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Research article

Methodological framework for supporting phytochemical bioprospecting re-search: A case study on carrot (*Daucus carota* L.) crop by-products

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ABSTRACT

Carrots are among the most crucial and globally preferred vegetables, widely recognized for their importance as a source of phytonutrients, including phenolic compounds, carotenoids, polyacetylenes, and ascorbic acid. However, its production phase incurs substantial losses, estimated at 30 %; these discarded carrots typically find application in animal feed, composting material or organic waste. Therefore, this study aims to develop a methodological framework focusing on the application of a phytochemical bioprospecting process based on scientific surveillance; using carrot crop by-products as a foundational example. Advanced methodologies, such as bibliometric, scientometric, and patent analyses, supported by technological tools such as VOSviewer and Patent Inspiration, were employed. This involved the creation of scientific landscapes, trend maps and co-occurrence networks, intending to explore the potential of carrot crop by-products, their applicability in generating new knowledge, and their utilization in the industry. This approach facilitated the identification of emerging trends in scientific research, providing a comprehensive view of commercial and industrial areas of interest, with a focus on circular economic principles. Furthermore, the study emphasized the importance of bioprospecting, supported by these methodologies and technological tools, as a key factor in the research process on the potential uses of carrot crop by-products, which could extend to other matrices.

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1. Introduction

One of the main goals of sustainable management of natural resources is the continuous and methodical search for new biological sources that may have commercial value. As a result, the use of surplus production and by-products produced by the agro-industry appears to be a very interesting alternative [1]. Food and vegetable production and processing are thought to be responsible for 14,8 % of waste generated by the food industry [2]. The food industry is currently interested and very concerned about these waste products, also known as by-products or co-products, due to their intrinsic effects on the environment and the economy [3,4]. Thus, work must be done to reintegrate them into the production chain, particularly if a sizable fraction is still safe and valuable [5].

Carrot (*Daucus carota* L.) is one of the most important and widely consumed vegetables globally [6], with a production of 41,7 million tons cultivated on 1,1 million hectares in 2021 [7]. Carrots are a well-known source of phytonutrients with high nutraceutical potential. These phytonutrients are mainly of four types: phenolic compounds, carotenoids, polyacetylenes, and ascorbic acid. It also has antioxidant compounds, vitamins, dietary fiber, and minerals [8–10]. Just the production stage losses, which include harvest and post-harvest losses, can, however, be close to 30 % [1,11], equivalent to 12,5 million tons in 2021 alone [7].

These losses refer to carrots that are discarded due to their uniqueness in size, length, shape, color, or mechanical damage [12]. Three categories are required for carrots in Colombia: the extra category, which includes carrots without flaws, regular shape, and free from freezing effects, bruises, or burns; the first category, which has a good appearance and accepts minor flaws; and the second category, which accepts flaws that do not affect quality, such as healed burns and wounds [13,14]. In contrast to the maximum recorded price of carrots in the additional category, which is 1,55 USD/kg, carrots that do not meet these selection criteria are typically sold for extremely cheap prices, with a maximum value of only 0,14 USD/kg [15,16]. Alternatively, they might not be commercialized and turn into a production surplus, in which case they are discarded, usually used for animal feed, compost material, or organic waste [12,17].

The rising demand for food directly contributes to the increase in waste or by-product generation, furthermore, the lack of knowledge regarding the nutraceutical and/or phytochemical composition of these by-products emphasizes how critical it is to use the principles of circular economy in the search for high-value molecules [18]. It is a well-known fact that pharmaceutical, cosmetic, agro-industry, food (both animal and human) and vegetable processing residues still contain a considerable amount of bioactive compounds of interest. These residues offer an easily accessible supply of high-value compounds [3,4,12,18,19]. In 2014, Baiano focused on the components that could be sold that are found in food industry waste and by-products. The goal was to explore and use high-value molecules such as proteins, polysaccharides, fibers, flavorings and phytochemicals as nutritional and pharmacologically functional ingredients [20]. As a matter of fact, these residues are being used as a source of bioactive compounds [3,21,22], in the generation of products with high added value, such as chemical and pharmaceutical inputs [2,12,23], or in the production of biofuels and other biorefinery products [24,25].

Regarding carrots, waste or by-products are now being utilized as raw materials or sources to produce high-value molecules. In order to produce biofuels, authors such as Clementz et al. (2019) and Jyot Kaur et al. (2020) have devised valorization methodologies for surplus production by extracting carotenoids, fiber, and fermentable sugars [12,17]. Furthermore, research has demonstrated the application of carrot pulp powder as a plentiful source of fiber, carbohydrates, and minerals, suggesting that it has the ability to improve the nutritional value of foods that are included [6]. Thus, it is crucial to identify and retrieve high-value molecules from waste and by-products in the carrot production chain. This is accomplished by creating a bioprospecting study.

The exploratory study of biodiversity concerning the search for biologically active substances with potential applications in industry, agriculture, and medicine is known as bioprospecting [26], its ultimate goal is to investigate biodiversity in hopes to identify key bioactive compounds, phytochemicals in bioprospecting of plants, that can be beneficial to humanity, as plant-based drug development [27]. Therefore, it is essential to understand current market trends by exploring publications, research articles, reviews, and relevant patents to achieve an effective bioprospecting process [28,29]. In order to accomplish this, technology tools are necessary to facilitate the analysis of existing and published information pertaining to the target matrix [30,31]. Therefore, a crucial first step in the bioprospecting process can be well-directed scientific or technical surveillance. Its goal is to seek, gather and evaluate information to turn it into knowledge that will support decision-making since it is a methodical, structured and selective process of monitoring the scientific and technical environment [32–34]. Two methods can be used to build this search: collection, standardization, and analysis of scientific data associated with scientific publications, such as articles; and collection, analysis, and normalization of patentometric data associated with intellectual property protection mechanisms, like patents [35].

Numerous studies are currently being conducted with an emphasis on the development and implementation of technological monitoring, scientific monitoring or bibliometric or patent analysis processes. These efforts aim to determine, across various agri-food matrices, the key players, trends, applications, and emerging literature, as well as scientific and patent productivity [30,36–38]. Furthermore, several studies have suggested a roadmap for their valuation [39]. Regardless of whether it involves an agri-food matrix, its production surplus, by-products, or waste, very few studies use this methodology as a basis for the application of a bioprospecting process [28]. The current work, which uses the surplus of carrot production as a foundational example, aims to develop a methodological framework that focuses on the application of a phytochemical bioprospecting process based on the development of scientific surveillance, and establish guidelines for the replication of these methodologies in different matrices and fields of study.

2. Materials and methods

2.1. Search strategy and data collection

Using the term "carrot" as the target of investigation in a search equation, the search technique was developed. The terms "*Daucus carota*", "carrot" and "zanahoria", were used in the initial build. The second construct dealt with the work object, more precisely terms associated with carrot cultivation by-products, their chemical characterization, and their uses in the food and cosmetic pharmaceutical sectors. A focal point was provided by a third construct that combined terms from the circular economy and bioeconomy. A fourth construct focused on terminology related to the agronomic features of carrot farming by using thematic or conceptual exclusions. Lastly, restrictions were applied to the duration that was used in the search equation.

The creation of this search approach enables the aggressive and targeted gathering of data concerning the exploration of a bioprospecting procedure, particularly in the by-products of carrot farming. Therefore, the established equation was used for both bibliometric data search, primarily collected from scientific articles and review articles using the Scopus® database, and patentometric data collection using the PatentInspiration® tool.

2.2. Bibliometric analysis

The Scopus® database was directly consulted to obtain details about the chosen papers, including authors, study fields, and publication counts. Scientific journals, research and review articles, books, patents, and other sources are only a few of the many sources of information that this application compiles and arranges.[1] This is achieved by extracting metadata from titles, authors, abstracts, and keywords. This is made possible through the use of search algorithms and semantic analysis, taking into account factors such as keywords used, document relevance, journal quality, and received citations [40]. These factors are described through bibliometric indicators implemented by Scopus®.

Rankings by knowledge domains are provided by the Scimago Journal Rank (SJR), which is determined by the number of citations each journal receives over a specific period of time. CiteScore determines the average number of citations received by an article published in a journal over the last three years, whereas Source Normalized Impact Paper (SNIP) assesses citation impact considering the features of each scientific field [41]. Additionally, Scopus® offers visualization and analysis tools for the examination and comprehension of the gathered data through the "analyze results" option, including publishing trend graphs, citation trends, and co-authorship networks [40].

2.3. Scientometric network analysis

The scientific landscape construction program VOSviewer® version 1.6.19, created by van Eck & Waltman (2009), was used to collect and analyze data pertaining to the found publications. By analyzing keywords, terms in titles and abstracts, and chemicals of scientific interest, this program created a number of co-occurrence networks employing overlay and density map features as well as network visualizations. The software analysis is based on mathematical models for network analysis to create visual co-occurrence maps. VOSviewer® arranges and visualizes interactions between metadata obtained through bibliometric searches. These maps show the connections and patterns of co-occurrence among different elements in a dataset, such as keywords, authors, or journals. The program uses network analysis techniques and clustering algorithms to help users discover patterns and understand the connections between the analyzed elements [42].

2.4. Patent analysis

The PatentInspiration® tool was used to directly collect and analyze data related to the publication of patents that were of interest. This web-based app harvest patent data from Europe, Asia, United States and World Intellectual Property Office databases. Powered by context-based and data-driven PatentInspiration enhance data recovery through search algorithms and semantic analysis of relevant terms [42]. Moreover, based on the recovered metadata quality co-occurrence networks were created on VOSviewer® version 1.6.19, using the information regarding the International Patent Classification (IPC) codes for each patent and the use of claims which define the rights sought and demonstrate the significance and value of patent concessions.

Main restrictions for the methodological framework used on this research comprise the database access to enrich the quantity and diversity of scientific publications of carrot value added products; the metadata quality on scientific publications mainly due to the origin sources and heterogeneity on journal indexing protocols; the completeness of patent data based on origin sources (regional patent databases). Finally, in this study every scientific publication metadata was used, by contrast, claims information regarding patents was limited to granted patents.

[1] Scopus® database provided by Elsevier® licensed access, was chosen for metadata recovery main due to the access availability through authors institutional affiliation. Otherwise, the methodological framework proposed in this research can be implemented using metadata for scientific databases such as Web of Science®, PubMed®, Dimensions®, Lens®, and others.

3. Results

3.1. Search strategy and data collection

In the first quarter of 2023, the search was conducted. In order to gather bibliometric and patentometric data, a search equation was developed that included terms associated with carrots as the central matrix of interest, as well as their by-products, characterization, and uses. For the search conducted in Scopus®, the terms used in the equation were included in the semantic parameters of titles, abstracts, and keywords, with a time window beyond 2011 as follows:

TITLE-ABS-KEY(("daucus carota" OR "carrot" OR "zanahoria") AND ("byproduct*" OR "by-product*" OR "coproduct*" OR "bioactive compound*" OR "compound* character*" OR "application*" OR "cosmetic application*" OR "food application*" OR "bioeconom*" OR "circular econom*") AND NOT ("soil*")) AND PUBYEAR >2011).

For the search of patentometric data in PatentInspiration®, the search equation was included in the semantic parameters of titles, abstracts, and claims, considering a time window of ten years from June 2013, as follows:

TITLE-ABS-CLAIMS (("daucus carota" OR "carrot" OR "zanahoria") AND ("byproduct*" OR "by-product*" OR "coproduct*" OR "bioactive compound*" OR "compound* character*" OR "application*" OR "cosmetic application*" OR "food application*" OR "bio-econom*" OR "circular econom*") NOT ("soil*"))

In both search parameters, the keyword "soil" was excluded to prevent the retrieval of articles or patents associated with the agronomic aspects of carrot farming. The result of this search yielded a total of 1.234 publications in Scopus® and 706 patents in PatentInspiration®.

3.2. Bibliometric analysis

The majority of the 1.234 publications that were found were scientific articles, review articles, conference papers, and book chapters written by 159 authors who were connected to 160 institutions. The yearly number of publications over the previous 10 years is shown in Fig. 1, which illustrates a significant increase in publication dynamics since 2013. With a total of 182 articles, the number of publications peaks in 2021, suggesting an overall exponential trend in the accumulation of related articles. The growth rate and doubling time calculations [31,43] make this clear. In this case, the growth rate is equal to 28 % and the doubling time of the publications is equivalent to 2.8 years. This suggests an increase in scientific research production and interest in exploring alternatives for the uses, characteristics, and potential uses of the by-products of carrot farming.

Price's law of exponential growth of science identify the growth rate and the period of time in which the number of publications doubles. This law allows us to identify, based on the accumulated increase in articles published each year, the period of years in which records double and the growth rate. To calculate these two indicators, an analysis of the exponential trend of each of the curves in Fig. 1 is carried out, using equation (1) as follows:

$$y = ae^{bx} \quad \text{(equation 1)}$$

where b is the constant that relates the speed of growth of science to the already acquired size of science (number of initial publications of the period under study) and where the average annual growth rate represents the percentage of growth in publications based in parameter b. Thus, this rate is calculated with equation (2):

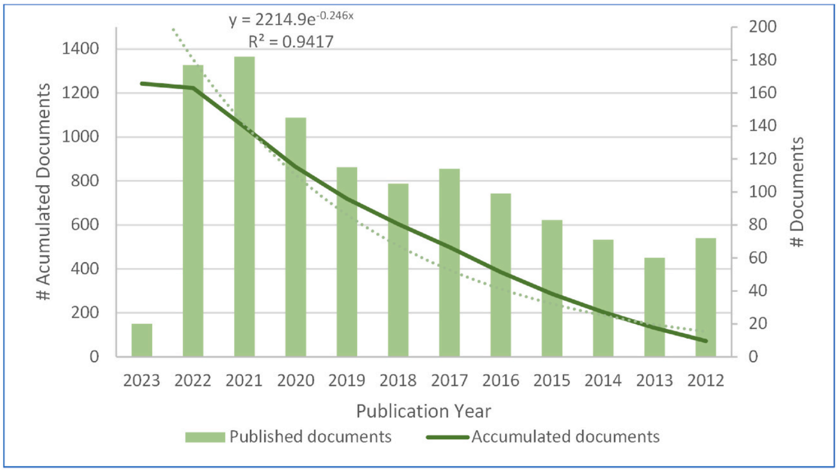

Fig. 1. Distribution of publications over time. Own preparation in Excel based on the information available in Scopus®. Consultation date: April 2023.

$$R = 100(e^b - 1) \quad \text{(equation 2)}$$

For its part, the doubling time establishes the equal periods of time in which the science or the magnitude under study related to it grows twice as much. Equation (3) measures this time as a function of the parameter b and is defined as:

$$D = Ln(2)/b \quad \text{(equation 3)}$$

It was also possible to determine the main areas of research: biological and agricultural sciences represented 29,4 % of the total number of publications, followed by chemistry (10,1 %), biochemistry, genetics and molecular biology (8,3 %), and pharmacology, toxicology, and pharmaceuticals (3,3 %) (Fig. 2). This establishes a connection between the current trend of publications in terms of research areas and the object of interest in this study.

Identification of the journals with the highest number of publications serves as evidence of this. This makes it possible to understand the current interests of these publications, the authors behind them, and how they relate to the current research from a bioprospecting perspective using by-products from carrot farming. Furthermore, understanding the impact index and importance of these publications can be achieved by determining their place or quartile in the SCImago ranking. Consequently, the following are the top five journals with the greatest number of publications, together with their corresponding quartiles: Journal of Food Processing and Preservation (Q2 and 47 publications), Food Chemistry (Q1 and 37 publications), Acta Horticulturae (Q4 and 30 publications), Foods (Q1 and 30 publications), and Journal of Food Process Engineering (Q2 and 25 publications) [47]. These journals provide insights into the topics covered in articles and other publications on the chemical, biochemical and functional fundamentals of food, particularly those related to their processing and preservation, properties, quality, and engineering-based manufacturing.

3.3. Scientometric network analysis

3.3.1. Semantic keywords network analysis

Using the bibliometric mapping program VOSviewer® (version 1.6.19), a scientific landscape was constructed based on keywords found in publications retrieved from the Scopus® search (Fig. 3). This visualization provides an intuitive representation of the overall trend of the publications, specifically the information related to keywords and their frequency.

The size of each node indicates how frequently it occurs; larger nodes are more frequent and significant than smaller ones. The network also makes it possible to visualize how keywords interact with each other and cluster together, which is useful for identifying research areas where terms are more closely related. Regarding this study, the keyword network shows five clusters (Fig. 3), offering information about the most prominent topics and their relationships, especially with regard to by-products of carrot farming.

The red cluster – Bioactive compounds, encompasses different chemical substances including carotenoids, beta-carotene, phenols and polyphenols, anthocyanins, flavonoids, ascorbic acid, among others, identified as compounds of interest in carrots [10,48]. Alongside the main functional property, antioxidant activity (Fig. 3), it is possible to establish a close and direct correlation between this attribute and the many bioactive compounds present in carrots [49,50]. Apart from the above, there is a direct correlation between these bioactive compounds and their antioxidant activity and keywords corresponding to pigments present in carrot juice [49,51,52]. Suggesting a connection with terms such as functional foods. This enables the interpretation of their addition to other matrices as a fortification process, similar to the work described by Camargo-Herrera et al., 2022, which phytochemicals from carrots, such as carotenoids, fiber and polyphenols, are added to a dairy beverage to create a probiotic [53]. Furthermore, words related to the

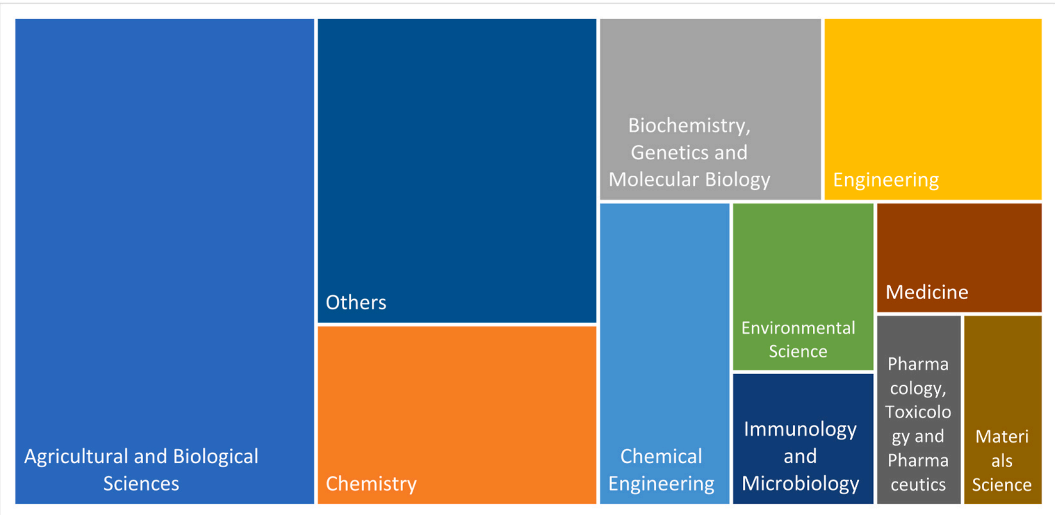

Fig. 2. Distribution of publications by research areas. Own preparation in Excel based on the information available in Scopus®. Consultation date: April 2023.

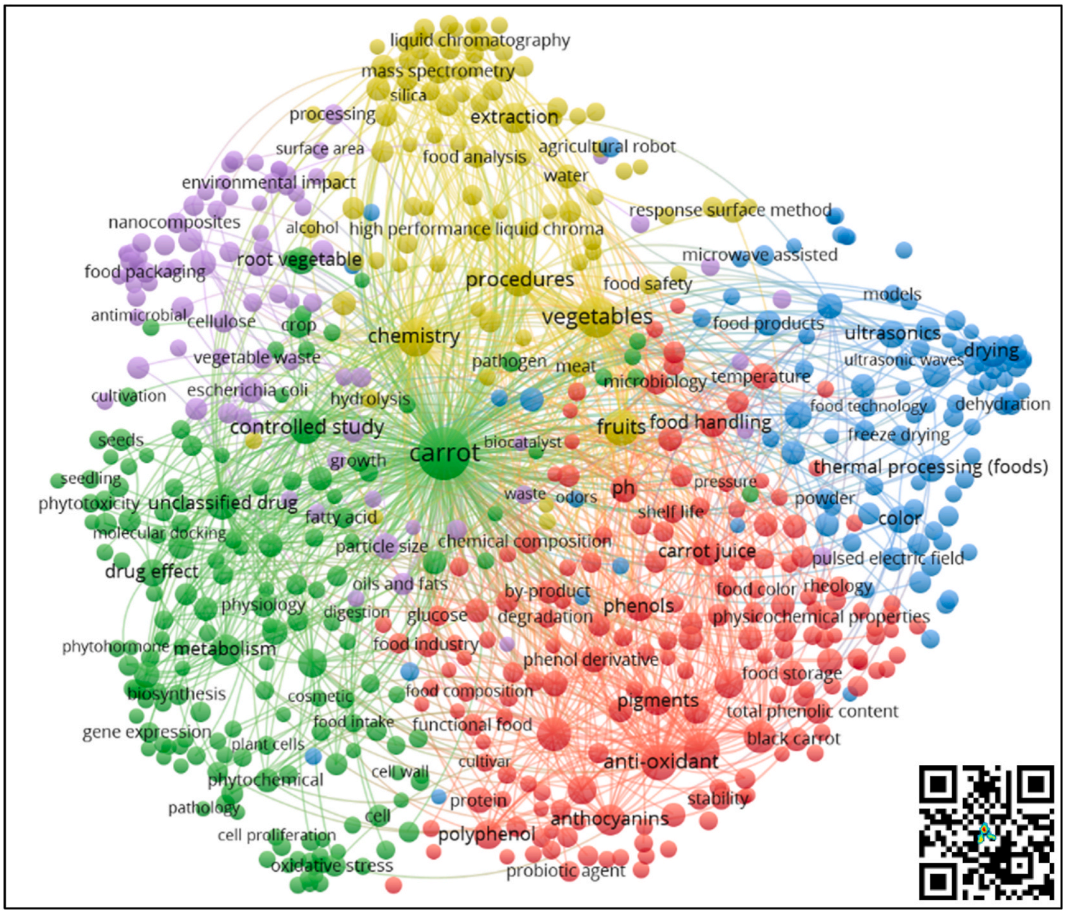

Fig. 3. Scientific landscape of general trends. Own preparation using VOSviewer® based on information available in Scopus®. Consultation date: April 2023. *The distance between nodes indicates their relative closeness, while node size represents the frequency of each keyword in the scientific documents (knowledge core). Furthermore, color categories classify keywords into specific clusters according to their thematic relatedness.

physiochemical characterization of carrots can be identified, including fiber content, sugars, fat, pH, vitamins [54,55].

Keywords related to carrot extracts, including essential oils, or terms linked to unclassified medications are placed in the green cluster, Functional Properties (Fig. 3). These have properties that are antifungal, anti-infective, antimicrobial, or antioxidant and are connected to the metabolism of carrots [56–58]. Because of their neutraceutical composition, these relationships also enable the association of these properties with terms such as medicinal plants, phytotherapy, and phytochemistry, and certain health benefits [9,10,59,60]; as the work focused on the carrot phytochemicals and their health benefits, described by Ahmad et al. (2019) [10] In addition to including some transformation techniques associated with carrots, such as drying processes (convection, solar, microwave, and freeze drying, among others), the blue cluster, Transformation and extraction of compounds, brings together terms related to food processing, production, and preservation [61,62]. Moreover, correlations between various bioactive compounds and their respective antioxidant activities and extraction methods such as sonication or ultrasonic applications can be found [63].

The yellow cluster, Bioprospecting, connects various terms associated with chemistry, chemical analysis, and food analysis, along with techniques to detect and identify compounds, such as chromatography, spectrophotometry, and mass spectrometry, among others (Fig. 3). Carrots and their by-products are frequently characterized using these methods [64,65], as the work described by Cubero et al. (2008), where metabolomic studies are implemented in carrot [66]. However, generally speaking, these techniques have been implemented as tools in the processes of characterization and phytotechnical bioprospecting [26]. They are, therefore, the most assertive methodologies for this kind of process. It is worth noting that analyzing these methods helps to understand how bioactive compounds interact, as well as their properties and production processes. Finally, the cyan cluster, Circular Bioeconomy, gathers terms from throughout the network that are interdisciplinary, such as circular economy, environmental impact, biocompatibility, and waste utilization [45,67].

From an alternative perspective, Fig. 4 shows the easy identification of the level of novelty in the use of keywords. In other words, it helps to distinguish which topics are recently used and which ones are already consolidated within the scope of the search.

Due to this, the terms that were most prominent in 2017 were those related to conventional carrot drying methods, terms that dealt with methods of separation and detection such as liquid chromatography and mass spectrometry, or terms associated with the

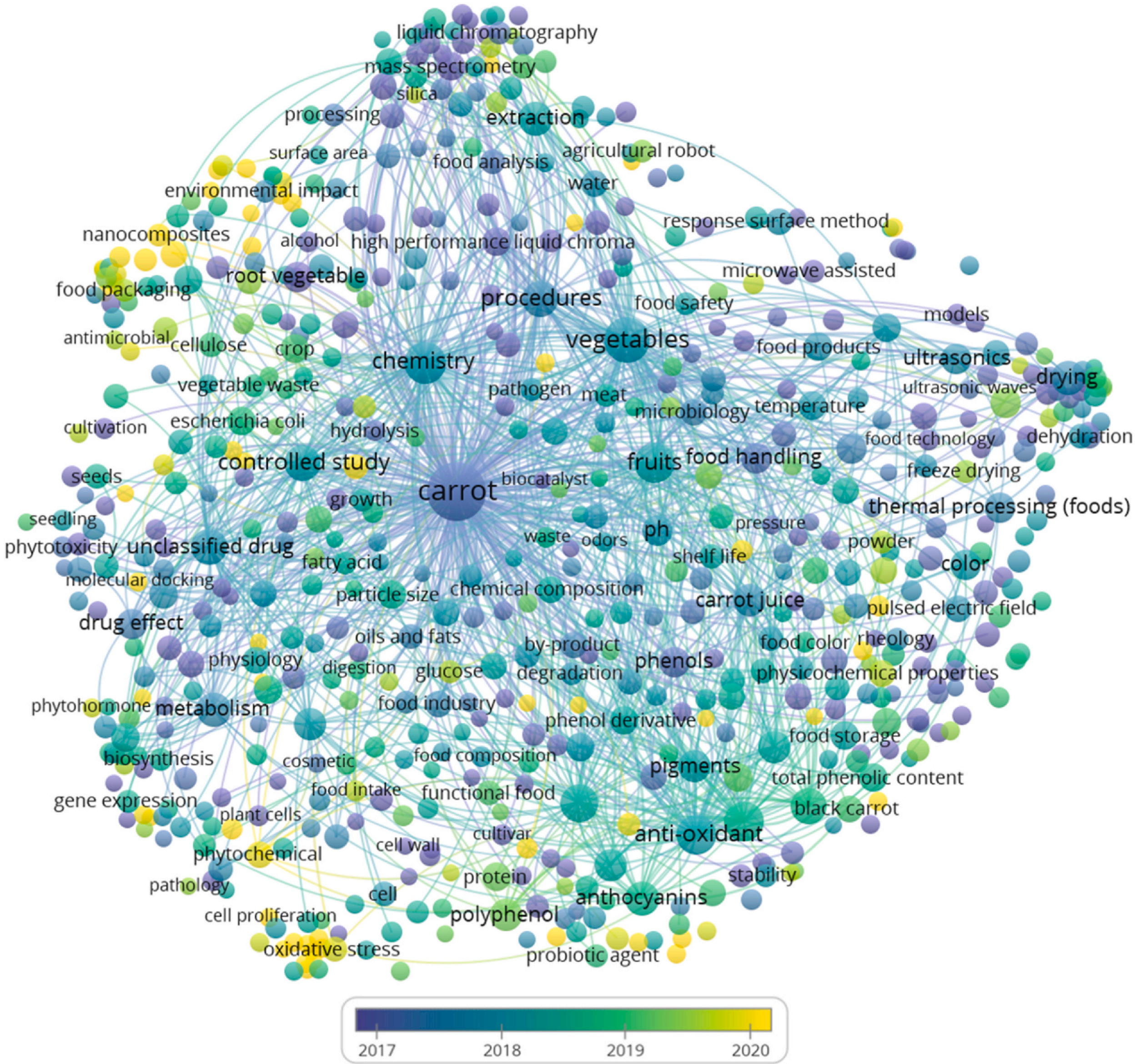

Fig. 4. Transition: Visualization of keyword overlap over time. Own preparation in VOSviewer® based on information available in Scopus®. Consultation date: April 2023. *Chronology of publications in the co-occurrence network based on keywords. Nodes represent words, and the color of the lines connecting the words indicates their chronological order. Blueish colors signify earlier publication times, while green-yellowish colors indicate more recent publication times.

nutritional value, processing, and food industry of carrots. However, it is evident that because cutting-edge topics are still in the early stages of this study, they do not have the highest frequency or the highest number of connections. These include the physicochemical properties of carrots, research areas including phytochemistry, nanocompound analysis, and metabolites from plant extracts such as carotenoids and flavonoids [10,68,69]. The stability of methodologies such as encapsulation or microencapsulation, which are being used as preservation strategies for bioactive compounds such as carrot carotenoid, is also highlighted [70,71]. Microwave support and the use of drying methodologies such as freeze drying to preserve carotenoid in the production of natural dyes are discussed [25,61], as the work described by Gong et al. (2015) where a drying optimization process is implemented in the obtaining of carrot powder [61]. It is emphasized that beta-carotene, fiber, and carbohydrates can be obtained from carrot by-products, including pulp and powder [6, 61]. Besides, terms associated with food packaging technologies, such as nanofibers, biopolymers, and biofilms, as well as concepts about food or agroindustrial waste, their valuation and the principles of circular economy, are discussed [1,45,54].

3.3.2. Scientometric network of research trends

In parallel, a scientific landscape of important texts was constructed using keywords from titles and abstracts. This made it possible to analyze specific trends related to the publications that were retrieved from the Scopus® database within the framework of this study. Six clusters are discernible in terms of formation (Fig. 5).

The main search term appears in the red majority cluster, Functional Activities and Applications in Medicine (Fig. 5). It includes new terms directly related to the isolation and purification of carotenoids present in carrots, which are part of these uncategorized drugs. Although it shares some similarities with the green cluster of keywords in terms related to drug effects, or uncategorized drugs, which are linked to antimicrobial and antifungal activities [56,72], it also differs in that it includes terms related to carrot metabolism. In addition to this, biomolecule-related terminology, including biomass, terpenes, monoterpenes, and secondary metabolites, can be identified in relation to agricultural production or biodegradation of vegetal and food waste [2,19].

The term “antioxidant” is the main emphasis of the green cluster, Carrot phytochemistry (Fig. 5), which shows interactions with chemical families of interest, including phenols, carotenoids, flavonoids, and anthocyanins, among others. Through concepts such as phytochemistry, they are connected to extracts and pigments from carrots and their derivatives [10,56]. Moreover, techniques for generating this kind of molecules are discussed, including encapsulation and microencapsulation [70,71].

Significant parallels may be seen between this cluster and the red cluster of bioactive compounds (red) present throughout the scientific landscape (Fig. 3). The latter, which is consistent with this particular trend in science, emphasizes the connection between the many bioactive compounds in carrots and their functional antioxidant properties. This suggests that various carrot metabolites and their antioxidant capacity are consistently correlated [49].

The blue cluster, Food Transformation and Preservation, and the yellow cluster, Bioprospecting, present in the scientific landscape of specific trends (Fig. 5), exhibit striking similarities with the descriptions found in the scientific landscape of general trends (Fig. 3). Keywords for food processing and methods for metabolite identification and measurement are included, respectively. This makes it easier to apply methodologies and techniques focused on carrot transformation, incorporating them or their by-products into other matrices and identifying the essential bioactive compounds that constitute them [19,20,53]. Despite these similarities, the cyan cluster, Carrot Characterization and Applications, demonstrates a marked distinction by associating the nutritional value and physicochemical parameters of carrots with various aspects of the food industry (Fig. 5), including shelf life, handling, control, microbiology, and food quality [54,69]. These terms are segregated into a new cluster in this particular trend landscape while being recognized in the red cluster of the overall scientific trend landscape (Fig. 3). Finally, the link between the potential antioxidant activity of carrots

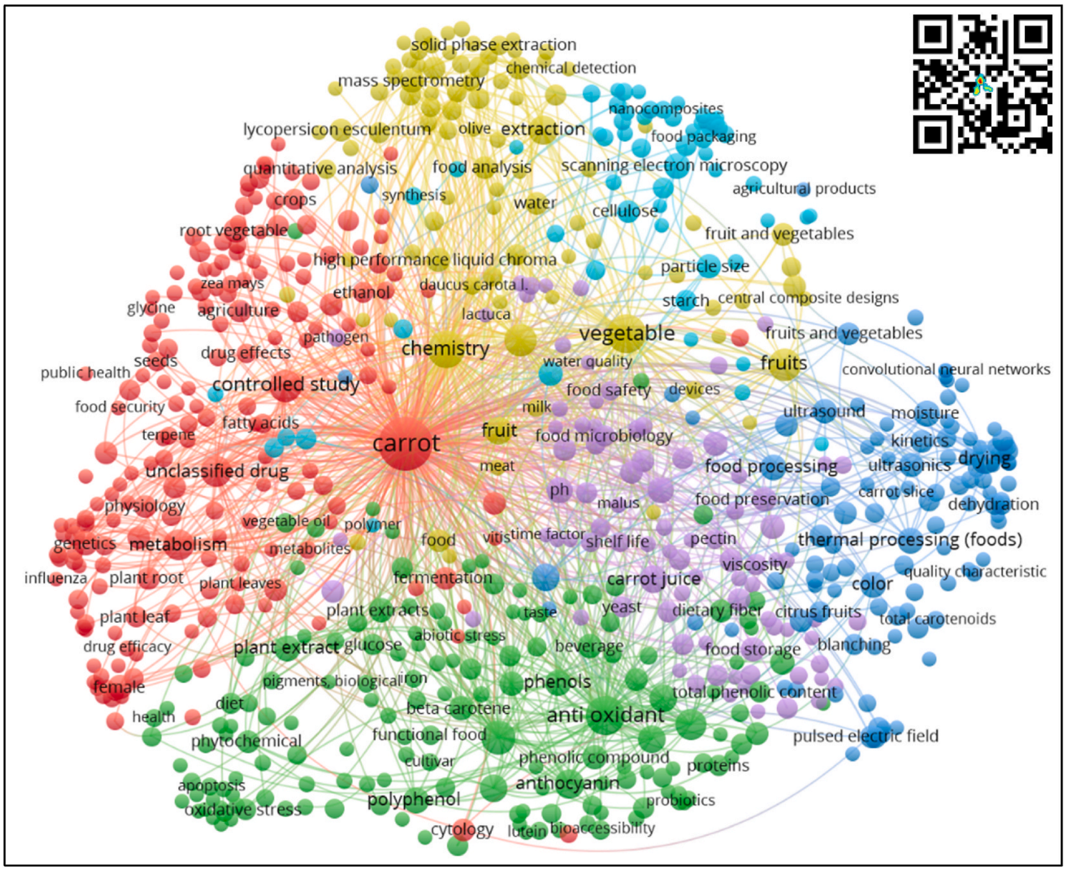

Fig. 5. Scientific landscape of key texts. Own preparation in VOSviewer® based on information available in Scopus®. Consultation date: April 2023. *The distance between nodes indicates their relative closeness, while node size represents the frequency of each keyword in the scientific documents (knowledge core). Furthermore, color categories classify keywords into specific clusters according to their thematic relatedness.

and their antibacterial action against pathogenic microorganisms such as *Escherichia coli* can be made thanks to the purple cluster, Other Applications [72,73].

The association between methods like particle size and carrot cellulose from scanning electron microscopy may also be observed. This cluster also contains several unique terms, such as biocompatibility, biopolymers, and food packaging. In the broader landscape of scientific trends (Fig. 3), this cluster is associated with the biochemistry cluster, wherein terminology related to packaging and biocompatibility is present, although less frequent.

3.3.3. *Interest bioactive compounds network*

A complementary trend map was created with respect to the chemical compounds mentioned in the articles that were consulted, accounting for the registration of the Chemical Abstracts Service (CAS) identification number (Fig. 6). The creation of a co-occurrence network of potential bioactive compounds is made possible by this map. The size of the node on this map represents its frequency and relevance within the network, much like the study of keywords and terms related to titles and abstracts.

Seeing the interactions among the many clusters of this network and the groups based on chemical types or families is fascinating. For example, the chemical compounds in the red cluster belong to the chemical family known as polyphenols. This cluster includes catechin, epigallocatechin and quercetin, which have been found in carrot bagasse [63] and are thought to be the main flavonoids in the human diet [59]. Carrots are thought to contain the highest concentration of vitamin E in the form of tannins, gallic acid and alpha-tocopherol, as well as phenolic compounds, including resveratrol or folic acid [49,74].

Chemicals, including cellulose, pectin, starch, and some monosaccharides, all polysaccharides, are found in the green cluster. This allows the use of carrots and their by-products as a dietary fiber and carbohydrate source [6,54].

Terms related to antibacterial agents are found in the blue cluster. These terms are connected to various chemical compounds found in different clusters, including acetic acid, carvacrol, tannins, terpenes, and ascorbic acid. This cluster also contains chlorogenic acid, which can represent up to 82 % of total phenolic acids in dietary fiber derived from carrots [54]. Numerous metallic elements that are important for human nutrition, such as calcium, manganese, potassium, magnesium, and zinc, are grouped together in the yellow cluster.

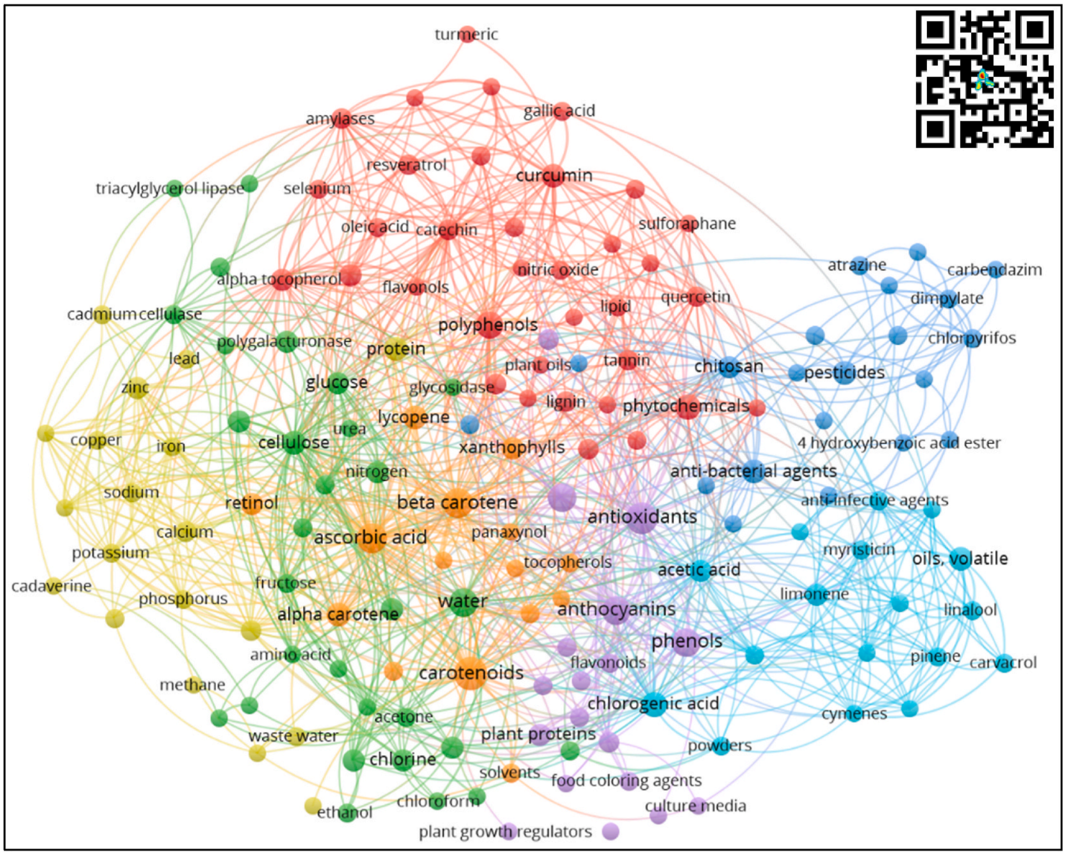

Fig. 6. Cooccurrence network of chemical compounds. Own preparation in VOSviewer® based on information available in Scopus®. Consultation date: April 2023. *Distance between nodes reflects their closeness to each other, while node size represents the number of times each key chemical compound is reported on knowledge core documents based on the American Chemical Society Standards. Furthermore, color categories group chemical compounds into specific clusters based on their relatedness to functional groups or functional characteristics.

The term "antioxidants" appears most frequently within the network in the purple cluster. This term refers to a broad class of chemical compounds that have this characteristic, such as phenolics, polyphenolics and flavonoids found in carrots and their by-products [49,63,75]. Additionally, pigment-related chemical compounds, including carotenoids and anthocyanins, have been connected to applications in food additives as preservatives and colorants [1,53].

Several terpenes, including pinene, carvacrol, cymene, caryophyllene, and limonene, are grouped together in the cyan cluster, those terpenes represent the principal volatile compounds, and are related with aroma and flavor of fresh carrots [76]. The term "anti-infective agent" is associated with these, and different biological activities have been reported related with antimicrobial activity [57,58,73]. Carotenoids are the core and the most commonly occurring term in the orange cluster. This group contains compounds with strong antioxidant capacity, including beta-carotene, alpha-carotene, lycopene, and xanthophylls. Due to their physicochemical structure and characteristics, these compounds are also credited with capabilities that may protect the skin from UV damage and reduce the risk of skin cancer [10,59,77]. Additionally, in this cluster, other chemical compounds were found, such as panaxinol (tocopherol) and vitamin A, or retinol, a compound of great importance in the human diet whose most potent precursor is beta-carotene [60], and ascorbic acid, recognized as a bioactive compound in carrots [64]. Those different carrot crop by-products bioactive compounds and its health benefits are present in Table 1.

The dataset related to the bioactive compounds network of interest has been included as supplementary material.

3.4. Patent research and analysis

A PatentInspiration® tool study was performed on 706 patents that were recovered on the characterization and potential applications of carrot crop by-products. It is possible to determine the primary regions or clusters of patents by taking into account the International Patent Classification (IPC) codes. With 145 patents, the focus of the majority group was on altering the nutritional value of food (Fig. 7). In this category, patents related to the preparation of fermented or probiotic-enriched foods were found [78,79]. These patents also involved the use of fresh carrots or by-products, such as peel, pulp, bagasse, or juice. These patents were created for food matrices with the intention of providing health benefits, including the reduction of visual fatigue [80] or blood glucose levels [81].

Animal feed is a further topic of special interest, with three subareas and 189 patents combined. Patents in this field focus on the formulation of feeds, particularly for the pet industry, with relevant features such as nutritional and oxidative resistance functions mediated by the use of carrot flour and its bioactive compounds, including carotenoids, vitamins, and minerals, among others [82]. Additionally, there are patents related to the use of these compounds in food additive formulations that have the property of eliminating or significantly reducing the harm and residues of dangerous heavy metals in animal organisms [83]. Within the purview of this study, analyzing these two major patents helps to understand the significance of the food and feed production and transformation sector as a trending field in the creation of new knowledge and technology.

Moreover, but to a lesser degree, two categories - cosmetic and medical preparations – were also found, totaling 55 and 37 patents, respectively. Patents in these fields cover everything from the creation of skincare and body care products that reduce wrinkles, lighten freckles, whiten skin, or preserve moisture [84,85] to the extraction of carrot polysaccharide fractions that have the potential to strengthen the immune system [86].

In addition, a co-occurrence network based on the IPC codes of the consulted patents was used to create a scientific patent landscape. Six clusters were discernible in this landscape, providing a clearer understanding of the connections between various trends in patent publishing (Fig. 8). Furthermore, 249 patents from 706 that already have been granted by intellectual property offices, were selected to construct a cooccurrence network of key text based on claims data (Fig. 9).

Upon initial observation, one cluster stands out as clearly distinct from the others: the blue cluster, which represents animal feed. It brings together different patents related to the formulation and production of animal feeds made from carrots or their by-products. Among them are patents specifically targeted at the pet industry, seeking to formulate foods with immune system-boosting or antioxidant effects, that is, nutraceutical animal feed [87,88].

Patents related to the manufacture, formulation and preparation of processed foods, or their modification, are categorized in the green cluster, Food Applications, where carrots or their by-products are being used. Patents specifically pertaining to the cosmetic

Table 1
Principal bioactive compounds in carrots.

Chemical family	Bioactive components	Health benefits
Carotenoids	Beta-carotene, alpha-carotene, lycopene, and xanthophylls.	Skin protection and antioxidant activity
Polyphenols	Catechin, epigallocatechin, quercetin, curcumin, gallic acid, alpha-tocopherol, resveratrol or folic acid, chlorogenic acid and other flavonoids or tannins	Antioxidant and anti-inflammatory activity
Terpenes	Pinene, carvacrol, cymene, caryophyllene, terpinene, and limonene	Antibacterial and anti-infective activity
Saccharides	Cellulose, pectin, starch, carboxymethylcellulose, fructose, sucrose and glucose	Source of fiber
Minerals	Calcium, manganese, potassium, magnesium, copper, iron, cadmium, phosphorus and zinc	Structural components and regulators of body processes
Organic acids	Acetic acid, coumaric acid, cinnamic acid and ascorbic acid	Antibacterial, antioxidant and anti-infective activity
Others	Anthocyanins, chlorophyll, retinol and chitosan	

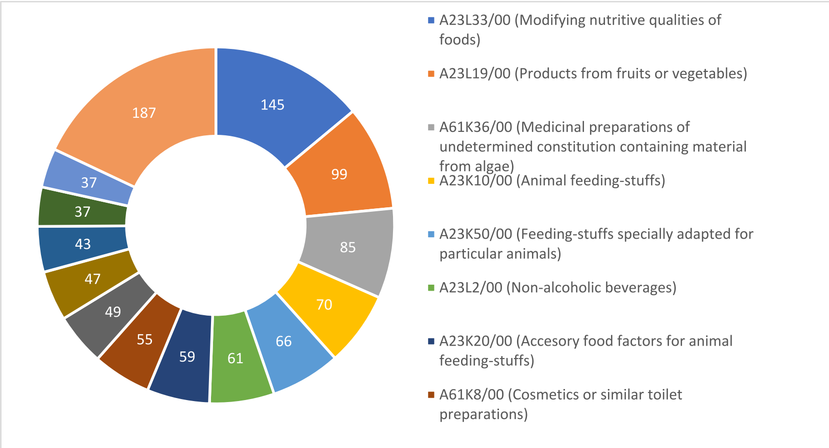

Fig. 7. Trends in patent publications. Own preparation in Excel based on the information available in PatentInspiration®. Consultation date: June 2023.

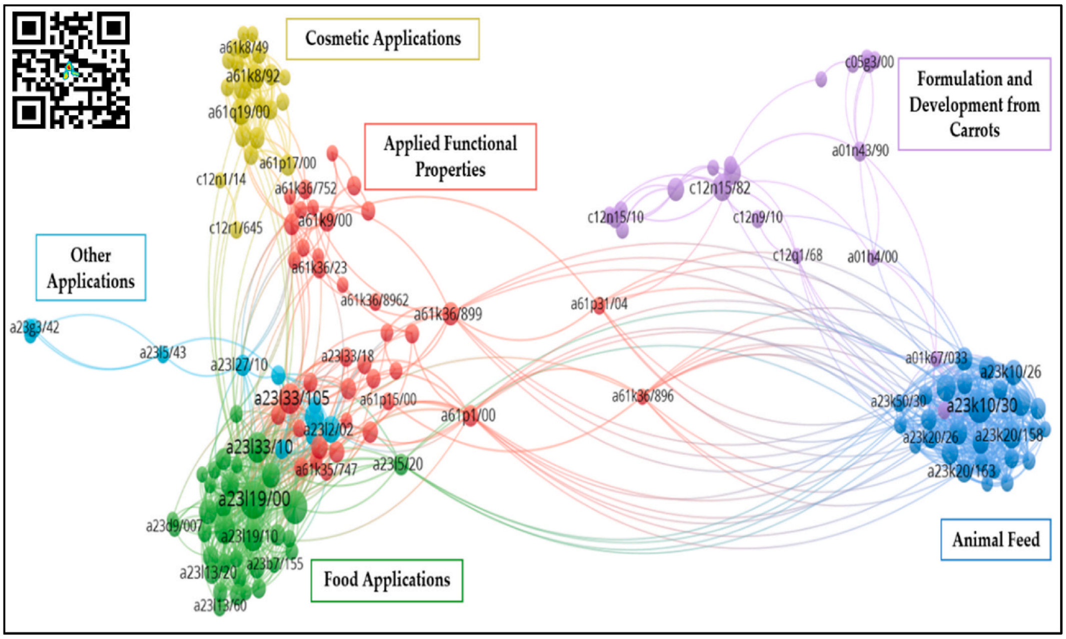

Fig. 8. Scientific Patent Landscape. Own preparation in VOSviewer® based on information available in PatentInspiration®. Consultation date: June 2023.

industry are grouped under the yellow cluster, Cosmetic Applications. Among these patents, there are products that have been formulated and applied to treat the skin, hair, or face using carrots as an ingredient. This cluster includes products such as creams and masks with antioxidant properties, acne removal, or spot reduction [85,89,90]. Yellow, green, and blue clusters represent the areas of greatest interest in terms of producing new knowledge and technology, because they contain the highest number of connected patents related to applied functional properties in red cluster.

Analyzing the patents found in red cluster, which are associated with a bioactive composition or a functional property that has positive benefits for human health, will help to understand this. A number of these patents focus on the formulation of functional foods, while others target the beneficial effects of cosmetic products that contain carrots or their by-products [81,84,90]. This suggests that these patents offer some positive health effects in addition to their focus on the food or cosmetic industry.

The purple cluster, Formulation and development of carrots, collects patents related to the creation of carrot-based beverages or the addition of carrot extracts. It also includes the development of fibers and colorants for use in food (Fig. 8). Finally, the cyan cluster – Other applications - compiles patents pertaining to carrot crop improvement or molecular biology applications.

Fig. 9 embraces the cooccurrence network of granted patents titles and claims that specifies added value characteristics related to

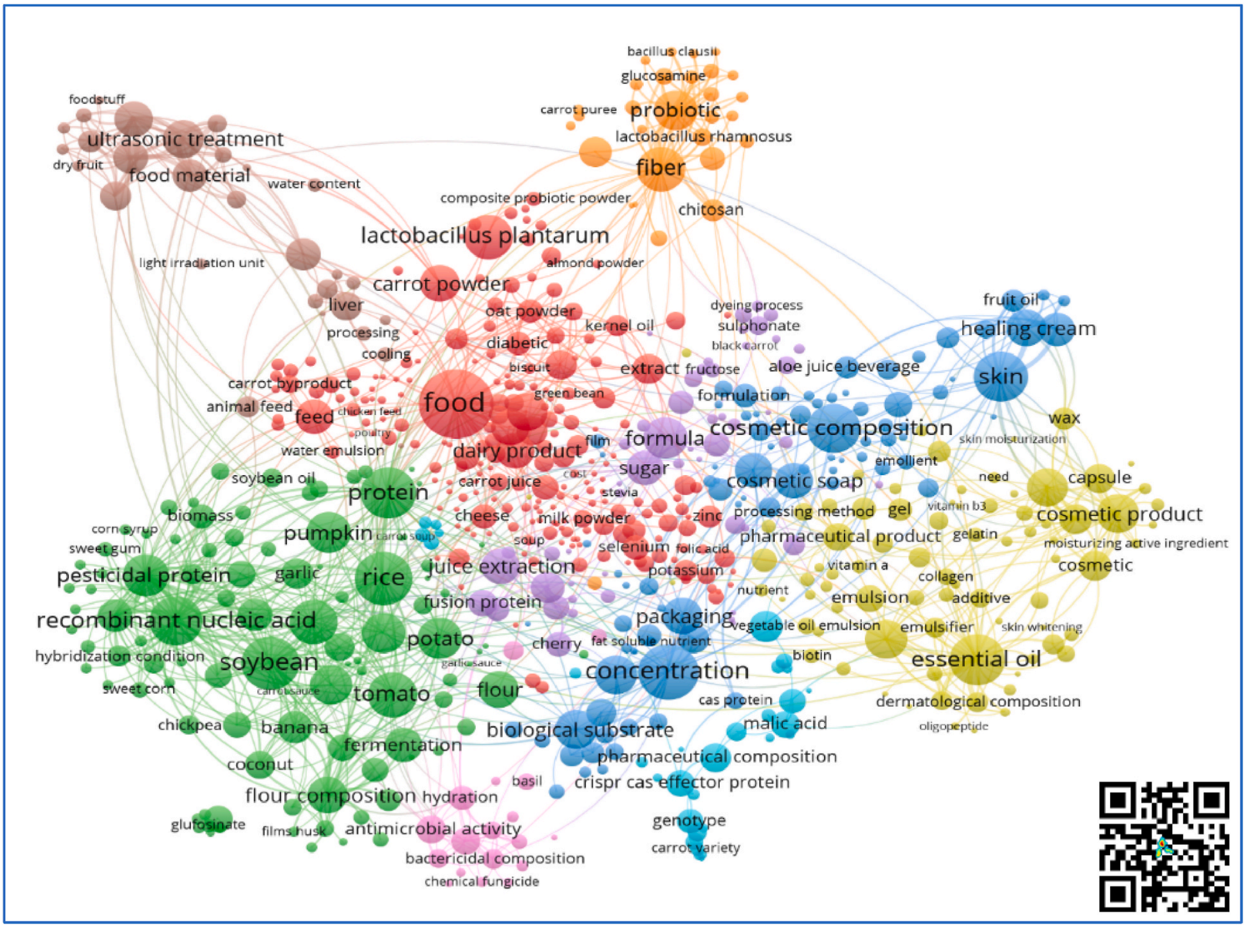

Fig. 9. Granted patents Title-Claims cooccurrence network. Own preparation in VOSviewer® based on information available in PatentInspiration®. Consultation date: June 2023.

products, processes and technologies, used in carrot transformation activities. Furthermore, the map clarifies three major market niches for research, development and innovation results, healthy food market for human consumption, functional feed for animal nutrition (both domestic and livestock purposes) and biocosmetic market.

Healthy food market its related with orange, red, green, brown and purple clusters focusing respectively on probiotics inclusion in rich fiber foods; carrot powder mixed with oat, soy, spinach powders and vegetal oil rich on essential fatty acids as a key functional formula for dairy products, bread an bakery preparations, and specialized foods for special conditions such as diabetic disease; rich protein formulations that comprise veggies, cereals, fruits and tubers; and finally bioactive aloe vera beverages ingredient.

Functional feed for animal nutrition feed (green, red and brown clusters) focuses on guarantee nutritional content in protein, carbohydrates, major and minor minerals and probiotic quality attributes. Carrot powder confers silage, nutritional blocks and pet formulas features related to digestive performance, skin and coating protection, muscle gain and tissue performance, and disease resistance. One of the main healthy benefits of carrot in feed formula is the improving of properly liver function.

Cosmetic market has been diversified in the last decade, through a biobased solution approach on skincare products (yellow and blue clusters), including sustainable alternatives to petrochemical industry derivates, such as, essential oils from coconut, avocado, lavender, linseed, clove, argan, macadamia, almond geranium and recently carrot oil/carrot seed oil. Oil extracts have been used to design novel skincare products for healing burns, moisturizing function, anti-age, and strength cellular regeneration. Furthermore, carrot extracts mixed with other seed, veggies and fruits inputs (mainly due to its bioactive compounds content and active vitamins contribution), are used to formulate cosmetics for hair, daily cleaning, and regenerative properties.

Finally, some exploratory uses are presented on yellow, cyan and pink clusters. Yellow cluster propose a highly specialized market in the pharmaceutical industry, especially in alternatives sources of vitamins and minerals for nutritional supplements, excipients, coatings and films for capsules and nano-capsules. Cyan cluster emphasizes on the use of bioactive compounds of carrot in medical formulation (biological pharmacology) for neurodegenerative diseases. Finally, pink cluster comprises functional properties related to antibacterial and antimicrobial activity.

4. Discussion

The substantial increase in the number of scientific publications (Fig. 1) can be attributed to a confluence of diverse factors, such as social, environmental, political, and economic elements, which reflect a shift towards technologies that prevent waste generation, regenerative economics, and a widespread increase in environmental awareness. Socially, the growing consumer demand for sustainable products has fostered deep cross-sector collaboration and the development of new characterization and transformation technologies to effectively utilize agricultural waste, as reflected in a substantial body of scientific literature [44]. From an environmental perspective, the urgency to address climate change and reduce waste accumulation as a human species issue has spurred governments and research centers to seek new developments for converting agricultural by-products, like carrots, into raw materials or valuable finished products for industries such as food and cosmetics [44]. Politically, the regulations and policies of both developed and developing countries that favor circular economy and bioeconomy have provided a robust framework supporting research and innovation in this field. This includes grants and policies that promote the valorization of agricultural waste into high-value products, reflecting a political environment that favors the transition towards sustainable practices [45]. Economically, the circular bioeconomy presents a strategy for transforming waste into biobased products, which not only reduces costs associated with waste management, generating the opportunity for tax benefits due to environmental responsibility but also opens new avenues for economic growth and the development of green markets, clearly correlating with the increase in publications in this area [44–46]. The interaction of these factors drives knowledge generation and fosters a collaborative and interdisciplinary framework that is fundamental for scientific advancement in these topics and, in turn, reflects a global movement towards the integration of sustainable and regenerative practices as a human species. In publications related to the carrot crop by-products, scientometric analysis facilitates the establishment of a general, specific and complementary trend, that is, the identification of key bioactive compounds. The patent analysis also identifies new developments in commercial applications that fall within the purview of this study. Thus, it is possible to understand the relationship between the generation of scientific knowledge, its maturity, its commercial applications, and its impact on the industry by integrating the two assessments. Table 2 provides information that makes this integrated analysis understandable.

The main areas of interest and development within the framework of this study are captured by the five general trends shown in Table 2. Carrot bioactive compounds, their antioxidant effect, and functional properties associated with them have shown solid scientific foundation, as present in Fig. 2, an increase in scientific research production as an interest in exploring potential uses of carrot crop by-products. The first general trend is visible in main clusters present in Figs. 3 and 5, where the antioxidant and functional properties of the carrot crop by-products represent the principal areas of interest, and the mayor amounts of scientific publications. The compounds present in the complementary trend (Carotenoids, polyphenols, ascorbic acid, flavonoids, and anthocyanins), related with the bioactive compound general trend, are being used in patents for the creation of functional foods, additives, medicinal products, and supplements. This could indicate that scientific knowledge has been successfully transferred to the commercial sector, where is possible to find patents related with carrot crop by-products in food matrices with the intention of providing health benefits [81], skincare and body care products [84], or with antioxidant properties [90].

On the other hand, the functional properties of carrots and their well-known positive effects – antioxidants, antimicrobial, and antifungal, among others – support a close relationship with the food industry for humans and animals. This includes creating animal feed, adding by-products, residues, and carrot extracts to other food matrices, as well as publishing patents for products that improve the health of both people and animals. As shown in Fig. 3 the green cluster connects different functional properties with phytotherapy term, and some health benefits. Similarly, Fig. 9 shows in a clear way these two major market niches for research, development and innovation; a healthy food market for human consumption, and a functional feed market for animal nutrition.

Table 2
Integration of scientific and commercial trends in the bioprospecting of carrot crop by-products.

General Trend	Specific Trend	Complementary Trend (Key bioactive compounds)	Vocations of use
Bioactive compounds and antioxidants	Food industry, functional foods, animal nutrition, health benefits, extracts and pigments.	Carotenoids (betacarotene, alpha carotene, lycopene, and xanthophylls), polyphenols (catechin, epigallocatechin, quercetine), ascorbic acid, flavonoids, and anthocyanins.	Functional foods, food additives, animal feed with emphasis on animal health, cosmetic products (skin and hair care); product encapsulation.
Functional Properties, phytotherapy, and development of medicinal applications.	Antimicrobial activities, antifungal activities, development of cosmetic products, and medicinal applications.	Acetic acid, ascorbic acid, chlorogenic acid, carvacrol, tannins, terpenes, gallic acid, alpha tocopherol, resveratrol, and folic acid.	Medicinal applications, development of medicinal products and supplements for eye health.
Food transformation, preservation and compound extraction.	Study and implementation of extraction and drying techniques.	Phenols, polyphenols, flavonoids, terpenes, and phytosterols.	Development of processing and preservation technologies; characterization and application of extracts and essential oils.
Bioprospecting, phytochemistry and chemical analysis	Study and implementation of techniques for detection and identification of metabolites.	Carotenoids, polyphenols, ascorbic acid, flavonoids and anthocyanins, polysaccharides.	Applications in the pharmaceutical industry, formulation of products for skin and hair care.
Sustainability and circular bioeconomy.	Biotechnology, bioeconomy, and circular economy.	Polysaccharides such as cellulose, pectin, starch, and some monosaccharides.	Development of sustainable production and transformation processes; obtaining valuable compounds as a source of carbohydrates and dietary fiber.

By implementing extraction and drying methodologies with the goal of maximizing the use of carrot crop by-products, research on food processing and preservation techniques related to commercial applications helps to develop and implement methodologies for the detection and quantification of metabolites. Chemical analysis and phytochemical bioprospecting are at the core of these approaches, whereby a cooccurrence network of chemical compounds (Fig. 6) is a determining factor, not only in identifying the main bioactive compounds (Table 1), but also in understanding how they interact with other compound, the chemical richness of a food or product and its inherent functional properties. In order to facilitate the use of carrots in commercial applications, these procedures are essential for the identification of bioactive compounds as well as the overall characterization of carrots and their crop by-products. This fits within a growing trend at the nexus of environmental sustainability and science. In other words, production systems that are affected by the principles of circular bioeconomy.

Therefore, it is essential to understand the scientific maturity status of a particular research area through the analysis of related publications. This is because establishing both general and specific trends in the field becomes crucial to support the development of commercial or industrial products and applications, in other words, patent development. Therefore, the application of a methodological framework for phytochemical bioprospecting, as described in this work, would allow an understanding of the different levels of technological maturity (TRL) in various scientific and technological developments [91,92]. This understanding extends not only to carrot crop by-products but also to any other agri-food matrix. Bibliometric and scientometric analyzes help identify advancements in research related to the initial TRL levels, while commercial and industrial developments determined in patent analyzes could be categorized as TRL 6 or higher. Additionally, this approach helps to understand that the absence of commercial or industrial development areas in a patent analysis may be linked to existing gaps in research, indicating opportunities for generating new knowledge.

5. Conclusions

Investigating and leveraging the untapped potential of carrot production by-products, along with similar residuals from various food sources, is made possible through bioprospecting. This approach is enriched by rigorous scientific monitoring and utilizes advanced tools and methodologies such as bibliometric analysis, scientometric studies, and patent evaluations. By highlighting emerging trends and focal areas in knowledge creation, bioprospecting not only propels scientific inquiry but also catalyzes innovation across multiple sectors by fostering the development of novel products and processes. It champions sustainability by optimizing the utilization of existing resources. The convergence of industry innovation, product development, and cutting-edge scientific research is driven by a phytochemical bioprospecting process that, although initiated with carrot by-products, is adaptable to any agricultural or food-based matrix. The phytochemical bioprospecting framework applied in this context has uncovered a variety of bioactive compounds in carrots, such as carotenoids, flavonoids, and polyphenols. These compounds are recognized for their functional properties and health benefits, indicating a promising future in food industries, pharmaceuticals, cosmetology, and medicine. The discovery has led to the creation of functional foods, skincare products, health supplements, and even specialized animal feeds. Over the past decade, research into carrot by-products has seen a significant uptick, reflecting a broader interest in potential applications across fields like phytochemistry, medicine, agriculture, and food sciences. This multidisciplinary interest underscores the versatile potential of carrots and their by-products. Despite this growth, areas such as phytochemistry, innovative food packaging technologies, and the identification of novel bioactive compounds remain underexplored. The technological framework established through this research accelerates the discovery and development process, promoting new uses for carrot by-products. Furthermore, it lays the groundwork for expanding this phytochemical bioprospecting approach to other agricultural and food contexts.

While this study focused on the analysis of documents from the Scopus® database, the results obtained allow for the identification of key trends in the phytochemical bioprospecting of carrots. However, it is necessary to conduct broader future research that includes other databases such as Web of Science®, PubMed®, Google Scholar, or Dimensions®, with the aim of strengthening knowledge in this area and advancing in phytochemical bioprospecting. This will allow for the construction of a more comprehensive knowledge base and an expanded horizon for more robust future research.

CRediT authorship contribution statement

Jaison Martínez-Saldarriaga: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Juan Camilo Henao-Rojas:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Diego Hernando Flórez-Martínez:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Edith Marley Cadena-Chamorro:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization. **Diana Paola Yepes-Betancur:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Funding acquisition, Conceptualization.

Data availability statement

The analyzed dataset related to the interest bioactive compound network has been included as supplementary material, it can be found in Mendeley Data, V1, https://doi.org/10.17632/kjg78vw2hs.1 (https://data.mendeley.com/datasets/kjg78vw2hs/1).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2025.e41822.

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