

Postharvest and agro-industry

Scientific and Technological Research Article

Identification of Knowledge and Technologies for Postharvest Use of Broccoli (*Brassica oleracea* var. *italica*) and Its By-products: A Scientometric Analysis

Identificación de conocimientos y tecnologías para el uso poscosecha del brócoli (*Brassica oleracea* var. *italica*) y sus subproductos: análisis cientométrico



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Abstract: Using crop by-products has become a key line of research in the current circular economy and bioeconomy scenario, specifically for extracting bioactive compounds of interest in designing and developing value-added products for food, cosmetics, health, biofuels, and animal feed industries. In Colombia, harvest and postharvest residues and crop surpluses have been underutilized as a potential source of bioactive compounds. Thus, the objective of this research is to analyze research insights and technologies used to take advantage of by-products from broccoli (*Brassica oleracea* var. *italica*) cultivation through a methodological design that combines scientific intelligence, surveillance technology, and scientometric analysis methods and tools. We identified the current lines of research in postharvest and processing and the respective technologies in the topics of senescence, packaging and transport, shelf life, quality, drying process, and by-products, as well as research insights and technologies in health, integrated crop management, and genetics. Furthermore, the scarcity of research results on broccoli by-products and their use is highlighted, showing an opportunity to strengthen research on this topic. Finally, the challenges and future work for research on the exploitation of broccoli by-products are established based on the use of their bioactive compounds in value-added products.

Keywords: bioactive compounds, antioxidant capacity, added value, broccoli powder, crop surplus, postharvest technologies, freeze-drying.

Resumen: El aprovechamiento de los subproductos de cultivos se ha convertido en una línea de investigación clave en el contexto actual de economía circular y bioeconomía. En Colombia, los residuos de cosecha y poscosecha, así como los excedentes de cultivos, han sido subutilizados como fuente potencial de compuestos bioactivos. El objetivo de esta investigación fue analizar las tendencias y tecnologías utilizadas para el aprovechamiento de los subproductos del cultivo de brócoli (*Brassica oleracea* var. *italica*). Se identificaron las líneas de investigación actuales en poscosecha y procesamiento, así como tecnologías en temas como senescencia, empaque y transporte, vida útil, calidad, proceso de secado y subproductos. Se destaca la escasez de resultados de investigación sobre los subproductos del brócoli y su uso o potencial aprovechamiento, lo que demuestra la oportunidad de fortalecer la investigación en este tema. Por último, se establecen retos y trabajos futuros para la investigación del aprovechamiento de los subproductos del brócoli mediante el uso de sus compuestos bioactivos en productos de valor agregado.

Palabras clave: compuestos bioactivos, capacidad antioxidante, valor añadido, polvo de brócoli, excedente de cosecha, tecnologías poscosecha, secado en frío.



Introduction

Conceptually, food loss is understood as decreased photosynthetic biomass suitable for human consumption. This phenomenon increases when large amounts of food are wasted due to logistical and social limitations or simply because of prices below the point of economic equilibrium for producers (Parfitt et al., 2010). Likewise, various authors have established meanings to categorize crop losses, including i) surplus, producing more than what is needed to survive (McCarthy et al., 2020); ii) residue, the material that remains after collecting the main crop product (Díaz-Monroy et al., 2014) iii) by-products, vegetables from production, harvest, transport, and processing in agricultural areas (Food and Agriculture Organization of the United Nations [FAO], 2012); iv) waste, food that is not used due to reduced quality or that is left over in establishments, restaurants, or consumer homes (FAO, 2012).

According to FAO (2021), 13.8 % of all food is lost yearly worldwide from postharvest to marketing activities across agri-food value chain dynamics. In Latin America and the Caribbean, losses and waste in fruits, tubers, and vegetables are estimated at 43 % in the phases of agricultural production (12.3 %), postharvest handling and storage (10 %), and processing and packaging (20 %). Harvest is the critical control point for food loss, while inadequate storage facilities and poor handling practices were the leading causes of farm losses (FAO, 2019).

In the case of the broccoli production system, Henao-Rojas et al. (2020) identified that after harvest, the types of broccoli surpluses are leaves, stems, and sometimes scarcely developed heads. These surpluses can fluctuate between 52 to 97 % of the production; the lowest percentages are represented in leaves and stems when the crop has a typical production cycle, and the highest percentages include the entire plant when the crop is affected by diseases such as cruciferous clubroot (*Plasmodiophora brassicae*) or by natural phenomena like hail. These surpluses are used as fresh animal food, for composting—incorporating it into the soil and waiting for its decomposition before new planting—for fresh consumption at home, or left as harvest waste, causing phytosanitary problems for the territories and producers.

Conzatti et al. (2015) propose that the functional attributes of broccoli in health are due to its nutritional value, being qualified as a ‘superfood.’ Furthermore, there are growing reports of its sulforaphane (SF) content, an isothiocyanate hydrolyzed from glucosinolates, which is a powerful compound used against cancer (Tian et al., 2017), with anti-inflammatory properties derived from its effect on the NRF2 and NRF α β genetic sequencing pathways (Conzatti et al., 2015), in addition to showing effects on phases 1 and 2 of liver detoxification and the regulation of the inflammatory cascade by interleukins IC1 and IC6 (Kensler et al., 2012). Similarly, SF reduces nitric oxide serum metabolites in patients infected with *Helicobacter pylori* (Kensler et al., 2012).

Thus, to take advantage of broccoli in the industry worldwide, researchers have developed broccoli-based patents as follows: Chen (2017), Dai et al. (2017), and Kang et al. (2019) obtained solid drinks rich in SF; Huang and Pan (2018) and Zhang et al. (2018) produced broccoli pressed caramel with high selenium content and published its preparation methods; Chi (2018) and Zhao (2018) developed a meal replacement food. Finally, Che et al. (2019), Long (2017), and Long and Long (2017a, b, c) made broccoli extract, presenting their preparation method and pharmaceutical compositions.

In the Colombian context, there is a need to reduce and transform harvested by-products in the broccoli production system through valorization and use in an intermediate product. This agro-industrial alternative will generate income for producers and be a source of raw materials with biofunctional potential for phytochemical laboratories. In short, reducing food loss or waste means more food, fewer sources of contamination, reduction of greenhouse gas emissions, reduction of environmental pressure, increased productivity, and economic growth (FAO, 2019). Accordingly, there is a gap in the availability and accessibility of research insights and technologies focused on exploiting broccoli surpluses from postharvest stages of in Colombia.

This research used an approach based on a scientometric analysis methodology and scientific and technological intelligence and surveillance (STIS) tool integration to identify and analyze the recent progress in research and technological development at the global and national levels. The focus was on the use and processing of broccoli by-products, as well as their potential to contribute to improving the lives of producers by developing new products that generate economic growth.

Material and Methods

STIS studies focus on identifying research-based trends that comprise a specific topic's state of the art to establish the current research activity scenario. This research's methodological design was completed in three phases, covering a period of available research publications between 1990 and 2021 (August).

Phase I. Design and Implementation of the Search Strategy

This phase includes activities such as equation design, implementation of search engines (Scopus, WoS, and AgroExplora), metadata normalization, and structuring of the information base to be analyzed in Bibliometrix (R Studio Package v 4.0.0, <https://www.bibliometrix.org/home/>; Aria & Cuccurullo, 2017) and VOSviewer (Leiden University, v 1.6.17, <https://www.vosviewer.com/>; van Eck & Waltman, 2010). The information is downloaded in .bib and .csv formats from the mentioned databases using a three-structured search equation:

- **Equation 1 - broccoli by-products:** TITLE-ABS-KEY ((“Brassica oleracea var. italica” OR “Broccoli”) AND (“harvest*” OR “postharvest*” OR “chemical characterization” OR “crop residue*” OR “crop surplus*” OR “harvest surplus*”)) AND (PUBYEAR > 1990) AND (LIMIT-TO (SUBJAREA, “AGRI”))
- **Equation 2 - broccoli bioactive compounds:** TITLE-ABS-KEY ((“Brassica oleracea var. italica” OR “Broccoli”) AND (“glucosinolate*” OR “Glucoraphanin*” OR “Sulforaphane*”)) AND (PUBYEAR > 1990) AND (LIMIT-TO (SUBJAREA, “AGRI”))
- **Equation 3 - broccoli powder:** TITLE-ABS-KEY ((“Brassica oleracea var. italica” OR “Broccoli”) AND (“powder*” OR “soluble powder*”)) AND (PUBYEAR > 1990) AND (LIMIT-TO (SUBJAREA, “AGRI”))

Phase II. Scientometric Analysis and Identification of Research Insights and Technologies

This phase includes the following activities:

- *Construction of the scientific research landscape (research insights and technologies)*: Using the Bibliometrix and VOSviewer software, a co-occurrence analysis of keywords in thematic maps was performed, allowing the identification and analysis of research insights and technologies related to the topic and the evolution of research (Mazov et al., 2020). Finally, knowledge evolution maps based on cluster analysis (Cobo, 2020; Cuccurullo et al., 2016) were constructed to identify technology evolution through time.
- *Categorization of research insights and technologies*: The prioritized research insights and technologies were categorized into four categories (Henao-Rojas et al., 2020): The first category comprises research insights and technologies that conducted evaluations only in the floret or head, with a 52 % application potential of by-products. The second category embraces research insights and technologies implemented only in leaf, stem, or both, with a 48 % application potential. The third category summarizes research insights and technologies used in leaf-floret-stem, leaf-floret, or stem-floret or use of losses or by-products. Presumably, there is no surplus from harvest and postharvest activities since the investigations have already identified their application. Hence, it is categorized as a technology with 0 % application potential. Finally, research insights and technologies that can be applied to any plant part (stem, leaves, and florets) are categorized with 100 % application potential (fourth category).

In addition, the research insights and technologies were categorized concerning the surplus as follows: i) if the study concluded that the technology was useful, it could be validated in the by-products, and “yes” will be chosen; ii) if the study concluded that it is not totally useful, “no, it will be validated” will be selected, and iii) research insights and technologies that do not apply for validation concerning surplus due to a high processing volume scope (between 20 and 129 t/ha; Henao-Rojas et al., 2020), neither will be selected for validation.

Phase III. Advances in Technological Development

A search was made for patents granted or not granted to products obtained from the vegetable broccoli “*Brassica oleraceae* var. *italica*” using the web app Patent Inspiration® (<https://app.patentinspiration.com/>), related to developments that included the keywords dehydrated broccoli, broccoli powder, and powder broccoli. This data was processed using VOSviewer®.

Results and Discussion

This section presents results and a discussion of each methodological phase.

Phase I. Design and Implementation of the Search Strategy

The strategy implementation comprises the three independent search equations previously described, whose retrieved records are unified for a comprehensive analysis. Table 1 synthesizes the retrieved data.

Table 1. Retrieved data for each search equation on each database

Equation	Scopus	WoS	AgroExplora
1	686	530	1
2	721	803	3
3	78	64	1

Source: Prepared by the authors.

Phase II. Scientometric Analysis and Identification of Research Insights and Technologies

In this phase, a keyword co-occurrence network analysis was implemented. The co-occurrence network comprises four thematic clusters that recognize the applicability of the most relevant research insights and technologies to specific activities in the broccoli production chain through 397 topics that interact in 19,244 relationships. Figure 1 shows the thematic clusters identified in broccoli: postharvest (green cluster), bioactive compounds (blue cluster), integrated crop management (red cluster), and genetic breeding (purple). The research insights and technologies were identified through articles related to each thematic theme. Technologies were prioritized as follows. i) by the highest number of citations per article and ii) by publication age (last five years).

Construction of scientific research landscapes: Thematic clusters and identified research insights and technologies

The co-occurrence network in Figure 1 embraces four key thematic clusters with related research insights and technologies.

Green cluster—Research insights and technologies identified for post-harvest factors (112 research topics): This cluster comprises research insights and technologies related to senescence, storage, quality, drying, and added value.

Senescence-related research insights and technologies include a controlled atmosphere (CA) with variable levels of O₂/CO₂ (Guo et al., 2013) and the use of Methyl Jasmonate and 1-Methylcyclopropene for induction of the quinone reductase (QR) activity (Ku et al., 2013); cooling and the combination of hot air and ultraviolet light C (UV-C) radiation for glucoraphanin content and organoleptic characteristic preservation (Lemoine et al., 2008); effects of electrostatic atomization on ascorbate (AsA) for delaying yellowing of florets (Ma et al., 2012); and *Sophorae subprostratae* and radix *Myristica fragrans* extract for keeping leave and stem freshness (Sun et al., 2013)



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Preservative technologies such as 6-BA (6-Benzylaminopurine) and SBN (sodium benzoate compounds) and edible protein wax coatings with fructose (Le et al., 2020), and the study of sauce with different fat concentrations are highlighted. Other research insights and technologies use the effect of red, blue, and white LED light irradiation on ascorbate content, gene expression, and preservation of fresh-cut broccoli (Castillejo et al., 2021; Hasperué et al., 2016) and UV-B light on flavonol and chlorophyll content to preserve broccoli during retail (Aiamlar et al., 2019).

Moreover, some research insights and technologies provide a practical approach to inhibiting senescence, delaying yellowing, reducing oxidative stress, extending shelf life, and improving the physical and sensory quality of the product. Fifty-six research insights and technologies were identified in the senescence topic, eight of which were prioritized (Table 2).

Storage-related research insights and technologies monitor the effects of hot and cold-water treatment temperatures on lipid peroxidation (LP; Perini et al., 2017), deterioration of broccoli flowers by glucosinolates during storage due to temperature changes (Gao et al., 2018), and leaf wax content on the response of broccoli. The use of packing materials such as low-density polyethylene (LDPE) bags, charcoal paper trays in modified atmosphere (MA), and sulfonated polyether ether ketone (SPEEK) modified atmosphere packaging improved permeability, freshness, and the absorption of a detrimental gas (Kapusta-Duch et al., 2019; Si et al., 2017). In addition, sensory and nutritional quality changes after industrial boiling, continuous microwave pasteurization, and microwave steamable bags were evaluated (Zhong et al., 2017).

Complementary packing technologies design focus on extending the useful life of broccoli (physical, bromatological, and microbiological factors) on supply chain stages, like hydro-cooling (Iribe-Salazar et al., 2015), micro-perforated wrap treatments and fumigation with nitric oxide gas. Four of the 55 research insights and technologies identified in the storage topic were prioritized (Table 2).

Quality-related research insights and technologies mainly focus on improving and preserving the nutritional and physical quality of fresh and minimally processed broccoli (Ben-Fadhel et al., 2018; Caleb et al., 2016) through LED light irradiation on ascorbate content, the combination of light and low temperature, neutral electrolyzed water, UV-C, and super atmospheric O₂ packaging (HO; Martínez-Hernández et al., 2013).

Furthermore, ethanol treatment reduces bacterial content, UV-B irradiation intensity enhances sprouts' quality, ultrasound response surface methodology (RSM) increases SF and other bioactive compounds in broccoli preservation (Aguilar-Camacho et al., 2019; Mahn et al., 2020), and the Box-Behnken method improves the quality of SF extracts (González et al., 2021).

Other complementary research insights and technologies were vacuum cooling process optimization by a tabu search algorithm (Ding et al., 2018), hot air use to improve SF yielding in broccoli sprouts with a new method of thermosonication (Shokri et al., 2021), and the influence of glucosinolates and vitamin C content (Soares et al., 2017) with different cooking methods (boiling, steaming, frying, and microwaving).

Finally, technologies to preserve the quality of minimally processed broccoli comprise edible coatings and mild heat shock, the use of a protein-wax coating for protection, the effect of pre-treatment with calcium chloride (CaCl_2) and alginate coating on the physicochemical and microbial properties of ready-to-eat broccoli, and the effect of microwave steamable bag design (Calderón-Alvarado et al., 2016). These processes provide better microbial quality, color, stem firmness, and sensory quality to broccoli and preserve glucosinolates and vitamin C. Six of the 46 research insights and technologies identified in the quality topic were prioritized, as shown in Table 2.

Research insights and technologies identified for the drying process, were microwave drying, steamable bag design on the preservation of ascorbic acid and antioxidant capacity, comparative study of drying, freeze drying (FD), warm air drying (HAD), microwave vacuum drying (MVD), drum drying (DD), and vacuum drying (VD). Likewise, research has been conducted on MVD combined with HAD (MVD + HAD) and MVD combined with VD (MVD + VD). Drying process research insights and technologies target different compositional richness, FD or lyophilization suitable for pigments and glucosinolates, and air drying for glucosinolates; meanwhile, MHG (microwave hydrodiffusion and gravity) promotes the extractability of phenolic compounds (Córdova et al., 2020; Mahn et al., 2016; Yilmaz et al., 2019). Three of the 15 research insights and technologies identified in the drying topic were prioritized (Table 2).

Research insights and technologies identified for by-product added value focus on producing valuable raw materials in the pharmaceutical, cosmetic, and food industries. Identified technologies enhance the extraction and characterization of bioactive ingredients attributes (antioxidants, polysaccharides, and glucoraphanin) to design beverages (Abellán et al., 2021), snacks (Lee & Lee, 2010), extracts (Fahey et al., 2019), enriched extrudates (Bisharat et al., 2015), biofuels (Razaghi et al., 2016), and silage (Monllor et al., 2020) mainly from leaves and stems (Bessler & Djaldetti, 2018; Georgikou et al., 2020). Eight of the 38 research insights and technologies identified in the added value topic were prioritized (Table 2).

Blue cluster—Research insights and technologies identified for bioactive compounds regarding health (88 research topics): This cluster includes research insights and technologies related to antioxidant and anticancer compounds of broccoli, such as glucosinolates and SF bioavailability. These two compounds have been related to benefits in human health, the treatment of several types of cancer, the content of anticancer compounds, and the prevention of cell damage. In this cluster, natural SF stands out. It is an isothiocyanate hydrolyzed from glucosinolates, a powerful compound against cancer found naturally, especially in broccoli (Becker et al., 2017; Yanaka, 2017).

Hence, the importance of research on SF in the nutraceutical and pharmaceutical industry, including antioxidant activity, statistical optimization of a blanching step, and a hydrolysis method to improve SF yielding (Cai et al., 2020; Wang et al., 2012); the effect of 2,4-epibrassinolide on the glucosinolates yield (Guo et al., 2014); and, the impact of *Agrobacterium*-infiltration and transient overexpression of BroMYB28 on glucoraphanin on broccoli leaves (Kim et al., 2020).

Other research insights and technologies are related to antioxidant compounds, protein, and antitumor protein phosphatase-2A (PP2A) levels. One of the most critical components for identifying phytochemical contents is procurement techniques used like high-performance liquid chromatography (HPLC), electron spin resonance spectroscopy (ESR), GC/MS spectrophotometry, UV spectrophotometry, gas chromatography, mass spectrometry, and ultra-high-performance liquid chromatography (Kokotou et al., 2017), as well preservation technologies like microwave cooking and chitosan and salicylic acid coating (Paulsen et al., 2021; Supapvanich et al., 2019). Seven of the 35 research insights and technologies identified in the health topic were prioritized (Table 2).

Red cluster—Research insights and technologies identified for integrated crop management (142 research topics): This cluster focuses on crop cultivation issues, such as fertilization (Mahn, 2017), soil (Rivera-Martin et al., 2020), pesticides, physiological development, irrigation, harvest, pesticide residues, biological control of pests, fungi, broccoli diseases (Javaid et al., 2018), nitrogen fertilization (Gaskin et al., 2020), and methyl jasmonate (MeJA) treatment to increase glucoraphanin content in broccoli (Aguilar-Camacho et al., 2019).

Research insights and technologies related to the topic of broccoli harvesting were also identified, such as end-of-day harvest delays, postharvest (Sohail et al., 2021), the establishment of respiration rates (Wang et al., 2017), the effect of sugars on ethylene synthesis, and identification of amplified fragment length polymorphism (AFLP) in high-temperature conditions (Ahlawat & Liu, 2021). Three of the 27 research insights and technologies identified in the crop cluster were prioritized (Table 2).

Yellow cluster—Research insights and technologies identified for genetic breeding (55 research topics): These research insights and technologies embrace topics related to metabolites, genetic expression, plant proteins, and genetic variations. Key research insights and technologies such as the sequencing and expression analysis of a cDNA encoding a glutamate dehydrogenase gene (Branham & Farnham, 2017), the ability of two plastid transit peptides and an ER signal peptide to target green fluorescent protein (GFP), expression of a gene encoding a putative CBR (*BoNYC1*), transcriptome analysis based on hybridization of broccoli floret mRNA, and genomic signature (Liu et al., 2020). One of the nine research insights and technologies identified in the gene cluster was prioritized (Table 2).

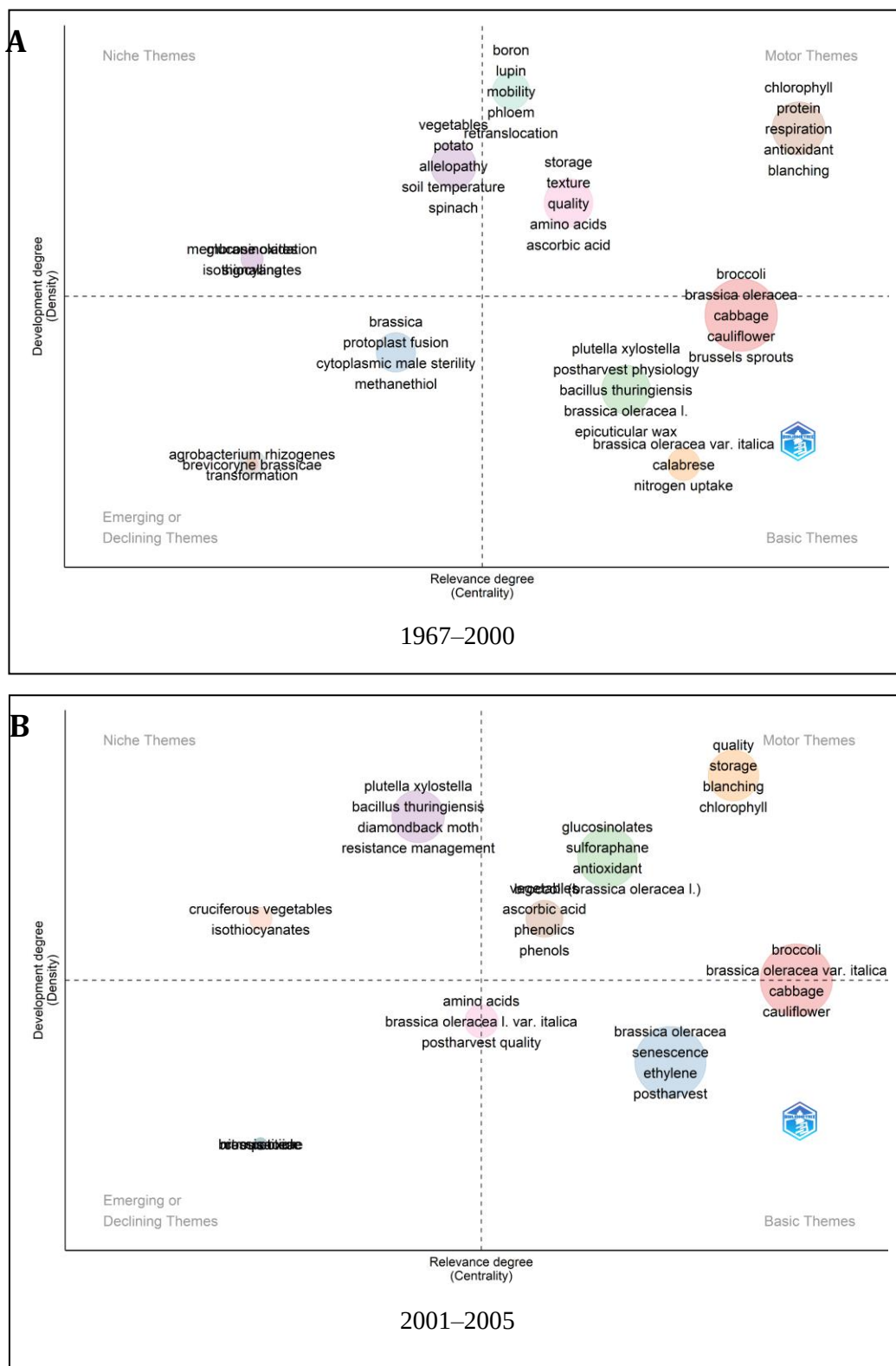
Evolution of the Insertion of Research Insights and Technologies in the Broccoli Production Chain

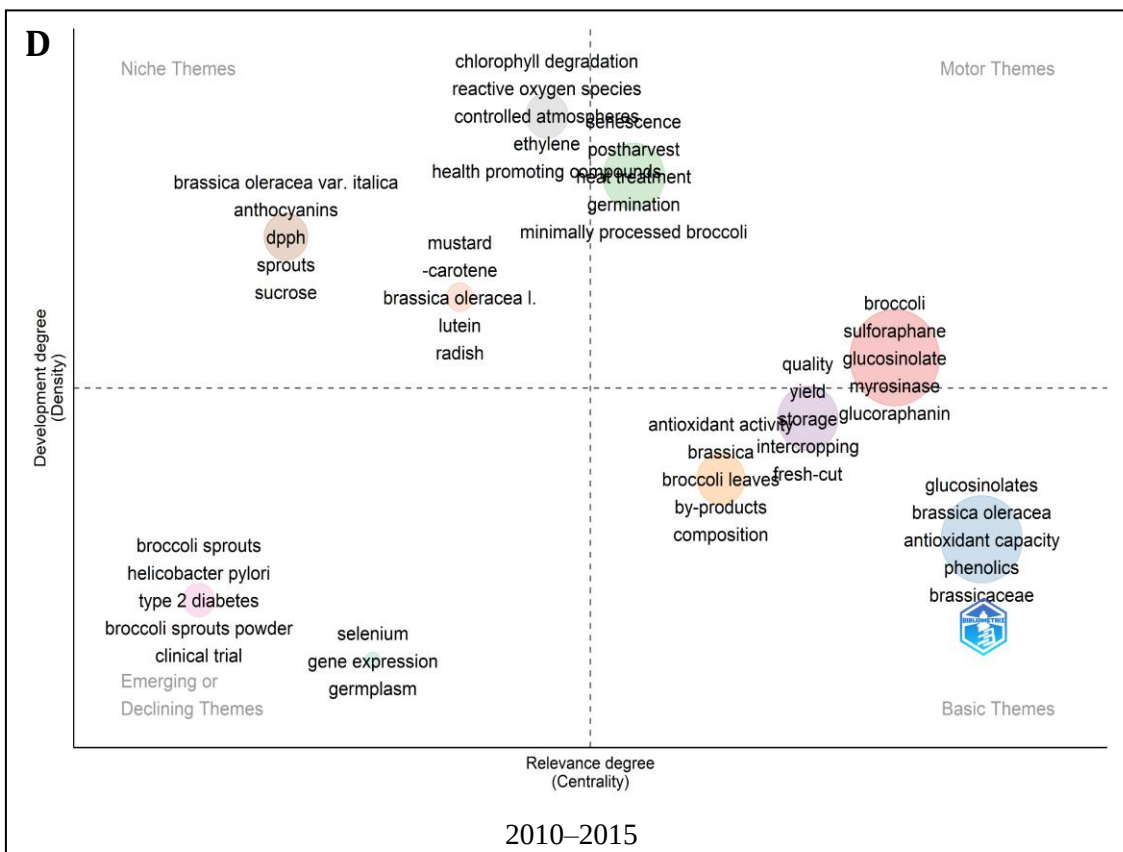
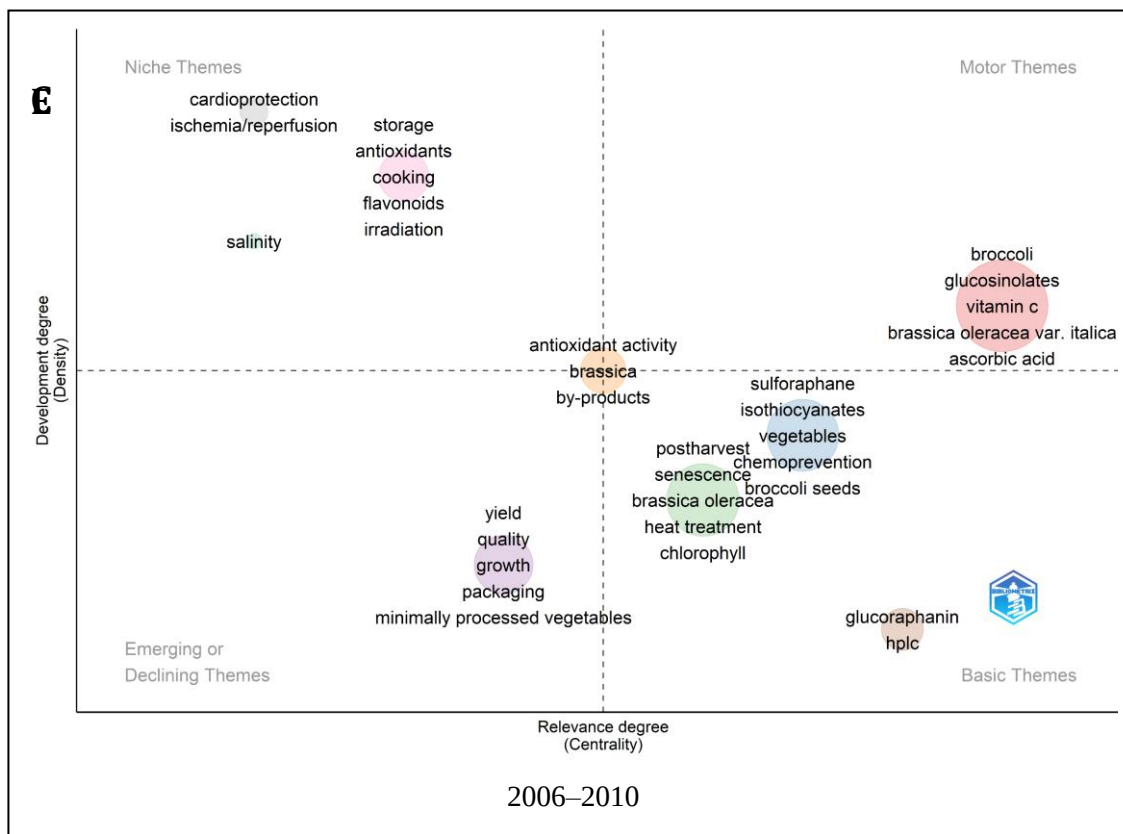
The analysis of thematic maps is presented in Figures 2A-E, which show the evolutionary stages of the immersion of crucial research insights and technologies in the broccoli production chain. According to Flórez-Martínez and Uribe-Galvis (2020), two key variables are considered—centrality (importance of the topic in the entire field of research or analysis) and density (measurement of how the developed the topic is)—as follows: i) upper right quadrant, driver topics with high development and of high importance; ii) lower right quadrant, basic and cross-cutting topics, topics of high importance with basic development; iii) lower left quadrant, emerging and declining topics, of importance with basic development; and iv) upper left quadrant, highly developed and isolated topics, with high development but of minimum importance.

The size of the bubbles is proportional to the number of occurrences of the topic in the retrieved records, and the color indicates that it belongs to a cluster (grouping of topics; Flórez-Martínez & Uribe-Galvis, 2020). Five periods were chosen to analyze the thematic maps: before 2000, 2001–2005, 2006–2010, 2011–2015, and 2016 onwards. Each period is an image of the behavior of the main topics in the study area, helping to identify distinct stages, cycles, and continuities in the macro time window.

- Driver topics (motor themes) showed prevalence in issues related to agronomic management, allelopathy, boron, morphological, oats, methanethiol, protoplast, and cytoplasmic topics. Nutritional contents (chlorophyll, protein) and antioxidants were also identified. In 2001, research appeared on anticancer components of broccoli (glucosinolates, glucoraphanin, and SF), postharvest, and quality. Specific postharvest topics are glimpsed in the 2006–2010 period, such as storage, bioavailability, shelf life, ethylene, and respiration rate. The studies on the benefits of the bromatological contents of broccoli on health (anti-inflammatory) began from 2011 to 2015; postharvest, health-promoting compounds and quality studies are maintained, and the use of microwave is initiated. New topics related to alternative oxidases, selenium, sensory quality, food composition, and organic agriculture have been recorded in the last six years (Figures 2A-E).
- Cross-cutting topics (basic themes) included studies on broccoli and other cruciferous crops. Furthermore, studies on pests such as *Plutella xylostella*, the evaluation of the *Bacillus thuringiensis* bacterium, and bioavailability studies began. From 1967–2021, postharvest topics (storage, packaging, texture, and senescence), SF, glucosinolates, and antioxidant capacity stood out. Specifically, between 2001 and 2005, the studies on harvest, sucrose, and chlorophyll catabolism became central. During 2006–2010, topics on glutamate, seed, biological growth variation, blanching, heat treatment, respiration, and water reuse started. For the 2011–2015 period, studies on selenium, reactive oxygen species, and shelf life were recorded. Between 2016 and 2021, new research topics arose, such as broccoli sprouts, oxidative stress, digestibility, and *in vitro* cultivation (Figures 2A-E).
- Emerging topics (emerging or declining themes), such as glucosinolates, isothiocyanates, and membrane oxidation, stood out in the 1967–2000 period; between 2001 and 2005, the competition topic emerged. For the 2006–2010 period, studies on digestibility, accumulation, plant and soil germination, and anthocyanins were conducted. From 2011 to 2015, research began on broccoli leaf conservation, tillage management, and weeds. Finally, between 2015 and 2021, research on methyl jasmonate, color, and drying was performed. Thus, the research dynamics in broccoli have generated emerging topics that later became driver, basic, or niche topics (Figures 2A-E).
- Highly developed topics (niche themes) appear in more than one period (Figures 2A-E). The first studies on crop residues were envisioned, and studies on the circular economy were conducted. Specifically, the following were found by period. From 1967 to 2000, no scientific advances were identified in the broccoli chain. In 2001–2005, nitrous oxide and tantalum powder were investigated; selenium was studied between 2006 and 2010, and studies on methyl selenocysteine, volatile issues, evapotranspiration, and leaf area index were registered. Organic matter expression, cardioprotection, ischemia/reperfusion, antibody-dependent issues, glutaredoxin, cell-mediated immunity, cytokines, and Ehrlich ascites carcinoma were also recorded. From 2011 to 2015, topics such as sprouts, *Helicobacter pylori*, diabetes, sprouts,

oviposition, S-methyl cysteine, sulfoxide, assimilation, crop residues, sulfate, and organic carbon were found. For the 2015–2021 period, studies on yellowing, cytokine oxidase, heat shock proteins, alternative feedstuffs, and circular economy were conducted in broccoli.





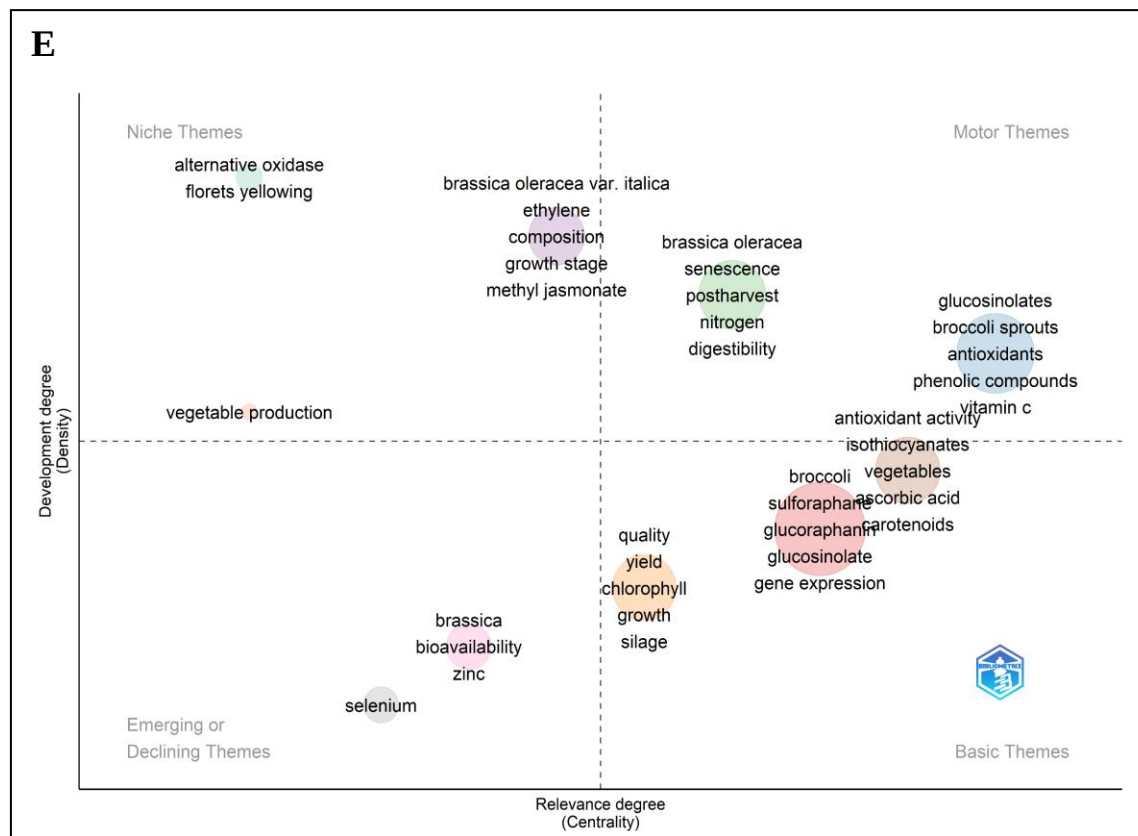


Figure 2. Thematic maps. Evolution of technology insertion in the production chain of broccoli per period. **A.** 1967–2000, **B.** 2001–2005, **C.** 2006–2010, **D.** 2010–2015, and **E.** 2015–2021.

Source. Prepared by the authors based on Scopus®, WoS®, and AgroExplora®. Data retrieved in August 2021. Analysis software: Bibliometrix 4.0

Categorization of Research Insights and Technologies

In the analysis of research insights and technologies related to the senescence topic (Table 2), promising techniques were found to preserve broccoli and other vegetables and improve the physical and nutritional quality during postharvest, transport, and sale. Most treatments described improved floret fading and chlorophyll degradation leading to delayed senescence, a characteristic that determines quality loss in broccoli. Regarding storage, packaging, transport, and shelf-life processes (Table 2), research insights and technologies that evaluated the decrease in heat were identified, and microbial reduction and maintenance of the nutritional balance applied to broccoli florets (head), leaves and stems. Research continues in coating films (polymers and biopolymers) and controlled atmospheres as feasible research insights and technologies to maintain intrinsic (chlorophyll and reduction of sucrose levels) and extrinsic quality (suppression of yellowing and texture), low-cost research insights and technologies that extend the shelf life of the product.

Regarding the research insights and technologies identified in the quality topic (Table 2), refrigeration is suggested as an adequate technology to preserve the quality of broccoli by-products for a short time under storage since high volumes of broccoli by-products, i.e., between

20 and 129 t/ha (Henao-Rojas et al., 2020), must be processed quickly in the industry and avoid decomposition. At the same time, refrigeration increases the commercial value of broccoli since, visually, the products are usually pleasant and maintain their sensory and microbial quality in fresh and minimally processed broccoli (Table 2).

Furthermore, its combination with other treatments provides effective and convenient methods to maintain or improve the antioxidant capacity of broccoli compounds. Research insights and technologies that evaluated drying optimization to preserve the quality of glucosinolates and the possible degradation of nutritional contents were identified in the drying topic. In this process, the variables still measured are temperature, moisture content, and dry matter. Likewise, studies on the influence of particle size on drying speed, yield, color changes, and texture of broccoli powder were identified (Table 2).

Table 2 identifies studies regarding broccoli by-products' physical, chemical, and physicochemical characteristics. Given their concentrations of biofunctional compounds and micronutrients, these are potentially usable for the dietary supplement industry.

Regarding the research insights and technologies identified in the health topic (Table 2), it is essential to consider that the entire broccoli plant (florets, head, stem, and leaves) should be cultivated safely to preserve quality and potentially enhance bioactive components, particularly glucosinolates. These compounds possess anti-inflammatory, anticancer, and antioxidant properties, which help prevent diseases such as metabolic syndrome, diabetes, obesity, hypertension, and autoimmune disorders. Additionally, fresh by-products should be marketed to promote their health benefits.

The identified trends suggest that broccoli by-products are a source of nutrients and phytochemicals and provide a scientific basis for their use as potent and easily affordable nutraceutical or functional foods.

Table 2. Prioritization of research insights and technologies by postharvest, added value (by-products), bioactive compounds, integrated crop management, and genetic breeding thematic clusters

Technology or Research Approach	Research Source	Number of Citations***	Use of Surplus* (%)	Was It Useful? **
<i>Research insights and technologies in the postharvest cluster—Senescence</i>				
Ultra-violet radiation (UV-C)	Duarte-Sierra et al. (2019)	9	52	Yes
	Martínez-Hernández et al. (2011)	69	52	Yes
Modified atmospheres with 1-MCP 1-methylcyclopropene	Xu et al. (2016)	23	52	Yes
Modified atmospheres with ethanol vapor	Asoda et al. (2009)	60	52	Yes

Technology or Research Approach	Research Source	Number of Citations***	Use of Surplus* (%)	Was It Useful? **
LED light exposure	Hasperué et al. (2016)	39	52	Yes
Hydrogen sulfide (H ₂ S) or DL-propargylglycine (PAG) inhibition treatments	Li et al. (2017)	38	52	Yes
Cytokinin-based inhibition treatment	Gómez-Lobato et al. (2014)	16	52	Yes
Preservative formulations of 6-BA and 0.2 % SBN	Wang et al. (2020)	1	100	Yes
<i>Research insights and technologies in the postharvest cluster—Storage (packaging, transport packaging, and shelf life)</i>				
Packings using three types of polypropylene films and modified atmospheres	Serrano et al. (2006)	129	52	No
Polymeric membranes with UV filters	Olarte et al. (2009)	64	52	No
Gene (<i>BoCAT</i>) induction to enhance heat tolerance	Chiang et al. (2014)	20	48	Yes
Basic research on measurement of the effects of different stalk lengths on the mineral content	Guo et al. (2018)	3	48	Yes
<i>Research insights and technologies in the postharvest cluster—Quality</i>				
Moderate UV-C pre-treatment	Martínez-Hernández et al. (2011)	69	52	Yes
Edible coatings of biopolymers	Ansorena et al. (2011)	43	48	Yes
Effect of ACC (1-aminocyclopropane-1-carboxylic acid) synthase (ACS) in stem tissue	Kato et al. (2002)	31	48	Yes
Supercritical fluid extraction (SFE)	Arnáiz et al. (2011)	21	48	Yes
Low-temperature steam heating	Kaneko et al. (1999)	14	48	Yes
Blanching treatments at an industrial scale	García-Saldaña et al. (2018)	5	52	Yes
<i>Research insights and technologies in the postharvest cluster—Drying</i>				
Degradation of nutritional compounds such as glucoraphanin (GR) and vitamin C (Vc)	Jin et al. (2011)	27	52	Yes
Mathematical model for predicting quality changes in the drying process based on free	Jin et al. (2011)	18	48	Yes

Technology or Research Approach	Research Source	Number of Citations***	Use of Surplus* (%)	Was It Useful? **
volume and Maxwell-Eucken theories				
Osmotic dehydration as pre-treatment followed by microwave-assisted warm air drying as finish drying	Md Salim et al. (2019)	5	48	Yes
<i>Research insights and technologies in the added-value cluster—By-products</i>				
Chemometrics and nanotechnology carriers	Mehta et al. (2010)	214	100	Yes
Glucoraphanin hydrolysis processes	Matusheski and Jeffery (2001)	173	100	Yes
Multi-residue determination of pharmaceuticals	Wu et al. (2012)	90	100	Yes
Broccoli leaf powder (BLP)	Drabińska et al. (2018)	33	48	Yes
Production performance and egg quality of laying hens fed with BLP	Hu et al. (2011)	21	100	Yes
Functional soup rich in bioactive sulforaphane	Alvarez-Jubete et al. (2014)	17	100	Yes
Ultrafiltration of broccoli juice	Yilmaz and Bagci (2019)	5	100	Yes
Extrudates enriched with broccoli	Bisharat et al. (2015)	3	100	Yes
<i>Research insights and technologies in the bioactive compounds cluster—Human health benefits</i>				
Spectrophotometric analysis of the antioxidant activity of vegetable extracts	Kaur and Kapoor (2002)	731	100	Yes
Bioactive components	Borowski et al. (2008)	78	52	Yes
Comparison of polyamine, phenol, and flavonoid	Lima et al. (2008)	55	48	Yes
Analysis of total glucosinolates	Rybarczyk-Plonska et al. (2016)	29	48	Yes
Functional food seeds and sprouts	López-Cervantes et al. (2013)	23	0	Yes
Sulforaphane through macroporous resins (broccoli seeds)	Li et al. (2008)	14	0	Yes
Benzylglucosinolates analysis by HPLC	Miranda Rossetto et al. (2013)	19	0	Yes
<i>Research insights and technologies in the integrated crop management cluster</i>				

Technology or Research Approach	Research Source	Number of Citations***	Use of Surplus* (%)	Was It Useful? **
Effects of fertilization conditions vs. vitamin C content	Vallejo et al. (2003)	91	52	Yes
Multiwalled carbon nanotubes	Martínez-Ballesta et al. (2016)	61	52	Yes
White and blue light-emitting diodes (WB LED)	Hasperué et al. (2016)	35	52	Yes
<i>Research insights and technologies in the genetic breeding cluster</i>				
Protocol for freeze storage and lightless conditions	Wojciechowska et al. (2013)	7	48	Yes

* Use of the surplus that remains from using the technology (%)

** Results of the technology. Was it useful? Yes/No

*** Received until August 2021

Source: Prepared by the authors.

Phase III. Advances in the Technological Development of Broccoli

The innovations and technologies identified in the patents found (123 applications, of which 18 have been granted) validated broccoli powder as a raw material to produce food and pharmaceuticals that can generate profits for producers, processors, and marketers using the entire plant. The highest volume of patents for product development with broccoli powder occurred in 2017, when 26 patent applications were filed, with the trend growing between 2014 and 2018 by the Republic of Korea (20) and China (18), as well as by Japan, the United States, and Canada.

Broccoli is considered an attractive food for industrial processes due to its high nutritional content and is consistent with most of the identified developments, which are part of the chemistry and food chemistry area (102), the science with the most patents, followed by pharmaceutical products (11) and mechanical engineering (10 patents). The latter includes methods or machinery to conduct the broccoli dehydration process. The information obtained from the patents allowed an analysis of the keyword networks identified in the abstract and title of the patents. This analysis allowed the identification of the clusters related to the use of broccoli, in this case, broccoli powder. Figure 3 describes the four clusters identified in the Scopus and WoS networks.



Source. Prepared by the authors based on PatentInspiration® web app data retrieved in August 2021. Analysis software: VOSviewer 1.6.17

Regarding storage and senescence research, key technologies focus on delaying or accelerating the maturity of physiological processes and managing temperature and humidity conditions with or without storage (i.e., packing). Cooling, freezing, and chilling conservation technologies are suitable for broccoli surplus volumes between 20 and 129 tons/ha.

Milling and drying processes are suitable for broccoli powder preparation. However, microwave technology is only suitable for small volumes (small-scale industries) due to high energy costs (Xu et al., 2020). Furthermore, these technologies, which have added-value characteristics, contribute to preserving phytochemicals, secondary metabolites, and bioactive compounds (Korus & Lisiewska, 2011). Preserving these compounds enhances the design of food, cosmetic, and pharmaceutical inputs, as well as products with highly antioxidant and anticancer activities for specific market niches.

Finally, it is vital to recognize the relevance of research on crop management processes, mainly on stress physiology (abiotic, biotic, and anthropic stresses), to improve bioactive compound content (Córdova et al., 2020). In the case of broccoli production systems, the research and development opportunities comprise adopting, using, and adapting technologies assessed in other crops.

Conclusions

Analyzing trends in research insights and technologies related to the utilization of broccoli by-products has revealed significant advancements in postharvest and processing techniques within the vegetable production system. This diversification of scientific and technological progress represents an opportunity to propose new research projects. It underscores the importance of conducting scientific intelligence studies to understand the current state of research and identify gaps where new contributions can be made. Potential allies can also be recognized by identifying the research community cluster or niche.

The focus on circular economy principles in utilizing broccoli by-products offers promising prospects for agro-industrial development. This is an economic opportunity for small- and medium-sized producers, contributing to the productivity and sustainability of agriculture in Colombia. Implementing a waste management model through environmental education, bioremediation, and by-product utilization can bring about a cultural shift in broccoli production practices.

Proposing the design and implementation of quality and safety practices for by-product management ensures that surplus materials meet market requirements. This can lead to the development of value-added products, serving as a reference for market niche development at the national level. Aligning with megatrends in scientific research, such as bioeconomy and circular economy, establishes a coherent research direction. While current research insights primarily focus on using broccoli florets or heads, there is potential to validate these insights on by-products like stems and leaves. Exploiting these by-products can diversify the vegetable production chain and extend to other vegetables, enhancing business opportunities.

The transfer, adoption, and adaptation of postharvest technologies depend not only on factors related to productive units but also on abiotic stresses affecting product availability and quality. Therefore, a comprehensive approach considering technological and environmental factors is essential for successful implementation.

Future analyses should consider specific capacities of production units and market trends when assessing suitable research insights and technologies for exploiting broccoli surplus. Evaluating technologies for pretreatment, drying, and preserving bioactive compounds like SF and glucosinolates can lead to developing fortified foods with added value.

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Authors' Contributions

All authors made writing contributions and corrections to the manuscript. The contributions made by the authors were as follows: Diego Hernando Flórez Martínez: design and development of methodology, analysis, and revision and writing of the manuscript final version; Luz Mary Quintero: design and development of project, data collection, analysis, and writing of the manuscript first version; Adriana del Pilar Zambrano: data collection, data normalization, analysis, and writing of the manuscript first version.

Ethical Implications

The authors declare that this article has no ethical implications.

Conflict of Interest

The authors declare no conflicts of interest in this study.

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