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Review

Bioactive Compounds in Tea: Emerging Trends in Their Extraction and Application

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Abstract: Tea (*Camellia sinensis*), particularly prominent in China as the largest producer, is rich in bioactive compounds like polyphenols (including flavonoids and catechins), theanine, and caffeine, known for their antioxidant, anti-inflammatory, and health-promoting properties. However, conventional extraction methods often lead to degradation, poor yield, and low bioavailability of these compounds, limiting their applications. Despite extensive research on tea bioactives, a comprehensive understanding of how emerging green extraction technologies improve yield, stability, and functionality across various application domains remains limited. This review aims to fill this gap by systematically evaluating the efficiency, mechanisms, and applicability of these advanced extraction methods based on the past five years of studies. Recent advances focus on optimizing green extraction techniques to overcome these challenges. Methods such as Supercritical Fluid Extraction (SFE) (temperature 35 to 60 °C, co-solvent 5 to 10%, and time 90 min) show superior yields (e.g., 25% higher Epigallocatechin gallate (EGCG)) and purity, Ultrasound-Assisted Extraction (UAE) (frequency 20 to 40 kHz, time 10 to 30 min) increases catechin yield by 30%, and Microwave-Assisted Extraction (MAE) offers improved efficiency compared to traditional techniques. Enzyme-Assisted Extraction (EAE) and Pulsed Electric Field (PEF) extraction also offer promising, sustainable alternatives. These extracted bioactives find growing applications in functional foods/beverages (acting as nutraceuticals and natural preservatives), cosmetics (via nanotechnology for enhanced efficacy), and pharmaceuticals (e.g., encapsulated EGCG for inflammation). By integrating recent developments and highlighting practical limitations, this review provides insights into the selection and optimization of green extraction methods for industrial applications. Despite progress, key challenges persist, including optimizing bioavailability and ensuring the scalability and environmental sustainability of advanced extraction methods.

Keywords: tea; bioactive compounds; applications; extraction techniques

1. Introduction

Tea (*Camellia sinensis*) is one of the most widely consumed beverages globally, with China being the largest producer, accounting for nearly half of the world's total production [1]. Tea production in China is deeply rooted in the country's history and culture, dating back thousands of years. It is well-known that China, the origin of *Camellia sinensis*, is the country with the largest planting area and production of tea leaves [1,2]. China's diverse climatic conditions and rich soils offer ideal environments for cultivating various tea types, including green, black, oolong, white, and pu-erh teas [2]. In addition to its cultural significance, tea has gained recognition for its numerous health benefits due to its rich profile of bioactive compounds, such as polyphenols, flavonoids, catechins, and theanine [3,4]. These compounds exhibit antioxidant, anti-inflammatory, and anti-cancer properties, making tea not only a popular beverage but also a significant subject of scientific research [4,5].

In recent years, increasing demand for applications in functional foods and nutraceuticals has sparked significant interest in the extraction and application of tea bioactive compounds [6,7]. However, the process of extracting these valuable compounds while maintaining their stability and bioactivity poses significant challenges [8,9]. Conventional extraction techniques (e.g., Soxhlet, maceration) often suffer from inefficiencies, such as long extraction times, high solvent consumption, and high temperatures, leading to the degradation of thermolabile compounds or poor yield [8,10]. These limitations hamper their practical applications in industries such as food, pharmaceuticals, and cosmetics [11].

To address the limitations of traditional extraction methods—such as prolonged extraction time, high solvent consumption, low selectivity, and degradation of thermolabile compounds—scientists have increasingly focused on developing and optimizing more efficient and environmentally friendly techniques for recovering bioactive compounds from tea leaves [12]. Traditional techniques like hot water or solvent maceration, while widely used, often yield lower purity and require intensive energy and solvent input. In contrast, emerging green technologies such as microwave-assisted extraction (MAE), ultrasound-assisted extraction (UAE), and supercritical fluid extraction (SFE) offer significant improvements by enhancing extraction yield and selectivity, reducing processing time, minimizing solvent use, and preserving compound integrity [12,13]. This shift toward advanced extraction methods is not solely driven by efficiency, but also by the urgent need for scalable, cost-effective, and sustainable solutions that align with environmental and industrial demands [14,15].

Despite the increasing interest in green extraction technologies, many current reviews focus either on a single method or lack a critical comparison of the latest innovations in terms of yield, compound stability, and industrial applicability. Furthermore, the limitations in bioavailability, scalability, and environmental concerns remain underexplored in the context of emerging technologies. This review aims to fill that gap by offering an integrated, up-to-date assessment of extraction methods while highlighting their comparative advantages and real-world challenges.

The need for better extraction techniques is critical to ensure the effective utilization of tea's bioactive compounds [6,15]. High-quality extraction will enable the development of superior functional products with enhanced health benefits, supporting both consumer demand and the advancement of tea as a valuable resource in various industries [7,12]. This review critically examines recent studies from the past five years (2019–2024) focusing on the extraction and application of bioactive compounds in tea. The literature was systematically retrieved using the Scopus database with relevant keywords including *"tea", "bioactive compounds",* and *"extraction techniques"* to ensure comprehensive coverage of the latest advancements in this field. It provides insights into advanced extraction techniques that have improved the yield and purity of these compounds and explores how these techniques, when combined with emerging applications, offer promising avenues for both research and industry.

2. Major Bioactive Compounds in Tea

Bioactive compounds in tea are primarily composed of polyphenols (including flavonoids and catechins), theanine (an amino acid), caffeine, and various vitamins and minerals (as shown in Table 1) [16]. Each category contributes differently to tea's health-promoting properties and varies significantly across different tea types—green, black, oolong, and white [17].

Table 1. Major bioactive compounds in different types of tea and their health benefits.

Compound Type	Key Compounds	Tea Type(s)	Concentration Range (mg/g dry wt.)	Health Benefits	References
Catechins	EGCG, EGC, ECG, EC	Green > White > Oolong	70–130 (EGCG in green tea)	Antioxidant, anti-inflammatory, anticancer, cardioprotective	[18–23]
Theanine	L-Theanine	Green ≈ White ≫ Black	6–20	Stress reduction, cognitive enhancement, calming effect	[24–30]
Caffeine	Caffeine	Black > Oolong > Green	20–40	Stimulant, alertness, mood enhancement	[16,17]

Table 1. *Cont.*

Compound Type	Key Compounds	Tea Type(s)	Concentration Range (mg/g dry wt.)	Health Benefits	References
Flavonoids (Black Tea)	Theaflavins, Thearubigins	Black > Oolong	15–25 (theaflavins)	Anti-inflammatory, antioxidant, gut modulation	[31–35]
Other Polyphenols	Quercetin, Kaempferol, Rutin	All types (esp. green/black)	2–10	Antiviral, immune support, vascular health	[17,31,34]
Vitamins	B-complex, C, E	All types	Trace–1	Antioxidant, metabolic health	[16,17]
Minerals	K, Mg, Mn, Ca, Zn	All types	Variable (1–30 mg/g)	Bone health, enzymatic function	[16,17]

2.1. Catechins

Catechins are flavonoids predominantly found in green tea and have been extensively studied for their potent antioxidant activity [18]. Epigallocatechin gallate (EGCG) is the most researched catechin, recognized for combating oxidative stress, inflammation, and certain cancers [19]. Earlier studies have demonstrated EGCG's role in cardiovascular health, weight management, and cognitive function [20]. However, its low bioavailability and rapid degradation during digestion remain major challenges [21], driving recent research toward encapsulation and delivery systems for enhanced absorption [22,23].

2.2. Theanine

Theanine, a unique amino acid almost exclusive to tea [24,25], is noted for inducing calmness without drowsiness [26]. Previous studies demonstrate its ability to enhance cognitive function and reduce stress via neurotransmitter modulation [27]. A clinical trial showed theanine mitigates caffeine-induced jitteriness, promoting focused relaxation [28]. Despite these benefits, low bioavailability and gastrointestinal degradation limit efficacy [29]. Recent work focuses on nanocarrier systems (e.g., liposomes, polymeric nanoparticles) to improve absorption [30].

2.3. Flavonoids and Other Polyphenols

Flavonoids like theaflavins and thearubigins (abundant in black tea) exhibit anti-inflammatory and gut-modulating properties [31,32]. However, low solubility, digestive instability, and poor bioavailability hinder therapeutic applications [33]. Recent studies employ nanoemulsions, encapsulation, and biopolymer-based carriers to enhance stability and absorption [34]. These advances improve gut microbiota modulation, digestion, and immunity [35].

3. Emerging Trends in the Extraction of Bioactive Compounds

The extraction of tea bioactives has evolved over the past decade, shifting from traditional methods (e.g., hot water extraction, Soxhlet) to advanced eco-friendly technologies [36]. Conventional techniques suffer from high solvent consumption, long extraction times, and degradation of sensitive compounds due to harsh conditions [12,14]. Recent studies confirm these methods yield low quantities of polyphenols and catechins, limiting their applications [3,10,12].

To address these limitations, emerging techniques like ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and supercritical fluid extraction (SFE) enhance efficiency, reduce environmental impact, and preserve bioactive integrity (as shown in Figure 1) [12]. For example, MAE and UAE reduce extraction time by 50% and increase polyphenol yields by up to 30% compared to conventional methods [18]. These advances improve bioavailability for nutraceutical/pharmaceutical applications while promoting sustainability [20]. However, while these innovations are promising, they also introduce technical and scalability challenges, including compound degradation (in MAE), regulatory hurdles (in EAE and PEF), and high capital costs (in SFE), which must be carefully evaluated when selecting appropriate techniques for industrial applications [6,12,20]. However, the choice of technique must be guided by comparative evaluation—SFE offers high-purity yields but is costly; EAE is sustainable and cost-efficient but has enzyme-dependency issues; UAE and MAE offer moderate-to-high yields with acceptable costs but present challenges in scaling up or controlling thermal degradation [6,12,20,30,31]. Thus, no single method is universally optimal trade-offs between cost, yield, and applicability must be carefully considered in industrial decision-making. Comparative summary of emerging techniques is shown in Table 2.

Table 2. Comparative Summary of Emerging Tea Extraction Techniques.

Extraction Method	Yield (Relative)	Cost	Sustainability	Scalability	Key Limitations
SFE	Very High	High	High	Moderate	Expensive setup, solvent polarity limitations
UAE	High	Moderate	Moderate to High	High	Cavitation control, solvent type dependency
MAE	Moderate to High	Moderate	Moderate	Moderate	Local overheating, thermal degradation
EAE	Moderate	Low	Very High	High	Enzyme variability, longer times
PEF	Moderate	Low to Moderate	High	High	Underexplored for small molecules, safety integration
Conventional	Low	Low	Low	High	Long times, solvent waste, compound degradation

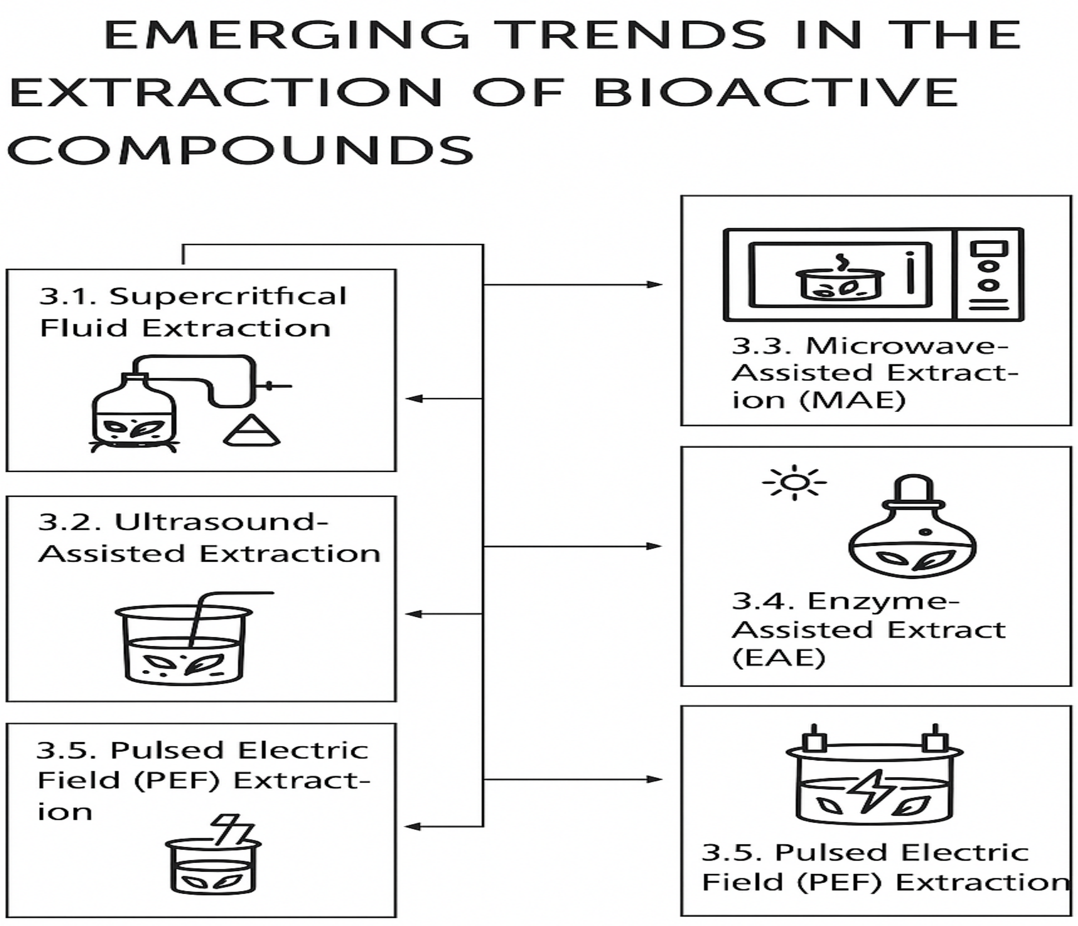

Figure 1. Emerging Trends in bioactive compounds extractions.

3.1. Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) has emerged as one of the most effective green extraction methods for bioactive compounds, particularly those sensitive to heat. SFE, often utilizing supercritical CO_2, operates at relatively low temperatures and avoids the use of harmful solvents [9]. Earlier studies have demonstrated that SFE is superior in extracting high-purity catechins and flavonoids compared to traditional solvent-based methods [44].

A comparative study published in 2020 found that SFE could achieve 25% higher yields of EGCG from green tea leaves while preserving its antioxidant properties more effectively than conventional extraction methods [20]. Researchers have also experimented with co-solvents like ethanol to enhance extraction efficiency, further increasing yields without sacrificing purity [14,16]. Nevertheless, despite its selectivity and environmental friendliness, SFE has limited solubility for highly polar compounds unless co-solvents are used, which partially offsets its ‘green’ label [9,14]. Moreover, the high cost of SFE equipment and the requirement for specialized operational expertise hinder its widespread adoption in small- and medium-scale tea industries [16,44].

3.2. Ultrasound-Assisted Extraction (UAE)

Ultrasound-assisted extraction (UAE) has become a widely adopted technique due to its energy efficiency and ability to enhance mass transfer during the extraction process. The key mechanism behind UAE is acoustic cavitation, which involves the formation, growth, and violent collapse of microbubbles in the solvent caused by the propagation of ultrasonic waves. This collapse generates localized high temperatures and pressures, creating shear forces that disrupt plant cell walls and increase solvent penetration into the plant matrix, thereby facilitating the release of bioactive compounds [28]. Recent studies have demonstrated that UAE significantly improves the yield of polyphenols and catechins from tea leaves [27]. For instance, catechin extraction using UAE has shown up to a 30% increase compared to traditional methods, along with a notable reduction in extraction time and solvent consumption [21]. Furthermore, UAE's mild operational temperatures help preserve the integrity of thermolabile compounds such as theanine and catechins, making it a promising approach for large-scale, sustainable applications that offer both economic and environmental advantages [4,6]. However, UAE's performance varies significantly with matrix type, solvent composition, and ultrasonic intensity, which can compromise reproducibility and limit standardization across tea cultivars and product formats [21,28]. Moreover, prolonged ultrasonic exposure may lead to degradation of delicate compounds, necessitating tight process control [6,27].

3.3. Microwave-Assisted Extraction (MAE)

Microwave-assisted extraction (MAE) utilizes microwave energy to disrupt plant cell walls and accelerate the release of bioactive compounds. MAE has been highlighted as a rapid and efficient extraction method, particularly for polyphenols and theanine [17]. Compared to conventional solvent extraction, microwave-assisted extraction (MAE) demonstrates significantly higher efficiency, with notable increases in the yield of catechins and theanine [15]. Additionally, MAE was found to reduce solvent consumption by 50%, making it a more sustainable option [22]. However, the main drawback is the potential degradation of sensitive compounds due to localized heating, although controlled microwave systems can mitigate this risk [8,12]. Despite these advantages, the key drawback of MAE lies in its non-uniform heating, which can cause hot spots and potential degradation of thermolabile compounds [8]. The scalability of MAE systems remains a bottleneck, especially when applied to bulk tea leaves or industrial-scale production, where maintaining consistency in heating and solvent distribution is critical [12,15]. Moreover, the limited penetration depth of microwaves in dense matrices restricts their application in certain tea products [22].

3.4. Enzyme-Assisted Extraction (EAE)

Enzyme-assisted extraction (EAE) has recently gained traction as a method to increase the yield of bioactives, particularly polyphenols and amino acids. EAE uses enzymes, such as cellulases and pectinases, to break down plant cell walls, releasing compounds that are otherwise difficult to extract through mechanical means [29]. Researchers have pointed out that enzyme-assisted extraction (EAE), when applied to black tea leaves, significantly increases the yield of theaflavins and flavonoids. For instance, EAE using cellulase and pectinase led to a 45% increase in total flavonoid content and a 32% increase in theaflavins compared to conventional extraction methods [29]. Similarly, optimized EAE conditions enhanced the extraction of bioactive polyphenols by up to 50%, demonstrating its potential for improving both yield and functionality in tea processing [30,31]. Furthermore, the environmental benefits of EAE, including reduced chemical usage and lower energy consumption, make it an appealing method for sustainable extraction [36]. Nonetheless, the success of EAE is highly enzyme- and substrate-specific. Variability in enzyme performance due to differences in tea cultivar, leaf maturity, and processing conditions can lead to inconsistent yields [29,31]. Furthermore, the cost of high-quality food-grade enzymes and the need for precise pH and temperature control can limit its cost-effectiveness on a commercial scale [30,36].

3.5. Pulsed Electric Field (PEF) Extraction

Pulsed Electric Field (PEF) technology is an emerging, non-thermal extraction technique that uses short bursts of high-voltage electricity to disrupt cell membranes, improving the release of intracellular compounds [19]. Though more commonly used in food preservation, PEF has shown potential in bioactive compound extraction, especially when combined with traditional methods [14]. Previous research demonstrated that PEF could increase the extraction yield of catechins by 20% while significantly reducing energy consumption and extraction time [37]. PEF's scalability and low energy input make it suitable for industrial applications, particularly in the functional food and nutraceutical sectors [38]. Yet, despite its promise, PEF's efficacy in extracting low-molecular-weight compounds like caffeine and theanine remains underexplored. Its integration into continuous extraction systems requires careful engineering, especially regarding safety and uniform electric field distribution [19,38]. Moreover, data on long-term stability and potential compound modification during high-voltage exposure are limited, warranting further investigation [14,43].

4. Critical Evaluation of Trends in Extraction Techniques

Each of these advanced extraction methods has its own set of benefits and limitations. While techniques like Supercritical Fluid Extraction (SFE) and Ultrasound-Assisted Extraction (UAE) offer higher yields and improved purity, they often require significant investment in specialized equipment. In contrast, methods like EAE are relatively low-cost and environmentally friendly, though their efficiency can be highly dependent on the type and quality of the enzymes used [31,33]. Several studies over the past five years have critically evaluated the integration of these techniques. For instance, UAE and SFE were integrated to improve catechin yield and reduce solvent use [14]. This integration approach has become a growing trend, as researchers recognize that combining methods often results in superior outcomes compared to relying on a single extraction technology [21]. This trend toward method hybridization reflects a more holistic approach to bioactive extraction in tea, balancing efficiency, sustainability, and scalability key factors for the successful translation of these methods from lab to industry. Future research should focus on optimizing these synergistic combinations and evaluating their techno-economic viability under real processing conditions.

5. Applications of Tea Bioactive Compounds

Bioactive compounds from tea are increasingly being applied in a variety of industries, including functional foods, beverages, cosmetics, and pharmaceuticals. These applications are driven by consumer demand for natural, health-promoting ingredients.

5.1. Functional Foods and Beverages

Functional foods and beverages have seen significant growth as consumers become more health-conscious. Tea bioactives, particularly catechins and theanine, are commonly incorporated into these products due to their well-documented health benefits [19]. The successful incorporation of green tea catechins into various food products, such as energy bars, functional beverages, and dairy products aims to enhance their antioxidant capacity, extend shelf life, and offer health-promoting benefits to consumers. Given catechins' well-documented bioactivities, including anti-inflammatory, cardioprotective, and anti-obesity effects, their inclusion in everyday foods provides a practical strategy to improve public health while meeting the growing demand for functional and clean-label products [39]. Catechins, particularly epigallocatechin gallate (EGCG), are recognized for their anti-inflammatory, cardioprotective, and anti-obesity properties. Studies have shown daily intake of 300–800 mg EGCG can reduce LDL cholesterol and waist circumference in overweight individuals over 12 weeks [12]. However, the stability and sensory impact of catechins during food processing remain key concerns. EGCG is sensitive to pH, heat, and oxygen, often leading to 40–60% degradation during baking or pasteurization [35]. To overcome this, encapsulation techniques, such as spray-drying, nanoemulsions, and biopolymer carriers have been deployed. For instance, nanoencapsulation of catechins in chitosan-alginate matrices improved thermal stability by over 50% and maintained 90% antioxidant activity after storage at 25 °C for 30 days [35]. Such strategies not only ensure retention of functional properties but also facilitate better sensory acceptance in commercial products.

5.2. Cosmetics and Skincare

Tea polyphenols have long been used in skincare products due to their antioxidant and anti-aging properties. Recent advancements in nanotechnology, including lipid-based nanocarriers and nanoemulsions, have allowed for more effective delivery of these compounds, enhancing their penetration and efficacy [2]. In a randomized controlled trial, topical application of EGCG-loaded lipid nanoparticles over 8 weeks led to a 31% reduction in wrinkle depth and a 28% improvement in skin elasticity compared to non-encapsulated formulations [31]. These outcomes were attributed to improved dermal delivery and enhanced cellular antioxidant defense mechanisms. Moreover, green tea-based topical gels have demonstrated efficacy in reducing erythema and UV-induced oxidative stress, positioning them as natural alternatives to synthetic sunscreens [4,25]. Despite these benefits, there are limitations regarding formulation stability and long-term skin compatibility, especially in individuals with sensitive skin. Future efforts must focus on optimizing carrier systems to balance efficacy, safety, and shelf life.

5.3. Pharmaceuticals and Nutraceuticals

The pharmaceutical and nutraceutical industries have increasingly embraced tea bioactives for their therapeutic potential. EGCG, in particular, has been studied for its role in preventing and managing chronic diseases, such as cardiovascular diseases, diabetes, and cancer [6]. Clinical trials have provided mixed but promising evidence. A 12-week double-blind placebo-controlled trial involving 94 subjects with metabolic syndrome showed that oral supplementation with 400 mg EGCG twice daily resulted in a 10% reduction in fasting glucose and a 14% decrease in CRP levels ($p < 0.05$), compared to placebo [6]. Similarly, liposomal encapsulation of EGCG has been explored to improve its notoriously poor bioavailability. One study demonstrated a 2.5-fold increase in plasma EGCG levels with liposomal delivery compared to free-form EGCG, accompanied by significantly reduced markers of systemic inflammation [8].

However, inter-individual variability in response and potential hepatotoxicity at higher doses (above 800 mg/day) raise safety considerations. Thus, while tea catechins show therapeutic promise, their clinical translation must be accompanied by optimized delivery systems and well-monitored dosage guidelines.

5.4. Food Preservation

Tea polyphenols have also been explored for their use in natural food preservation. Their antioxidant and antimicrobial properties make them suitable for extending the shelf life of perishable products without the need for synthetic additives [11]. Experimental studies have validated their efficacy: incorporation of green tea extract (0.5–1.0%) into minced meat reduced lipid oxidation (TBARS values decreased by ~45%) and microbial growth (total viable count reduced by ~2 log CFU/g) over 7 days of refrigerated storage [10,11]. These effects are primarily attributed to EGCG's ability to chelate pro-oxidant metals and disrupt bacterial cell membranes. However, practical application at the industrial scale is limited by flavor interference, color changes, and regulatory acceptance of concentration limits. Moreover, polyphenol migration and interaction with food matrices must be assessed to ensure consistent preservative activity across different product types.

6. Challenges and Future Prospects

Despite advancements in extraction technologies and formulation strategies, key research challenges persist. A primary concern is the inherently low bioavailability of tea catechins particularly EGCG—which undergo rapid metabolism and poor intestinal absorption, limiting their therapeutic efficacy in functional foods and nutraceuticals [38]. Future research should prioritize the development of standardized, scalable nano-delivery systems (e.g., liposomes, polymeric nanoparticles) that can enhance EGCG stability and absorption without compromising product safety or sensory properties. Additionally, long-term in vivo studies are needed to evaluate pharmacokinetics, tissue distribution, and dose–response relationships for these advanced carriers [40].

Another critical research direction involves improving the environmental sustainability of bioactive extraction. While green methods, such as Supercritical Fluid Extraction (SFE) and Enzyme-Assisted Extraction (EAE) reduce chemical use and waste generation, their scalability and energy demands remain a concern [41]. Future studies should focus on life cycle assessments (LCA) of extraction processes, the use of low-impact solvents (e.g., deep eutectic solvents), and the integration of renewable energy sources (e.g., solar-assisted extraction units) to lower the carbon footprint of tea bioactive production [42]. Moreover, coupling sustainable extraction with circular economy models, such as valorizing tea waste streams, represents an emerging priority for both environmental and economic optimization [43–45].

7. Conclusions

The past five years have seen significant advancements in both the extraction and application of bioactive compounds from tea. Innovative extraction techniques, such as SFE, UAE, and PEF, have improved the efficiency, yield, and purity of tea bioactive, while reducing the environmental impact of the extraction process. These compounds are now being applied in a diverse range of products, from functional foods and beverages to cosmetics and pharmaceuticals. However, challenges remain, particularly in improving the bioavailability of key compounds like EGCG and ensuring the sustainability of large-scale production. As research in this field continues to evolve, the future holds great promise for the continued integration of tea bioactives into everyday products, benefiting both health-conscious consumers and the environment.

Author Contributions

S.R and N.W.: Conceptualization and Writing—original draft preparation, Writing— review and editing, and Project administration. Z.S and M.Y and R.W.: Visualization and Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no competing financial interest.

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