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Bioactive Compounds and Antioxidant Activity in Various Citrus Peels: A Significant Systematic Review

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ABSTRACT

Citrus peels, traditionally considered byproducts in fruit processing, have garnered increasing attention due to their bioactive compounds and antioxidant characteristics. This systematic literature review aims to comprehensively evaluate and consolidate existing research on the bioactive compounds and antioxidant properties found in various citrus peel varieties. Citrus fruits, particularly their peels, have emerged as substantial repositories of bioactive compounds, including flavonoids, phenolics, and essential oils. Nevertheless, the fragmented nature of existing research on various citrus species, cultivars, and extraction methods underscores the need for a systematic approach. This is essential to provide a cohesive understanding of the inherent bioactive profiles and antioxidant capabilities present within these peels. Employing the Pre-Recording Systematic Reviews and Meta-Analysis (PRISMA) approach, this study executed a systematic search using academic strategies on Scopus and Web of Science databases to identify and select pertinent studies. Advanced search strategies utilizing keywords (1) citrus peel and (2) antioxidant was employed. A rigorous evaluation of methodological and analytical procedures was undertaken, and data were systematically collected for analysis, resulting in a final dataset of studies. This systematic review covered three key themes: (1) Citrus Fruit and Peel Utilization for Health and Nutrition, (2) Anticancer Properties and Chemical Composition of Citrus Products, and (3) Citrus By-Products and Waste Utilization. The review reveals substantial variability in bioactive compounds and antioxidant activities across different citrus peels. This review offers a comprehensive examination of each study's methodology and findings. Ultimately, the findings emphasize the importance of citrus peels as abundant sources of bioactive compounds and antioxidants, with far-reaching implications for nutrition, health, and biotechnological applications. While providing a comprehensive overview of the diverse bioactive profiles in different citrus peels, this review also advocates for further research to unlock their full potential and encourage sustainable practices in the food industry.

Keywords:
Citrus Peel; bioactive compounds; antioxidant; health; nutrition

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1. Introduction

The citrus genus, a diverse group of fruit-bearing plants, has long held a prominent place in human nutrition and traditional medicine due to its remarkable array of bioactive compounds [1-4]. Citrus fruits are renowned for their delectable taste and vibrant colors, but it is the peels of these fruits that have recently garnered considerable attention in the fields of nutrition, health, and food science [5-9]. The principal objective of this systematic review is to provide a comprehensive and exhaustive analysis of the bioactive constituents and antioxidant capacities found in the peels of diverse citrus varieties. This endeavor seeks to elucidate the plausible health advantages these compounds offer while highlighting their broad-ranging utility in fields like food safety, packaging, and preservation. A visual representation of the various potential uses of distinct citrus peels is illustrated in Figure 1.

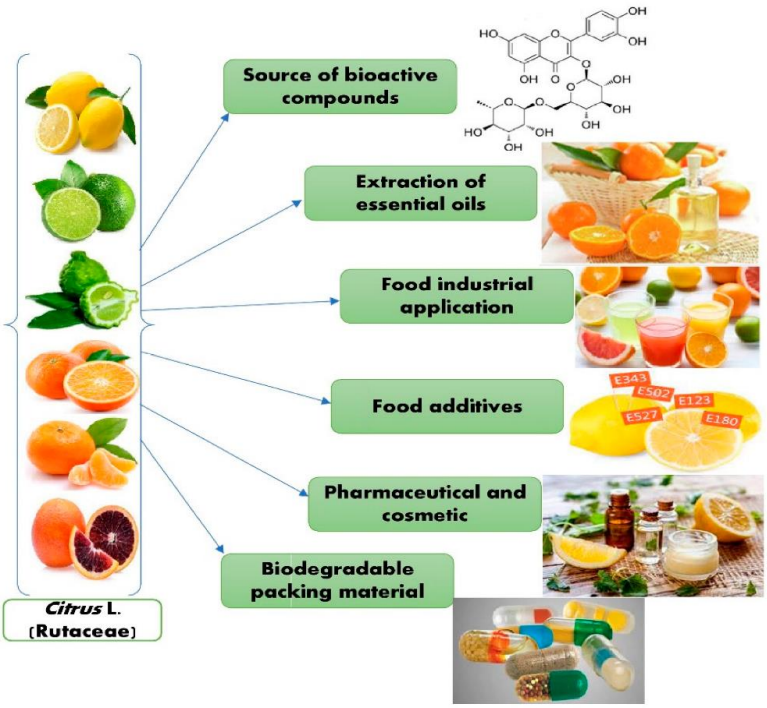

Fig. 1. Potential applications of different citrus peel

Citrus peels, often considered waste in fruit processing, have become a valuable source of bioactive compounds with numerous health benefits [10]. These compounds encompass a wide range of phytochemicals, incorporating flavonoids, phenolic acids, carotenoids, limonoids, and essential oils, all of which contribute to the characteristic aroma, flavor, and therapeutic potential of citrus peels [11-15]. The significance of these bioactive compounds lies in their potent antioxidant, anti-inflammatory, and antimicrobial properties.

Antioxidants have a vital function in safeguarding the body from oxidative stress, a condition intricately linked to several enduring maladies, encompassing cardiovascular ailments, cancer, and neurodegenerative conditions. Citrus peel extracts have been proven to display remarkable antioxidant prowess, mainly ascribed to their elevated concentrations of flavonoids like hesperidin, naringin, and quercetin. These constituents actively counteract free radicals and diminish oxidative harm, thereby potentially ameliorating the susceptibility to chronic illnesses [16-18].

Moreover, citrus peels possess a wide range of other bioactive compounds with potential health benefits [28]. Limonoids, for instance, have shown anticancer properties, while essential oils from citrus peels are known for their antimicrobial and anti-inflammatory effects. The diverse array of bioactive compounds found in citrus peels suggests a multifaceted approach to health enhancement [19-22].

A noteworthy contribution of this systematic review lies in its investigation of variations in the content of bioactive compounds and antioxidant activities across diverse citrus species, including *Citrus sinensis* (sweet orange), *Citrus limon* (lemon), *Citrus aurantium* (bitter orange), and *Citrus paradisi* (grapefruit). These variations are critical for understanding the potential applications of citrus peels in functional foods, dietary supplements, and pharmaceuticals, as different species may offer distinct health benefits [23-27].

In summary, the primary aim of this systematic review is to offer a thorough exploration of the bioactive constituents and antioxidant capacities found in the rinds of diverse citrus fruits. The potential health benefits associated with citrus peel consumption make it a significant subject of investigation in the fields of nutrition and health sciences. Understanding the distinctions between bioactive compounds and antioxidant activities in different citrus species' peels is essential for harnessing their full potential for human health. As such, this review aims to be a valuable resource for researchers, nutritionists, and food scientists seeking to exploit the health benefits of citrus peels and develop novel applications for these underutilized agricultural byproducts.

2. Literature Review

This research has a dual objective which is the enrichment of the nutritional value of food products through bioactive polyphenols and the reduction of waste in the citrus industry by harnessing the bioactive potential of citrus peels. Citrus fruits serve as plentiful of valuable bioactive components, encompassing ascorbic acid, essential oils, and antioxidants. The essential oils extracted from citrus peels provide an array of health advantages, including antioxidant, anticancer, antidiabetic, and anti-inflammatory properties [13]. In a particular study, orange and kinnow peels subjected to sun-drying and tray-drying were compared, revealing that the latter exhibited the highest yields of essential oils. These essential oils were extracted using an environmentally sustainable hydro-distillation method and were found to contain compounds like D-limonene, terpenoids, and sesquiterpenes, all of which enhance their therapeutic potential. Consequently, this study contributes to the advancement of an eco-conscious approach to citrus essential oil extraction, simultaneously addressing both nutritional enhancement and waste management concerns [11].

Citrus fruits serve as rich reservoirs of hesperidin, a flavanone glycoside well-regarded for its diverse advantages, including antioxidative, hypocholesteric, antitumor, anticancer, antimicrobial, antibacterial, anti-inflammatory, and anti-diabetic properties. Hesperidin is employed in the treatment of a diverse range of health conditions. This study places particular emphasis on recent discoveries concerning the nutritional, phytochemical, and biological attributes of hesperidin, as well as the exploration of various extraction techniques to enhance its yield and unlock its health potential. The outcomes of this research in the context of different citrus peel species provide a foundation for adopting a sustainable, eco-friendly approach to extracting valuable compounds, thereby making significant strides in transforming waste into profitable solutions that offer advantages for both human well-being and the ecological system [13].

3. Materials and Method

This section underscores the necessity for a comprehensive examination of the bioactive components and antioxidant potential of various citrus peels worldwide [28]. Conversely, the subsequent section outlines the approach adopted to address the research inquiries posited in this study. This review will be categorized into three principal themes: (1) Utilization of Citrus Fruit and Peel for Health and Nutrition, (2) Anticancer Attributes and Chemical Composition of Citrus Products, and (3) Exploitation of Citrus By-Products and Waste. The research followed the PRISMA approach, ensuring precision and thoroughness through a systematic review and combination of scientific literature. In terms of the research methodology, robust databases, namely Scopus and Web of Science, were harnessed, encompassing four pivotal phases: (1) recognition, (2) screening, (3) qualification, and (4) extraction of data.

3.1 Identification

The systematic review in this study comprises three fundamental stages in the paper selection process. In the initial phase, the first step involves the identification of keywords and the exploration of related terminology through the utilization of thesauruses, dictionaries, and prior research as references. Following the identification of relevant keywords, search queries were developed for the Web of Science and Scopus databases, as outlined in Table 1. In this initial phase of the systematic review, a total of 302 papers were successfully retrieved from both databases for the present study.

Table 1
The search string

Scopus	TITLE-ABS-KEY (“citrus peel” AND antioxidant) AND (LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023)) AND (LIMIT-TO (LANGUAGE , “English”))
Web of Science	**“**Citrus peel” AND antioxidant (Title) and 2023 or 2022 or 2021 or 2020 (Publication Years) and English (Languages)

3.2 Screening

In the preliminary screening phase, the elimination of duplicate papers is carried out. Within this stage, one article was disregarded, and subsequently, 38 articles underwent screening, guided by a set of inclusion and exclusion criteria established by the researchers. The primary inclusion criterion centered on research articles, chosen for their provision of practical and empirical insights. Conversely, the study excluded systematic reviews, general reviews, meta-analyses, meta-syntheses, book series, books, book chapters, and conference proceedings. Additionally, the review exclusively focused on articles published in the English language. Notably, the study's temporal scope spans four years, covering the period from 2020 to 2023. Based on these specific criteria, a total of 261 publications were excluded. The criteria for the second-stage examination is shown in Table 2.

Table 2
Criteria for the second-stage examination

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2020 – 2023	< 2020
Literature type	Journal (Article)	Conference, Book, Review

3.3 Eligibility

In the third phase, denoted as the eligibility assessment, a compilation of 37 articles was assembled. In this stage, a meticulous evaluation of the titles and crucial content of these articles was carried out to determine their conformity with the inclusion criteria and their pertinence to the specific research goals of the present investigation. Subsequently, 11 reports were omitted from consideration due to their lack of relevance to the study's focal point, as their titles and abstracts did not adequately align with the research objectives. Consequently, 26 articles were chosen for further review.

3.4 Data Abstraction and Analysis

In this study, a diverse range of research designs were thoroughly examined and combined using integrative analysis as a method of evaluation. These designs include quantitative, qualitative, and mixed methods, intending to identify relevant topics and subtopics within the study's scope. The initial step involved data collection, as depicted in Figure 2, where a thorough examination of 26 publications was conducted to gather relevant information about the study's themes. Subsequently, a detailed analysis of the bioactive compounds and antioxidant activity of different citrus peels was carried out by the authors and experts, leading to the identification of the three main themes mentioned earlier. The corresponding author collaborated with co-authors to refine and interlink these themes based on the research findings. To address any disparities in the theme development process, the authors compared their findings and resolved inconsistencies through discussions. Finally, the established themes underwent a refinement process to enhance their coherence and consistency. To ensure the validity of the assessments, two experts, one specializing in food waste and the other an expert in bioactive compounds from natural sources in food ingredients, conducted the evaluations. Feedback and comments from these experts were thoughtfully integrated to augment the overall quality of the study.

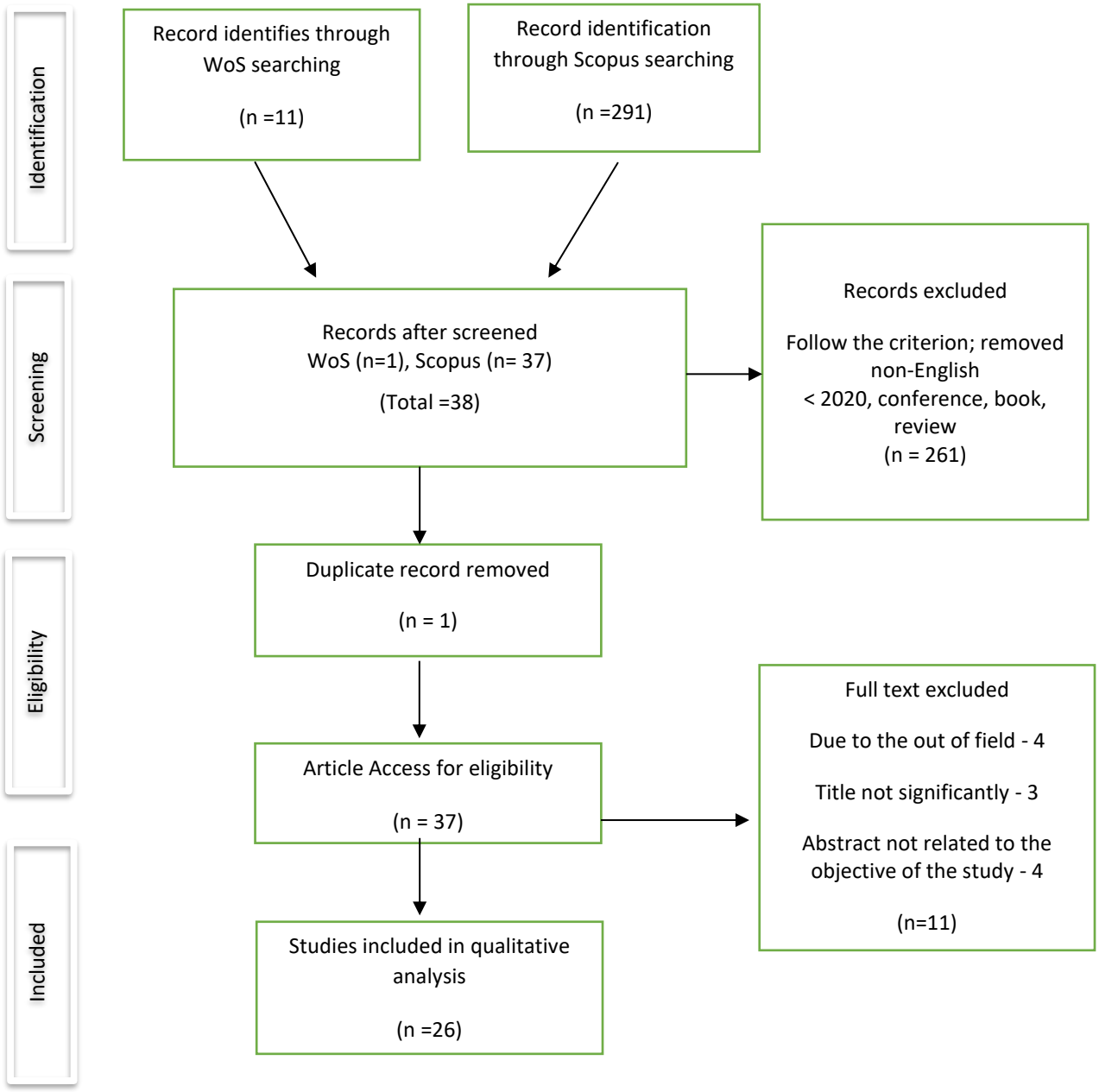

Fig. 2. The PRISMA flow diagram for selecting reviewed articles

4. Result and Findings

4.1 Citrus Fruit and Peel Utilization for Health and Nutrition

The studies within the "citrus fruit and peel utilization for health and nutrition" theme collectively examined a wide range of applications and attributes related to various citrus species as shown in Table 3. The utilization of citrus waste as a source of bioactive compounds was explored, a comprehensive review was conducted to identify a diverse array of bioactive compounds in various plant foods, and hesperidin was successfully extracted from citrus peel waste, offering insights into its potential health implications.

Table 3
Summary of citrus fruit and peel utilization for health and nutrition

References	Research Scope	Journal	Methodology	Findings
[3]	Developing novel sports supplements utilizing *Aronia melanocarpa* and bee pollen to elevate antioxidant efficacy and nutritional content	Molecules	Experimental study, formulation of supplements.	Developed supplements with enhanced antioxidant capacity.
[4]	Investigating the lipid digestion characteristics of oil-in-water emulsions stabilized by insoluble dietary fiber derived from citrus peel, with a focus on the impact of varying particle sizes	Food Chem X	The study investigated oil-in-water emulsions stabilized by citrus peel insoluble dietary fiber (CIDF) through the application of a gastrointestinal tract (GIT) model. The researchers varied particle sizes and concentrations of CIDF to study their effects on lipid digestion. They also compared CIDF-stabilized emulsions to Tween80-stabilized emulsions.	They illustrated that both the rate and scope of lipid digestion experienced notable influence from the varying particle sizes. and concentrations of CIDF in citrus species. Smaller particle sizes and higher CIDF levels in citrus species led to a more pronounced inhibition of lipolysis.
[6]	Enhancing the biomass and protein quality of Chlorella vulgaris through fortification with amino acids extracted from citrus peel	Biotechnol Rep (Amst)	Experimental investigation involving the fortification of *Chlorella vulgaris* with amino acids derived from citrus peel.	Enhanced biomass yield and elevated protein quality in *Chlorella vulgaris*.
[7]	Evaluation of nutritional profile, phytochemical potential, functional characteristics, nutritional attributes, and investigations into anti-nutritional components of *Citrus limetta* peels	J Food Sci Technol	Analytical investigation assessing the nutritional profile and phytochemical potential.	Identified nutritional and phytochemical properties of *Citrus limetta* peels.
[8]	Investigation of the volatile organic compounds in *Citrus reticulata 'Chachi'* peel through diverse drying techniques utilizing E-nose, GC-IMS, and HS-SPME-GC-MS	Front Plant Sci	Analytical study, comparison of drying methods using advanced techniques.	Compared volatile compounds in citrus peel using various drying methods.
[9]	Natural Variation Confers *'Aiyuan 38'* Citrus Mutant a New Color and Unique Flavor	Int J Mol Sci	Genetic study, characterization of a citrus mutant.	Discovered a new citrus mutant with unique color and flavor.

[12]	Utilization of Citrus Waste for the Extraction and Application of Bioactive Compounds in Health and the Food Industry: An Exploration	Molecules	Experimental investigation focusing on the extraction of bioactive compounds.	Emphasized the capacity of citrus waste as a reservoir of bioactive compounds with implications for both health and the food industry.
[11]	The investigation into the anti-inflammatory attributes of a fraction of grapefruit essential oil enriched with aldehydes	J Food Sci	Experimental study, assessment of anti-inflammatory properties.	Demonstrated anti-inflammatory properties of grapefruit essential oil.
[27]	Exploring Bioactive Compounds in Plant Foods Beyond Insoluble Dietary Fiber	Nutrients	Review and analysis of bioactive compounds in plant foods.	Identified various bioactive compounds in plant foods.

4.2 Anticancer Properties and Chemical Composition of Citrus Products

The theme is enriched with findings related to grapefruit rot pathogens in France and evaluations of bioactive compounds, antioxidant potential, and fruit quality across diverse blood orange cultivars. Additionally, the valorization of citrus peel waste is presented as a sustainable approach to producing value-added goods. The summary of anticancer properties and chemical composition of citrus products is shown in Table 4.

Table 4
Summary of anticancer properties and chemical composition of citrus products

References	Research Scope	Journal	Methodology	Findings
[22]	The study aims to investigate the nutritional composition, health advantages, and bioactive compounds present in chickpeas *(Cicer arietinum L.)*	Front Nutr	Literature review and analysis of chickpea nutritional composition and bioactive compounds.	A comprehensive review of chickpea's nutritional composition and bioactive compounds, highlighting its potential health benefits.
[25]	Administering Oxytetracycline via trunk injection for the Management of Huanglongbing in Mature Grapefruit and Sweet Orange Trees	Phytopathology	Investigation of the efficacy of oxytetracycline trunk injection for managing Huanglongbing (HLB) in citrus trees.	Trunk injection of oxytetracycline showed promise as a management strategy for HLB in mature grapefruit and sweet orange trees.
[1]	The study aims to conduct the asymmetric synthesis of chiral (thio) chromanes and systematically investigate their structure-activity relationship within macrophages	RSC Adv	The synthesis of chiral (thio) chromanes with asymmetry and the investigation of the structure-activity relationship in macrophages.	The study focused on the synthesis of chiral (thio)chromanes and their impact on macrophages, delving into the relationship between structure and activity.

[5]	Sequencing the entire genome and identifying genetic variations in *Citrus reticulata "Kinnow"* originating from Pakistan	Funct Integr Genomics	The study involved the comprehensive sequencing of the entire genome and the identification of genetic variations in *Citrus reticulata "Kinnow*."	The study involved whole-genome sequencing of *Citrus reticulata "Kinnow"* from Pakistan and the discovery of genetic variants, contributing to the understanding of its genetic makeup.
[2]	The Chemical Foundations of Anticancer Properties: Investigating the Southern European Atlantic Diet and Its Supplements	Nutrients	Review and analysis of dietary patterns and supplementary nutrition.	Explored the chemical foundation of anticancer attributes within the Southern European Atlantic Diet and its supplementary components.
[23]	Citrus Carotenoid Extracts Induce Anticancer Effects via Anti-Proliferative Mechanisms, Oxidative Stress Modulation, and Mitochondrial-Dependent Apoptosis in MCF-7 Cells	Foods	Experimental study, assessment of anticancer effects.	Demonstrated anticancer effects of citrus carotenoid extracts.
[17]	Investigation of the Chemical Composition, Antioxidant, Anti-Bacterial, and Anti-Cancer Properties of Essential Oils Isolated from Residual *Citrus limetta Risso* Peel Post-Commercial Utilization	Molecules	Experimental study, chemical analysis, and assessment of activities.	Examined the chemical composition and functionalities of essential oils derived from discarded citrus peel.
[18]	The research investigates the potential mitigating effects of *Citrus sinensis* (orange fruit) peel extract on chemotherapy-induced toxicity in male rats	Food Funct	Experimental study, assessment of extract's effects.	Extract derived from orange peel mitigated the toxicity induced by chemotherapy in male rats.
[20]	Metabolomic Profiling of Phytochemical Constituents in the Ethanol Extract of Lime *(Citrus aurantifolia)* Peel and Its Anticancer Efficacy Against Human Hepatocellular Carcinoma Cells	Molecules	Metabolomic analysis and experimental study.	Examined phytochemical compounds and illustrated their anticancer properties against hepatocellular carcinoma cells.
[21]	Exploration of the influence of coumarins, furocoumarins, and limonoids extracted from *Citrus trifoliata* on human colon adenocarcinoma cell lines	Heliyon	Experimental study, assessment of compounds' effects on colon cancer cells	Studied the effects of citrus compounds on colon adenocarcinoma cells.
[16]	Exploring the Anti-Cancer Properties of Citrus Peel-Derived Antioxidants	Braz J Biol	Review and analysis of antioxidants in citrus peels.	Suggested that antioxidants in citrus peels provide a safeguard against cancer.

[24]	Initial Documentation of Grapefruit Rot Induced by *Colletotrichum gloeosporioide*s and *C. karstic* in French Agricultural Context	Plant Dis	Survey and identification of grapefruit rot pathogens.	Reported the presence of rot pathogens in French grapefruit.
[14]	Exploration of Bioactive Compounds, Antioxidant Potential, and Quality Assessment in Eleven Cultivars of Blood Oranges	J Sci Food Agric	Analytical methods to assess fruit quality and antioxidant activity.	Examined the bioactive compounds and antioxidant potential across eleven cultivars of blood oranges.
[13]	Enhancing the Sustainability of Value-Added Product Production through the Utilization of Citrus Peel Waste	Bioresour Technology	The utilization of citrus peel waste through diverse sustainable methodologies.	Demonstrated the potential to enhance the value of citrus peel waste through the production of value-added products.
[19]	Exploring the Health-Promoting Attributes and Potential Utilization in the Food Sector of Essential Oils from *Citrus Medica L.* and *Citrus x Clementina Hort. Ex Tan.*, Along with an In-Depth Analysis of Their Key Constituents	Plants (Basel)	Investigated chemical composition and health-related attributes of essential oils.	Emphasized the health-enhancing characteristics and possible uses of essential oils derived from Citrus medica and Citrus x clementina.

4.3 Citrus By-Products and Waste Utilization

The articles within the theme "citrus by-products and waste utilization" encompass a range of studies as shown in Table 5. They investigate the extraction of (poly)phenols from natural resources using innovative techniques, assess the flavonoid diversity and antioxidant potential of underutilized citrus species through metabolomic analysis, and demonstrate the valorization of essential oils from citrus peel powder using hydro-distillation.

Table 5
Summary of citrus by-products and waste utilization

References	Research Scope	Journal	Methodology	Findings
[15]	Determinants Influencing the Extraction of (Poly)Phenols from Natural Sources through the Integration of Deep Eutectic Solvents and Ultrasound-Assisted Extraction	Crit Rev Anal Chem	Experimental study, assessment of extraction factors.	Investigated elements influencing the extraction of (poly)phenols from natural sources utilizing innovative methodologies.
[26]	Exploring Metabolic Variability in Flavonoids and Antioxidant Capacity to Profile Underexplored Citrus Varieties for Nutritional Enhancement	Plants (Basel)	Metabolomic analysis, assessment of flavonoid diversity.	Examined the variety of flavonoids and assessed the antioxidant capacity in less-utilized citrus species.

5. Discussion and Conclusion

The reviewed literature offers valuable insights into the bioactive constituents and antioxidant attributes inherent in diverse citrus peel varieties. It illuminates the potential health advantages and applications of these natural resources. Specifically, the analysis of Citrus limetta peels reveals their substantial nutritional and phytochemical value, wherein flavonoids, polyphenols, and vitamins with well-recognized antioxidant properties are prominent. These antioxidants play a pivotal role in safeguarding cells against oxidative damage and mitigating chronic disease risks, underscoring the prospect of harnessing Citrus limetta peels for their antioxidative attributes.

Furthermore, the recognition of bioactive compounds extending beyond insoluble dietary fiber in an array of plant-based foods underscores the presence of an extensive spectrum of compounds, including carotenoids, flavonoids, and alkaloids, distinguished for their antioxidant and health-enhancing characteristics. The extraction of hesperidin from discarded citrus peel material, with its attendant health implications, stands as another noteworthy revelation. Hesperidin, an abundant flavonoid in citrus peels, is lauded for its antioxidant and anti-inflammatory potential. The extraction of hesperidin and its possible health applications serves as a compelling exemplar of repurposing citrus waste to harness bioactive compounds.

Collectively, these inquiries enhance our comprehension of the bioactive components and antioxidant characteristics inherent in disparate citrus peels, emphasizing the remarkable diversity of constituents, spanning from flavonoids to terpenes. This diversity possesses significant potential to promote health and nutrition, reiterating the importance of citrus peel utilization for extracting bioactive compounds and deploying them in various dimensions of health and the food industry.

In summary, the aggregated insights across these studies underscore the extensive and versatile utilization prospects of citrus by-products and extracts. They underscore the significance of adopting sustainable and eco-friendly approaches in leveraging citrus resources, which not only curtail waste but also offer manifold health and industrial benefits. These findings contribute substantively to a comprehensive understanding of the potential residing in citrus-derived compounds, thus amplifying their role in fostering health-conscious and sustainable lifestyle practices.

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