—were applied, it is advisable to conduct further analyses of specific topics and technologies prioritized through the Delphi process using the same methodological tools. This is recommended because different quadrant positions may emerge depending on the publication and patenting dynamics of individual technologies, which would further enrich and nuance the conclusions derived from the aggregated search strategy.

Author Contributions: C.G.H. contributed to the conceptualization; formal analysis; research; methodology; and writing of the original draft. J.W.Z.S. contributed to formal analysis and methodology. L.H.B.M. contributed to conceptualization; formal analysis; and writing—review and editing. J.A.V.C. contributed to project administration; supervision; validation; and visualization. N.M.E. contributed to research, data curation, visualization, methodology, writing and supervision. J.C.B.M. contributed to formal analysis and methodology. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study is waived for ethical review as the methodology used was a stakeholder consultation survey in order to get their perspective/opinion on the issue to be evaluated. Due to the fact that the sample used was not aleatory, stakeholder research was performed, and an initial approach was adopted. In this initial approach stage, telephone contact was made to each respondent to request their authorization to send and fill out the questionnaire. In addition, the questionnaire was accompanied by a text in which they authorized the use of the data, which states: "In compliance with the stipulations of Law 1581 of 2012 and Regulatory Decree 1377 of 2013 that develop the right to Habeas Data, we request your authorization for the processing of data provided in this survey". In this way, the respondents had the opportunity to decide whether or not they agreed to participate in this study. The aforementioned regulations correspond to Colombian legislation, and cite the following: Law 1581 of 2012 aims to develop the constitutional right that all persons have to know, update, and rectify the information collected about them in databases

or files. It is based on the principles of legality in data processing, purpose, freedom, truthfulness or quality, transparency, restricted access, circulation, security, and confidentiality. All of these principles were properly applied in the study. On the other hand, Decree 1377 of 2013 states that those responsible for the processing of personal data shall establish mechanisms to obtain the authorization of the owners. These mechanisms may be predetermined through technical methods that facilitate the automated manifestation of the Data Controller. According to regulations, these methods may be written or oral. Taking into consideration that both oral and written information was given and considering that no personal data or sensitive information (sensitive information is understood as those that affect the privacy of the holder or whose improper use can generate discrimination, such as those that reveal racial or ethnic origin, political orientation, religious or philosophical convictions as well and data related to health, sexual life, and/or biometric data) were asked or disclosed in this research, the present study complies with Colombian regulations and did not require to be taken to the ethics committee for its evaluation.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zickafoose, A.; Lu, P.; Baker, M. Forecasting food innovations with a Delphi study. *Foods* **2022**, *11*, 3723. <https://doi.org/10.3390/foods11223723>.
2. Zhang, N.; Sun, C.; Xu, M.; Wang, X.; Deng, J. Catching Up of Latecomer Economies in ICT for Sustainable Development: An Analysis Based on Technology Life Cycle Using Patent Data. *Sustainability* **2023**, *15*, 9038. <https://doi.org/10.3390/su15119038>.
3. Sinisterra, S.; Camargo-Amado, R.; Triviño, D.; Machuca-Martínez, F. Metodologia para elaboração de análise de patentes e ciclo de maturidade tecnológica. *J. Fac. Eng.* **2023**, *32*, e14299. <https://doi.org/10.19053/01211129.v32.n63.2023.14299>.
4. Anoraga, S.B.; Shamsudin, R.; Hamzah, M.H.; Sharif, S.; Saputro, A.D. Cocoa by-products: A comprehensive review on potential uses, waste management, and emerging green technologies for cocoa pod husk utilization. *Heliyon* **2024**, *10*, e35537. Available online: <https://www.cell.com/action/showPdf?pii=S2405-8440%2824%2911568-X> (accessed on 4 September 2025).
5. Hernández, R.E.; Céspedes, J. Bioeconomy: A Sustainability Strategy in the Fourth Industrial Revolution. *J. Agric. Res. Innov. Nat. Resour.* **2020**, *7*, 126–133. Available online: http://www.scielo.org.bo/scielo.php?pid=S2409-16182020000200015&script=sci_arttext (accessed on 4 September 2025).
6. Shiferaw, B.; Prasanna, B.M.; Hellin, J.; Bänziger, M. Crops that feed the world 6. Past successes and future challenges to the role played by corn in global food security. *Food Secur.* **2011**, *3*, 307–327. <https://doi.org/10.1007/s12571-011-0140-5>.
7. Food and Agriculture Organization of the United Nations (FAO). *Cereal Supply and Demand Brief—October 2025 Update*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2025. Available online: [http://www.fao.org/worldfoodsituation/csd/](http://www.fao.org/worldfoodsituation/csd/ (accessed on 4 September 2025)) (accessed on 4 September 2025).
8. Maraveles Delgado, J.A.; García Salazar, J.A.; Mora Flores, J.S.; Botello Aguillón, C. Effects of the Guaranteed Price Policy and the Fertilizer Program on corn production and the Mexican agri-food system. *Acta Univ.* **2025**, *35*, 1–14. <https://doi.org/10.15174/au.2025.4439>.
9. United Nations. Sustainable Development Goals. 2015. Available online: <https://www.un.org/sustainabledevelopment/es/objetivos-de-desarrollo-sostenible/> (accessed on 4 September 2025).
10. Acharya, G.D. Sustainable transformation of agrifood systems: A circular economic and agroecological perspective. *SAARC J. Agric.* **2023**, *21*, 1–12. <https://doi.org/10.3329/sja.v21i1.66340>.
11. Observatory of Economic Complexity—OEC. Brazil: Corn Exports. 2023. Available online: <https://oec.world/en/profile/hs/corn> (accessed on 4 September 2025).
12. Food and Agriculture Organization of the United Nations (FAO). Argentina Country Brief. Corn Exports Preliminarily Forecast at Average Levels in 2024/25 Marketing Year. 2024. Available online: <https://www.fao.org/giews/countrybrief/country.jsp?code=ARG> (accessed on 4 September 2025).

13. Hernandez-Arango, J.F.; Ortiz-Sanchez, M.; Solarte-Toro, J.C.; Salcedo-Mendoza, J.; Alzate, C.A.C. Analysis of planetary boundaries and economic assessment for waste valorization in the context of a biorefinery: Case study of the corn value chain in Sucre, Colombia. *Environ. Sci. Pollut. Res.* **2025**, 1–19. <https://doi.org/10.1007/s11356-025-36266-x>.
14. Bongiovanni, R.; Tuninetti, L.; Vigneau, P.; Gayo, S. Carbon footprint of corn produced in Argentina. *RIA J. Agric. Res.* **2025**, 51, 54–69.
15. Leite, M.; Freitas, A.; Barbosa, J.; Ramos, F. Mycotoxins in Portuguese Agricultural Corn Fields and Dairy Farms. *Toxins* **2024**, 16, 335. <https://doi.org/10.3390/toxins16080335>.
16. García-Lara, S.; Chuck-Hernandez, C.; Serna-Saldivar, S.O. Development and structure of the corn kernel. In *Corn*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 147–163. <https://doi.org/10.1016/B978-0-12-811971-6.00006-1>.
17. Erenstein, O.; Jaleta, M.; Sonder, K.; Mottaleb, K.; Prasanna, B. Global maize production, consumption and trade: Trends and R&D implications. *Food Secur.* **2022**, 14, 1295–1319. <https://doi.org/10.1007/s12571-022-01288-7>.
18. Unidad de Planificación Rural Agropecuaria—UPRA. Productive Management Plan for the Corn Chain. 2022. Available online: <https://upra.gov.co/es-co/search/node?keys=corn-chain-productive-management%20plan> (accessed on 4 September 2025).
19. Sawangwong, W.; Kiattisin, K.; Somwongin, S.; Wongrattanakamon, P.; Chaiyana, W.; Poomanee, W.; Sainakham, M. The assessment of composition, biological properties, safety and molecular docking of corn silk (*Zea mays* L.) extracts from the valorization of agricultural waste products in Thailand. *Ind. Crops Prod.* **2024**, 212, 118352. <https://doi.org/10.1016/j.indcrop.2024.118352>.
20. Vijayalaxmi, S.; Jayalakshmi, S.K.; Sreeramulu, K. Polyphenols from different agricultural residues: Extraction, identification and their antioxidant properties. *J. Food Sci. Technol.* **2015**, 52, 2761–2769. <https://doi.org/10.1007/s13197-014-1295-9>.
21. Jiao, Y.; Chen, H.-D.; Han, H.; Chang, Y. Development and utilization of corn processing by-products: A review. *Foods* **2022**, 11, 3709. <https://doi.org/10.3390/foods11223709>.
22. Dey, D.; Richter, J.K.; Ek, P.; Gu, B.-J.; Ganjyal, G.M. Utilization of food processing by-products in extrusion processing: A review. *Front. Sustain. Food Syst.* **2021**, 4, 603751. <https://doi.org/10.3389/fsufs.2020.603751>.
23. Deepak, T.S.; Jayadeep, P.A. Prospects of maize (corn) wet milling by-products as a source of functional food ingredients and nutraceuticals. *Food Technol. Biotechnol.* **2022**, 60, 109–120. <https://doi.org/10.17113/ftb.60.01.22.7340>.
24. Zereyesus, Y.A.; Cardell, L.; Farris, J.; Ajewole, K.; Johnson, M.E.; Lin, J.; Valdes, C.; Zeng, W. Global Food Assessment, 2025–35. Available online: https://ers.usda.gov/sites/default/files/_laserfiche/publications/113294/GFA-36.pdf?v=69234 (accessed on 4 September 2025).
25. Eziefula, U.G. Developments in Utilisation of Agricultural and Aquaculture By-Products as Aggregate in Concrete—A Review. *Environ. Technol. Rev.* **2018**, 7, 19–45. <https://doi.org/10.1080/21622515.2017.1423399>.
26. Irmak, S.; Canisag, H.; Vokoun, C.; Meryemoglu, B. Xylitol production from lignocellulosics: Are corn biomass residues good candidates? *Biocatal. Agric. Biotechnol.* **2017**, 11, 220–223. <https://doi.org/10.1016/j.bcab.2017.07.010>.
27. Fernández-Ocamica, V.; Palacino, B.; Bartolomé, C.; Figueirêdo, M.B.; Lázaro García, C. Trade-offs and Synergies of Key Biobased Value Chains and Sustainable Development Goals (SDGs). *Sustainability* **2025**, 17, 3040. <https://doi.org/10.3390/su17073040>.
28. Ramírez, P.A.A.; Suescún Barón, C.A.; Parrado, C.V.M. Potential of the bioeconomy in the industrial sector: An input-output analysis for the Colombian case. *Circ. Econ. Sustain.* **2025**, 5, 4075–4092. <https://doi.org/10.1007/s43615-025-00602-7>.
29. McCarthy, J.; Kulenkampff, A.; Furtado, M.; Martins, G.; Maia, L.; Martins, J.; Marquez, V.G.; Hansmann, J.P. Harnessing the Bioeconomy-Climate Nexus for Sustainable Development, 2025. Available online: <https://publications.iadb.org/en/harnessing-bioeconomy-climate-nexus-sustainable-development> (accessed on 1 July 2025).
30. Jin, C.; Hu, J.; Wu, J.; Liang, H.; Li, J. Innovative and economically beneficial use of corn and corn products in electrochemical energy storage applications. *ACS Sustain. Chem. Eng.* **2021**, 9, 10678–10703. <https://doi.org/10.1021/acssuschemeng.1c02613>.
31. Vivas, M.A.U.; Amórtégui, L.S.; Guerrero-García-Rojas, H. Understanding the characteristics of the green, circular and bioeconomy models within the context of sustainable development. *Energy Sustain. Soc.* **2025**, 15, 27. <https://doi.org/10.1186/s13705-025-00528-w>.
32. Fei, G.; Khan, R.; Yang, L.; Chi, Y.; Wang, Y.; Zhou, X. Uncovering the Potentials of Long-Term Straw Return and Nitrogen Supply on Subtropical Corn (*Zea mays* L.) Photosynthesis and Grain Yield. *Field Crops Res.* **2023**, 302, 109062. <https://doi.org/10.1016/j.fcr.2023.109062>.
33. Girelli, A.M.; Astolfi, M.L.; Scuto, F.R. Agro-Industrial Wastes as Potential Carriers for Enzyme Immobilization: A Review. *Chemosphere* **2020**, 244, 125368. <https://doi.org/10.1016/j.chemosphere.2019.125368>.
34. Ortigueira, J.; Silva, C.; Moura, P. Assessment of the adequacy of different Mediterranean waste biomass types for fermentative hydrogen production and the particular advantage of carob (*Ceratonia siliqua* L.) pulp. *Int. J. Hydrog. Energy* **2018**, 43, 7773–7783.

35. Liu, D.; Wang, Y.; Jia, B.; Wei, J.; Liu, C.; Zhu, J.; Tang, S.; Wu, Z.; Chen, G. Microwave-assisted hydrothermal preparation of corn straw hydrochar as supercapacitor electrode materials. *ACS Omega* **2020**, *5*, 26084–26093. <https://doi.org/10.1021/acso-mega.0c03605>.
36. Rani, M.U.; Nanaji, K.; Rao, T.N.; Deshpande, A.S. Corn husk derived activated carbon with enhanced electrochemical performance for high-voltage supercapacitors. *J. Power Sources* **2020**, *471*, 228387. <https://doi.org/10.1016/j.jpowsour.2020.228387>.
37. Ochoa-Castaño, M.; Montoya-Escobar, N.; Velásquez-Cock, J.A.; Gómez-Hoyos, C. Corn Stover for Food Applications: Approaches, Advances and Insights. *Molecules* **2025**, *31*, 27. <https://doi.org/10.3390/molecules31010027>.
38. Hidayat, S.; Mubarak, I.; Adiperdana, B.; Suroto, B.J.; Rivel, N.; Hartati, Y.W.; Rahayu, I. Characteristics of CMC from corncob and its application as electrode binder in lithium ion battery. *Mater. Sci. Forum* **2019**, *966*, 433–436. <https://doi.org/10.4028/www.scientific.net/MSF.966.433>.
39. Luque, L.; Oudenhoven, S.; Westerhof, R.; van Rossum, G.; Berruti, F.; Kersten, S.; Rehmann, L. Comparison of ethanol production from corn cobs and switchgrass following a pyrolysis-based biorefinery approach. *Biotechnol. Biofuels* **2016**, *9*, 242. <https://doi.org/10.1186/s13068-016-0661-4>.
40. Okeke, F.O.; Ahmed, A.; Imam, A.; Hassanin, H. A review of corncob-based building materials as a sustainable solution for the building and construction industry. *Hybrid Adv.* **2024**, *6*, 100269. <https://doi.org/10.1016/j.hybadv.2024.100269>.
41. Lin, Y.; Wang, J.; Wang, X.; Sun, X. Optimization of butanol production from corn straw hydrolysate by *Clostridium acetobutylicum* using response surface method. *Chin. Sci. Bull.* **2011**, *56*, 1422–1428. <https://doi.org/10.1007/s11434-010-4186-0>.
42. Hasan, H.; Islam, S.; Sajib, S.M.; Rahman, G.M.S.; Sabur, A.; Ahmed, A.N.; Al Mamun, M.A. A comprehensive study of agricultural waste corn husk as a potential reinforcement in corn fiber/glass fiber hybrid composites. *SPE Polym.* **2025**, *6*, e70000. <https://doi.org/10.1002/pls2.70000>.
43. Enawgaw, H.; Tesfaye, T.; Yilma, K.T.; Limeneh, D.Y. Multiple utilization ways of corn by-products for biomaterial production with bio-refinery concept; a review. *Mater. Circ. Econ.* **2023**, *5*, 7. <https://doi.org/10.1007/s42824-023-00078-6>.
44. Mujtaba, M.; Fraceto, L.F.; Fazeli, M.; Mukherjee, S.; Savassa, S.M.; de Medeiros, G.A.; Pereira, A.D.E.S.; Mancini, S.D.; Lipponen, J.; Vilaplana, F. Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics. *J. Clean. Prod.* **2023**, *402*, 136815. <https://doi.org/10.1016/j.jclepro.2023.136815>.
45. Perwitasari, D.S.; Nathania, G.Y.; Alghifari, A. Utilization of Corn Husk Waste as Raw Material for Making Biobutanol. *Nusant. Sci. Technol. Proc.* **2023**, 269–274. <https://doi.org/10.11594/nstp.2023.3639>.
46. Sun, X.; Dou, Z.; Shurson, G.C.; Hu, B. Bioprocessing to upcycle agro-industrial and food wastes into high-nutritional value animal feed for sustainable food and agriculture systems. *Resour. Conserv. Recycl.* **2024**, *201*, 107325. <https://doi.org/10.1016/j.resconrec.2023.107325>.
47. Narancic, T.; Cerrone, F.; Beagan, N.; O'connor, K.E. Recent advances in bioplastics: Application and biodegradation. *Polymers* **2020**, *12*, 920. <https://doi.org/10.3390/polym12040920>.
48. Hong, L.G.; Yuhana, N.Y.; Zawawi, E.Z.E. Review of bioplastics as food packaging materials. *AIMS Mater. Sci.* **2021**, *8*, 166–184. <https://doi.org/10.3934/matricsci.2021012>.
49. Tan, S.X.; Andriyana, A.; Ong, H.C.; Lim, S.; Pang, Y.L.; Ngoh, G.C. A comprehensive review on the emerging roles of nanofillers and plasticizers towards sustainable starch-based bioplastic fabrication. *Polymers* **2022**, *14*, 664. <https://doi.org/10.3390/polym14040664>.
50. Costa, A.; Encarnação, T.; Tavares, R.; Todo Bom, T.; Mateus, A. Bioplastics: Innovation for green transition. *Polymers* **2023**, *15*, 517. <https://doi.org/10.3390/polym15030517>.
51. Wei, T.; Jiang, T.; Feng, D.; Xiong, J. Exploring the Evolution of Core Technologies in Agricultural Machinery: A Patent-Based Semantic Mining Analysis. *Electronics* **2023**, *12*, 4277. <https://doi.org/10.3390/electronics12204277>.
52. Xu, J.; Li, Y.; Zhang, M.; Zhang, S. Sustainable agriculture in the digital era: Past, present, and future trends by bibliometric analysis. *Heliyon* **2024**, *10*, e34612. <https://doi.org/10.1016/j.heliyon.2024.e34612>.
53. Cano, P.B.; Carcedo, A.J.; Hernández, C.M.; Gómez, F.M.; Giménez, V.D.; Kyveryga, P.M.; Ciampitti, I.A. Trends in agricultural technology: A review of US patents. *Precis. Agric.* **2025**, *26*, 59. <https://doi.org/10.1007/s11119-025-10257-x>.
54. Gherțescu, C.; Manta, A.G.; Bădîrcea, R.M. Smart Agriculture and Technological Innovation: A Bibliometric Perspective on Digital Transformation and Sustainability. *Agriculture* **2025**, *15*, 1388. <https://doi.org/10.3390/agriculture15131388>.
55. Motshabi, N.; Lenetha, G.G.; Malimabe, M.A.; Gumede, T.P. Cellulose Nanofibril-Based Biodegradable Polymers from Corn Husk: A Review of Extraction, Properties, and Applications. *Polymers* **2025**, *17*, 1947. <https://doi.org/10.3390/polym17141947>.
56. Shi, X.; Cui, L.; Xu, C.; Wu, S. Next-Generation Bioplastics for Food Packaging: Sustainable Materials and Applications. *Materials*, **2025**, *18*, 2919. <https://doi.org/10.3390/ma18122919>.

57. Anand, A.; Garg, K.; Singh, O. Transition Time Based Modelling for Sustainable Innovation Adoption. *Sustain. Futures* **2025**, *9*, 100759. <https://doi.org/10.1016/j.sfr.2025.100759>.
58. Zartha, J. Toma de decisiones en Agroindustria apoyada en Cuadrantes/Matriz Patentes—Papers. Presentación de Conferencia Magistral. In Proceedings of the Congreso Internacional de Agroindustria para el Desarrollo, Pereira, Colombia, 17–19 September 2025.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.