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Sustainable valorization of tea flower (*Camellia sinensis*) blossoms: bioactive phytochemicals and functional food applications – a review

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Tea (*Camellia sinensis*) is the second most widely consumed drink after water, with an annual production of 6.5 million tons worldwide. Black tea (78%) and green tea (20%) account for the majority of global tea production, resulting in large amounts of waste, such as tea flowers, which are an underexploited resource. The theoretical fresh weight of Assam tea flowers alone is 1.4–4.6 billion kg per year, but only 600–3000 kg per ha of dry matter is recovered after processing. This review discusses the biochemistry of tea flowers, which are rich in catechins (24.85–28.02 mg g^{-1}), polysaccharides (30–38%), and saponins (0.47–4.23%). Antioxidant, anti-inflammatory, antiproliferative, antidiabetic, and anti-obesity properties have been reported in preclinical models, but the human equivalent doses (243 mg per day to 2.4 g per day) are considered impractical. Hot air and microwave drying methods are optimal for preserving phenolic compounds, but freeze-drying preserves the highest quality at a high cost. Toxicity studies have revealed low toxicity (LD_{50} > 12 g kg^{-1}) with a safe daily intake of 24 g for a 60 kg human; however, efficacy, variety standardization, EU novel food approval, and US GRAS status are yet to be established. The next research priorities should focus on human bioavailability, allergenicity, and processing effects. Until then, tea flowers should be considered novel food ingredients with traditional use rather than evidence-based functional foods.

Sustainability spotlight

Tea flower (*Camellia sinensis*) blossoms are increasingly recognized as a sustainable source of bioactive phytochemicals, even though they are historically under-utilized relative to tea leaf production. The bioactive phytochemicals in tea flowers are rich in polyphenols, flavonoids, and saponins that exhibit antioxidant, anti-inflammatory, and medicinal properties. Tea flowers add value to tea production systems while enhancing sustainability by reducing waste and utilizing approaches that support a circular bioeconomy for functional food and pharmacological applications related to waste products.

1 Introduction

Camellia sinensis (tea) is an evergreen shrub native to China and Assam (India) and serves as the source of tea, a widely consumed beverage. Out of all the varieties, two noteworthy botanical varieties are the Chinese cultivar (*C. sinensis* var. *sinensis*) and the Indian cultivar (*C. sinensis* var. *assamica*).[1] China leads in tea production with 2 400 000 tonnes, followed by India (900 000 tonnes), Kenya (305 000 tonnes), Sri Lanka (300 000 tonnes), and other tea-producing countries. In India, tea production was documented to be 1.375 million tonnes by the end of 2023. Approximately 83% of India's tea production originates from Assam and West Bengal, the northern states, while the southern states of Tamil Nadu, Kerala, and Karnataka contribute around 17%. Assam produced 672 140 tonnes of tea in 2023, followed by West Bengal (408 730 tonnes), Tamil Nadu (165 880 tonnes), Kerala (60 360 tonnes), Karnataka (5120 tonnes) and other states (63 000 tonnes).[1,2] Collectively, such large outputs indicate a substantial and continuous stream of secondary biomass and residues that can create opportunities for resource recovery and valorization. The demand and consumption of tea continue to be on the rise due to its various nutritional and health benefits. Along with the huge production of tea, there is also an increase in the waste generated by the by-products of tea. Tea waste is generated throughout the line of production, from plucking, pruning, processing to post-consumption. Assam, the "Tea State of India," has a land area for tea cultivation of 312 210 hectares and has an annual production of 507 million kilograms of tea.[2]

After the vegetative propagation of the shrubs, the flowers are considered as waste. From a circular bioeconomy

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perspective, these flowers are a promising underutilized secondary raw material. Flowers are generally removed manually or are left attached to the shrub to wither away naturally.[3] In Assam, surveys have shown that instead of employing workers to remove tea flowers, they are left to wither away as their removal is physically impractical. However, recent studies have shown that tea flowers compete with leaves for water and nutrients, with the flowers acting as a sink and the tea leaves being the source.[4] In China, 4.0 billion kilograms of tea blossoms are produced per year. In the annual harvest, up to 12 000 kilograms are usually plucked from one hectare. However, almost a billion kilograms of tea blossoms remain accessible but uncollected annually, resulting in substantial waste.[5] With efficient logistics and post-harvest management, this biomass could serve as a stable feedstock for downstream processing and value-added applications. Documented field yields of 4500–14 800 kg fresh flowers per ha across 312 210 ha of cultivated area indicate a theoretical annual biomass of 1.4–4.6 billion kg.[6]

Recent breakthroughs in tea blossoms, which have a similar chemical makeup to tea leaves and hence can also exhibit significantly desirable characteristics, have garnered increased curiosity in the last few years.[7] These similarities provide enough evidence to consider tea flowers as functional substitutes or complements to tea leaves in value-added formulations (Table 2). Tea possesses numerous bioactive compounds, such as catechins, tannins and alkaloids, which confer secondary benefits beyond its primary uses; the antioxidants present in tea promote dermal and trichological health, and show supporting evidence for application in agricultural and functional food systems.[8] It has also shown promising results against UV radiation-induced photo-immunosuppression; cutaneous erythema; photoaging; thickening of the epidermis; and overexpression of MMP-2, MMP-9, CK5/6, and CK16 and the associated inflammation and oxidative stress.[9] Numerous incisive and valuable breakthroughs are currently being made in the genetics, extraction, verification, and assessment of bioactive components of *C. sinensis* blossoms.[10] These components exhibit many biotic activities, including antioxidant activity from catechins and polysaccharides; antidiabetic and immunomodulatory properties from polysaccharides; and anti-hyperglycemic, antihyperlipidemic, hypoallergenic, and obesity regulation attributes from saponins, which have only been investigated *in vitro* and in animal models with minimal clinical validation to date.[7,10] China and Japan have recently produced functional foods and beverages derived from tea blossoms. Flower teas are made mainly by combining tea leaves with various flower varieties.[11,12] In black tea made with tea flowers, it was found that the polyphenol content remained mostly constant, and the amounts of catechin and caffeine were reduced as more tea blossoms were added. Catechin and caffeine concentrations varied significantly among the examined tea cultivars, whereas polyphenol levels stayed constant. To maintain the catechin and caffeine content of black tea, a smaller proportion of oven-dried tea flowers should be utilized.[13] Various concoctions of flower teas have been manufactured and marketed, such as chrysanthemum, cinnamon, jasmine, lotus, and rose. Such products have received initial market interest and consumer acceptance, but broader acceptance is based on standardization, safety and regulatory approval. Unfortunately, a commercially accepted beverage of tea leaves combined with tea flowers has not yet been formulated. It is crucial to determine whether tea blossoms are suitable for producing a palatable beverage.

This study aims to better recognize tea flowers, which are considered a waste resource, and to emphasize their potential utilization by reviewing the functional compounds present and their applications. This review systematically classifies the bioactive constituents of tea flowers and critically evaluates their mechanistic and translational relevance, with particular emphasis on the current lack of clinical validation. Beyond compiling biomedical findings, this work reframes tea flowers from a pharmacological curiosity to an underutilized agricultural by-product. Importantly, tea flowering is agronomically undesirable, as flowers act as metabolic "sinks" that divert assimilates away from leaf growth, thereby reducing photosynthetic efficiency and influencing nitrogen allocation related to vegetative yield. Consequently, routine removal of flowers is already practiced to improve tea production. This unavoidable biomass can be valorized as a sustainable source of functional ingredients, extracts, and infusion materials without requiring additional land, inputs, or cultivation burden. By integrating chemical profiling with practical utilization pathways, this review positions tea flower removal and valorization as a zero-waste, circular strategy linking crop management, sustainable processing, and functional food development.

2 Literature search methodology

A comprehensive literature search was conducted to collect relevant studies on tea flowers and their valorization potential. The search was limited to studies published between 2019 and 2025 to ensure inclusion of recent research (2026). The search included keywords consisting of "tea flower", "*Camellia sinensis* flower", "tea flower bioactive compounds", "tea waste valorization", "tea flower valorization", "tea flower applications", and "tea flower health benefits". The literature comprised experimental studies, randomized controlled trials, and *in vitro* studies.

2.1 Availability, harvesting and processing of tea flowers

Tea flowers are actinomorphic (radially symmetrical) and typically white, emitting a mild fragrance, with a central cluster of yellow stamens. They are arranged singly or in small clusters and have a diameter of approximately 2.5–4 cm (1–1.6 inches).[13] The flowers are bisexual (gynandrous), possessing both male and female reproductive organs, enabling self-fertilization. The flowering period generally occurs from late September to early February, although it may vary depending on climatic conditions and the growing environment. The flowering phase is short-lived and represents an important reproductive stage of the plant.[14,15] Fig. 1 shows the different flowering phases in tea. Tea flowers are typically removed manually during pruning or immediately after anthesis in the early morning, often along

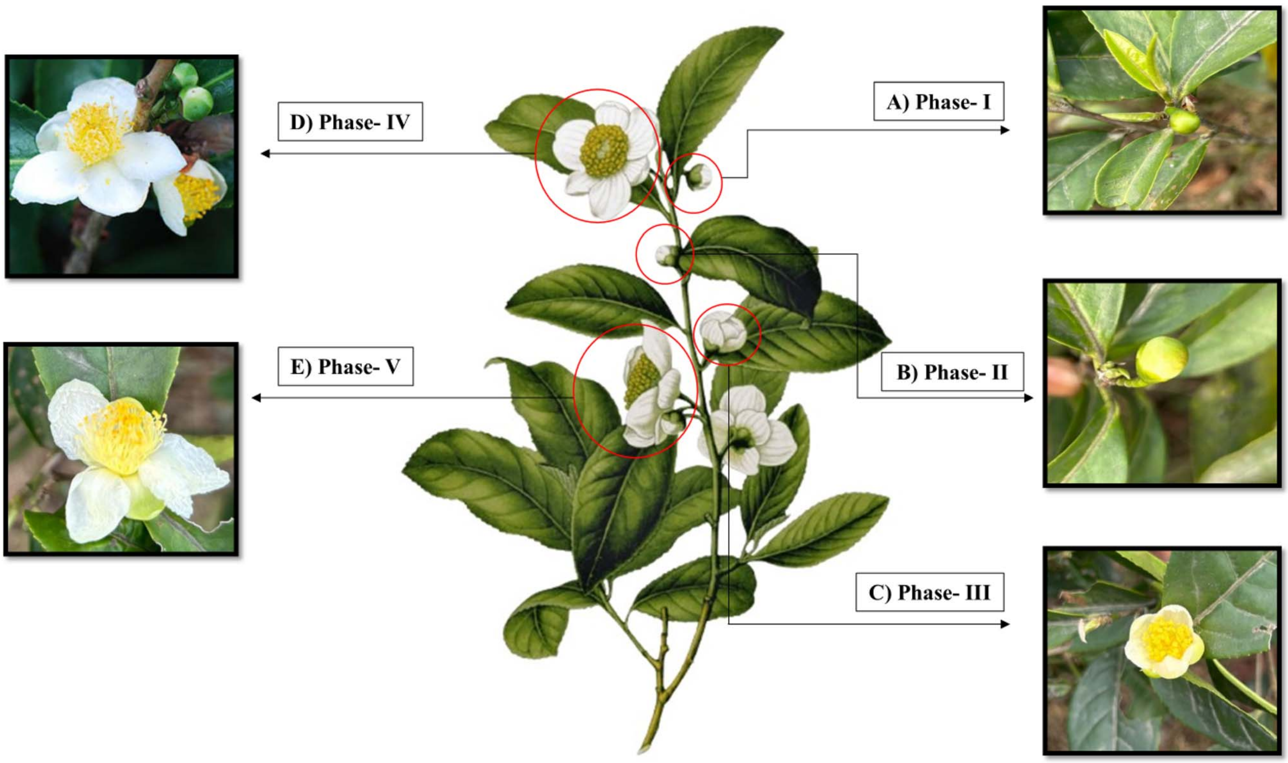

Fig. 1 Morphological stages of *Camellia sinensis* flower development. (A) Phase I: unopened bud; (B) phase II: early opening; (C) phase III: partial opening; (D) phase IV: full anthesis; (E) phase V: senescence. Scale bar = 1 cm. Photographs were taken at the Korangani Tea Estate in March 2025 under natural lighting conditions. Stages were classified according to Joshi *et al.* (2011).[111]

with the plucking of tea leaves, to prevent competition for vegetative growth. This practice generates a predictable and low-cost biomass stream without requiring additional agronomic inputs. In regions such as Assam, tea flower yields range from approximately 4500 to 14 800 kg per ha, contributing to an estimated annual production of up to 4.6 billion kilograms. Considering a moisture content of 70–80%, the theoretical dry matter yields range between 900 and 4440 kg per ha per year. After accounting for losses during harvesting (10–15%), spoilage prior to processing (5–10%), and drying losses (approximately 10–20% trimming and 5–10% incomplete dehydration), the recoverable dry biomass is estimated to be approximately 600–3000 kg per ha per year, with a median value of around 1800 kg per ha per year.[16] Despite this substantial biomass availability, systematic utilization remains limited, particularly in India, where flowers are typically discarded during pruning. In China, where approximately 4 billion kilograms of fresh flowers are produced annually, only a small fraction (<1%) is utilized for value-added products such as flower tea, tea flower wine, and confectionery. No published data are available on organized collection rates or the proportion of flowers harvested *versus* those left in the field. Importantly, flower removal has been shown to enhance tea leaf yield and quality by approximately 30% in the subsequent year. Nutrient redistribution studies indicate that approximately 5.3–21.1 kg of phosphorus (P) and 31–124 kg of potassium (K) are diverted away from leaves, leading to alterations in carbon metabolism, nitrogen metabolism, photosynthesis, and starch and sugar accumulation. These estimates are based on tissue nutrient concentrations (P: 0.12–0.48% DW; K: 0.7–2.8% DW) and dry flower biomass yields (4.4–17.6 tonnes per ha per year). Multi-omics analyses further indicate that these metabolic changes are regulated by transcription factors (bHLH, NAC, WRKY, MYB, G2-like, and trihelix) and sugar/amino acid transporters, highlighting the complexity of source–sink regulation.[17,18]

Fresh tea flowers have high moisture content and contain abundant bioactive compounds, necessitating rapid post-harvest handling to minimize oxidative degradation. After harvesting, flowers are graded, sorted, and transported in ventilated containers and processed within a few hours.[19] Drying is the most critical step, as it significantly influences the retention of bioactive compounds and overall product quality. It is also reported to contribute to the reduction of potentially toxic components present in tea flowers, similar to fermentation processes in tea leaves. Conventional hot air drying (≤60 °C) remains the most widely used and scalable method, achieving safe moisture levels within approximately 180 minutes while preserving catechins, flavonol glycosides, saponins, and color quality.[20] However, higher temperatures (>100 °C) can lead to increased degradation of these compounds. Hybrid drying techniques, such as microwave-assisted drying followed by hot air drying, have been shown to reduce processing time and improve the retention of phenolic and aromatic compounds.[21] Freeze drying has also been explored and demonstrates superior preservation of structural and biochemical integrity;

however, its industrial application is limited due to high capital and energy costs. Overall, hot air drying and hybrid drying methods are considered the most practical and scalable approaches for tea flower valorization.[21]

Hot air drying is industrially scalable, whereas freeze-drying remains cost-prohibitive. Extraction yields vary significantly depending on the solvent system and processing conditions.[22] Significant variability exists due to cultivars, flowering stages, and geographic origin. Lack of standardized extraction protocols limits reproducibility. Industrial scalability is constrained by energy requirements and processing costs. Sensory acceptability and bitterness due to saponins may limit direct food incorporation. From a technological perspective, the large-scale valorization of tea flowers requires careful consideration of processing feasibility and standardization. Among the available drying methods, hot air drying remains the most industrially viable due to its scalability and relatively low operational cost, whereas freeze-drying, despite superior retention of bioactive compounds, is economically prohibitive for bulk applications.[23] Similarly, extraction efficiency varies widely depending on solvent systems, temperature, and time, leading to inconsistencies in the yield and composition of bioactive fractions. A major challenge lies in the lack of standardized processing protocols, as the chemical composition of tea flowers is highly influenced by the cultivar, flowering stage, geographical origin, and post-harvest handling. This variability poses significant constraints on reproducibility, quality control, and industrial adoption, highlighting the need for optimized and validated processing frameworks.[24] In the context of food applications, several practical constraints must be addressed before tea flower-derived ingredients can be widely utilized. The presence of saponins and certain polyphenols may impart bitterness and astringency, potentially limiting sensory acceptance in food formulations. Additionally, the stability of bioactive compounds during processing, storage, and digestion remains a critical concern, as degradation may reduce functional efficacy. Regulatory considerations, including the need for safety validation, standardization, and approval under frameworks such as novel food regulations or GRAS status, further complicate commercialization pathways.[25] Moreover, most reported bioactivities are derived from *in vitro* and animal studies using concentrated extracts, with limited evidence supporting efficacy at realistic dietary intake levels. Bridging this translational gap requires integrated efforts in formulation development, bioavailability assessment, and well-designed human studies to establish the practical relevance of tea flower-based functional ingredients.

2.2 Chemical profile of tea flowers

The chemical framework of tea leaves and flowers is quite comparable. Tea leaves contain various types of metabolites, which include simple phenolics, such as catechins and flavonols, alkaloids like caffeine, and such non-phenolic compounds, such as theanine.[26,27] Tea blossoms are composed of amino acids, catechins, polysaccharides, proteins, and saponins; however, the types and quantities of these chemicals change between species and the flower's developmental stages.[28] Tea blossoms possess a chemical composition corresponding to that of tea leaves. Tea flower extract (Longjing 43) has a high concentration of functional components, such as carbohydrates (34.02% ± 1.42%), polyphenolic compounds (11.57% ± 0.14%), crude proteins (27.72% ± 3.07%) and saponins (2.81% ± 0.00%) among other functional groups.[29] Numerous significant and insightful discoveries have been made in physiological genetics, as well as in the isolation, identification, and assessment of bioactive chemicals found in tea florets.[31] Consequently, tea flowers have the potential for applications across multiple industries, including food, pharmaceuticals, and chemicals. Aside from tea flower wine and tea flower confectionery, the market has also seen the introduction of processed tea flower drinks. Due to their appealing look and distinct flavor, these beverages have sparked tremendous consumer interest and increased the tea industry's economic advantages.

3 Primary nutrients

3.1 Polysaccharides

Polysaccharides are a group of geometrically diverse biomolecules with a very large chemical structure connected by various glycosidic bonds between monosaccharide residues, which were previously identified as a notable element in tea blossoms.[32] According to the general chemical analysis, tea flowers contain a very high percentage of soluble sugars, accounting for nearly 40% of the total constituents. The four samples under study differ minimally in their soluble sugar content, since their values range from 400.74 to 449.30 mg g^{-1}.[33] Tea flower polysaccharides (TFPs) are composed of arabinose, galactose, galacturonic acid, glucose, and rhamnose, with smaller molar contents of glucuronic acid, mannose, and xylose. In the tea flowers, sucrose, fructose, and glucose are the principal soluble sugars, which together constitute nearly 70% of the total soluble sugars.[33] Experiments have revealed that tea flower extract (TFE) contains about 34% carbohydrates, wherein carbohydrates such as glucose, fructose, sucrose, and polysaccharides account for 75.30–90.43 mg g^{-1}, 90.15–124.24 mg g^{-1}, and 88.38–137.63 mg g^{-1}, respectively.[13] Raw TFPs frequently harbor contaminants, such as polyphenols and pigments, underscoring the necessity for purification as a crucial step in advancing TFP research.[32] Altogether, 13 raw and relatively refined TFPS types were previously recognized in *C. sinensis* florets.[34,35]

3.2 Proteins and amino acids

Various effective biomolecules have been extracted and identified from *C. sinensis* blossoms, but only a few are known and recognized for their protein content. The protein content of the tea florets grossly accounts for 30–50% of the dehydrated tea blossom mass, which corresponds to around 300–500 mg g^{-1} (dry weight) across four cultivars (Baiye No.1, Huangjinya, Yujinxiang, and Jiukeng) at the full bloom stage.[35] The protein levels increase during phases I and II (Fig. 1), then decrease as the florets reach the final bloom stage. Eighteen amino acids have been identified in tea flowers, of which nine are proteinogenic and three are non-protein amino acids, *e.g.*, theanine, γ-aminobutyric acid, and ornithine, while free amino acids ranged between 24.10 and 36.35 mg g^{-1} in the four varieties.[37] Six were essential amino acids, such as threonine, valine, methionine, isoleucine, leucine, and lysine. The essential amino acids were estimated to comprise approximately 7.4–11.0% of the four tea flower samples (Baiye No.1, Huangjinya, Yujinxiang, and Jiukeng). These include theanine, the highest amino acid in tea flowers, and proline, which ranked second highest in amount; tea flowers from Yujinxiang were 40% richer in proline compared to those from Baiye No.1 and Huangjinya.[37] The concentrations of the free amino acids found in the four varieties were present in the following ranges (μg g^{-1}): aspartate (46.8–112.8), threonine (90.9–189.1), serine (373.7–799.6), asparagine (130.3–181.4), glutamic acid (428.9–707.2), theanine (2914.4–5357.4), proline (1124.8–1580.9), glycine (23.2–42.3), alanine (595.7–1000.7), valine (126.7–187.2), methionine (179.5–362.2), isoleucine (40.0–69.8), leucine (19.1–41.9), γ-aminobutyric acid (218.3–340.9), histidine (64.3–99.8), ornithine (28–35.0), lysine (44.0–54.4) and arginine (150.2–440.1).[36]

3.3 Phytochemicals

3.3.1 Anthocyanins. *Camellia* plants, belonging to the Theaceae family, are evergreen shrubs that are quite well known for their ornamental flowers. The tea source is the most widely known subspecies. *Camellia* flower colors range from white to pink to red and variegated. Colored flowers of the *Camellia* species that are commonly known are *C. reticulata*, *C. sasanqua*, and *C. mairei*, while *Camellia* flowers are only observed in pure white. Red Benibana-cha and Baitang purple tea are the two new mutations with pink and red flowers.[37] Most tea flowers are white, but there may be a slight color change due to the accumulation of anthocyanins. Recently, a total of 16 anthocyanins have been extracted and recognized in tea blossoms.[30,38] Cyanidin 3-*O*-glucoside, peonidin, cyanidin 3-*O*-rutinoside, cyanidin 3,5-*O*-diglucoside, malvidin 3,5-diglucoside, pelargonin, cyanidin, procyanidin B2, and procyanidin B3 were quantified (in counts per second) across five different phases of flowering, namely phases I, II, III, IV, and V.[37] The white coloration of tea flowers is primarily attributed to higher expression levels of flavanol synthase (FLS), which reduces anthocyanin accumulation. In contrast, increased expression of dihydroflavonol-4-reductase (DFR) and its downstream genes, including anthocyanin synthase (ANS) and leucoanthocyanidin reductase (LAR), promotes anthocyanin biosynthesis, leading to pink or red pigmentation. Therefore, the relative balance between FLS and DFR expression determines anthocyanin accumulation and ultimately influences flower coloration.[37]

3.3.2 Catechins. Catechins, also known as flavan-3-ols, are major polyphenolic compounds in tea and are primarily responsible for its biological activities, including antioxidant, anti-inflammatory, antimicrobial, and cardiometabolic effects.[39] Structurally, catechins consist of a flavan-3-ol backbone (α-phenyl-benzopyran) and are broadly classified into esterified forms, such as epigallocatechin gallate (EGCG) and epicatechin gallate (ECG), and non-esterified forms, including epigallocatechin (EGC) and epicatechin (EC). Among these, EGCG is the predominant catechin, contributing the largest proportion of total catechin content.[40,41] Tea flowers exhibit a catechin profile comparable to tea leaves, with variations depending on the developmental stage and cultivar. Eight major catechins have been identified in tea flowers, with total monomeric catechin content ranging from 24.85 to 28.02 mg g^{-1}. EGCG consistently represents the dominant compound, followed by ECG and EGC, while EC is present in relatively lower concentrations. The proportion of esterified catechins is notably high, accounting for over 85% of total catechins.[42] The catechin content in tea flowers is strongly influenced by the flowering stage, increasing during bud development, peaking at the onset of petal opening (phase III), and subsequently declining toward full bloom.[43] This trend highlights the importance of harvest timing for maximizing catechin yield. Despite these variations, the overall catechin composition remains relatively consistent across cultivars, suggesting that tea flowers can serve as a viable alternative source of catechins. However, most evidence regarding their bioactivity is derived from *in vitro* and animal studies, and further research is required to establish their functional relevance in human applications[44,45] (Table 1).

3.3.3 Caffeine. Caffeine, as a dominant bioactive component of tea leaves, is an alkaloid and secondary metabolite that plays a crucial role in determining tea quality. It is known to have stimulatory and diuretic effects.[41] It is one of the

Table 1 Comparison of the contents of catechins from tea leaves and tea flowers[a]

Catechins	Tea leaves	Tea flowers	Ref.
EGCG	52.2 ± 1.07 to 141 ± 1.35 mg g^{-1}	7.11 ± 0.17 to 12.96 ± 0.14 mg g^{-1}	20 and 54
ECG	14.2 ± 0.69 to 60.2 ± 0.69 mg g^{-1}	4.05 ± 0.10 to 5.19 ± 0.12 mg g^{-1}	20 and 54
EGC	15.9 ± 1.63 to 68.5 ± 4.22 mg g^{-1}	1.10 ± 0.02 to 1.82 ± 0.14 mg g^{-1}	20 and 54
EC	6.20 ± 0.55 to 37.2 ± 0.35 mg g^{-1}	2.57 ± 0.31 to 4.89 ± 0.18 mg g^{-1}	20 and 54
C	1.40 ± 0.21 to 15.2 ± 0.99 mg g^{-1}	0.15 ± 0.02 to 1.15 ± 0.04 mg g^{-1}	54
GC	—	1.91 ± 0.11 to 4.75 ± 0.12 mg g^{-1}	54
CG	—	0.37 ± 0.01 to 0.56 ± 0.01 mg g^{-1}	54
GCG	1.10 ± 0.35 to 3.16 ± 0.49 mg g^{-1}	1.30 ± 0.03 to 2.30 ± 0.03 mg g^{-1}	54
Total catechins	121 ± 4.45 to 238 ± 8.41 mg g^{-1}	24.85 ± 1.03 to 28.02 ± 0.44 mg g^{-1}	20 and 54

[a] EGCG: epigallocatechin gallate; ECG: epicatechin gallate; EGC: epigallocatechin; EC: epicatechin; C: catechin; GC: gallocatechin; CG: catechin gallate and GCG: gallocatechin gallate.

Table 2 Comparative chemical composition of tea leaves and tea flowers across cultivars, processing states, and analytical methods[a]

Component	Matrix	Cultivar/season	Processing state	Extraction/preparation	Analytical method	Range/mean ± SD	Unit	Source
Catechins								
EGCG	Leaf (young shoots)	Longjing 43, spring	Fresh	70% methanol	HPLC	8.5–12.5	% DW	36
EGCG	Leaf (young shoots)	Assamica, spring	Fresh	70% methanol	HPLC	6.2–9.8	% DW	29
EGCG	Flower	Longjing 43, phase III	Fresh	70% methanol	HPLC	0.71–1.30	% DW	1
EGCG	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.711–1.296	% DW	5
EGCG	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.98 ± 0.15	% DW	5
EGCG	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	1.05 ± 0.18	% DW	5
EGCG	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.89 ± 0.12	% DW	5
Total catechins	Leaf (young shoots)	Multiple cultivars	Fresh	70% methanol	HPLC	18–36	% DW	29
Total catechins	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.485 ± 0.35	% DW	5
Total catechins	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.68 ± 0.42	% DW	5
Total catechins	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.80 ± 0.38	% DW	5
Total catechins	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.65 ± 0.31	% DW	5
Caffeine								
Caffeine	Leaf (young shoots)	Multiple cultivars	Fresh	70% methanol	HPLC	2.5–4.0	% DW	36
Caffeine	Leaf (young shoots)	Assamica, spring	Fresh	Hot water infusion	HPLC	2.8–3.5	% DW	17
Caffeine	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.329 ± 0.05	% DW	5
Caffeine	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.412 ± 0.06	% DW	5
Caffeine	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.497 ± 0.08	% DW	5
Caffeine	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	0.385 ± 0.04	% DW	5
Caffeine	Flower	Multiple cultivars	Fresh	70% methanol	HPLC	0.3–1.1	% DW	1
Caffeine	Flower	Not specified	Dried	Hot water infusion	HPLC	0.07–0.13	% DW	
Polysaccharides								
Total polysaccharides	Leaf	Not specified	Fresh	Hot water extraction	Phenol–sulfuric acid	1.5–4.0	% DW	1
Total polysaccharides	Flower	Longjing 43	Hot-air dried (60 °C)	Hot water extraction	Phenol–sulfuric acid	34.02 ± 1.42	% DW	79
TFP-2 (fraction)	Flower	Not specified	Purified	DEAE-cellulose, Sephadex	GPC	MW 1.12×10^4	Da	8
TFP-1 (fraction)	Flower	Not specified	Purified	DEAE-cellulose, Sephadex	GPC	MW 15.9×10^4	Da	8
Saponins								
Total saponins	Leaf	Not specified	Dried	Methanol extraction	Vanillin–sulfuric acid	0.04–0.07	% DW	1
Total saponins	Flower	Longjing 43	Hot-air dried (60 °C)	Methanol extraction	Vanillin–sulfuric acid	2.81 ± 0.00	% DW	79
Total saponins	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	11.58 ± 1.2	% DW	5
Total saponins	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	12.85 ± 1.5	% DW	5
Total saponins	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	13.50 ± 1.8	% DW	5
Total saponins	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	12.20 ± 1.4	% DW	5

Table 2 (*Contd.*)

Component	Matrix	Cultivar/season	Processing state	Extraction/preparation	Analytical method	Range/mean ± SD	Unit	Source
Chakasaponin I	Flower	Not specified	Purified	*n*-Butanol fractionation	LC-MS	0.5–2.5	mg g^{-1}	40
Floratheasaponin A	Flower	Not specified	Purified	*n*-Butanol fractionation	LC-MS	1.0–3.0	mg g^{-1}	40
Amino acids								
Theanine	Leaf (young shoots)	Multiple cultivars	Fresh	70% methanol	HPLC	1.0–3.0	% DW	40
Theanine	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.91 ± 0.45	mg g^{-1}	5
Theanine	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	4.15 ± 0.62	mg g^{-1}	5
Theanine	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	5.36 ± 0.78	mg g^{-1}	5
Theanine	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	3.82 ± 0.51	mg g^{-1}	5
Total free amino acids	Leaf	Not specified	Fresh	70% methanol	HPLC	1.0–4.0	% DW	37
Total free amino acids	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.41 ± 0.35	% DW	5
Total free amino acids	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	3.04 ± 0.48	% DW	5
Total free amino acids	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	3.64 ± 0.52	% DW	5
Total free amino acids	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.89 ± 0.41	% DW	5
Proteins								
Crude protein	Leaf	Not specified	Fresh	Kjeldahl method	Kjeldahl	15–25	% DW	37
Crude protein	Flower	Longjing 43	Hot-air dried (60 °C)	Kjeldahl method	Kjeldahl	27.72 ± 3.07	% DW	78
Crude protein	Flower	Multiple cultivars	Dried	Kjeldahl method	Kjeldahl	30–50	% DW	84
Flavonols								
Total flavonols	Leaf	Not specified	Fresh	70% methanol	HPLC	2–3	% DW	20
Quercetin glycosides	Flower	Meizhan, Shuigu, Huangyezao, Zhenghe Dabai, Fujian Shuixian	Fresh	70% methanol	UHPLC-MS	5 identified	Compounds	20
Kaempferol glycosides	Flower	Meizhan, Shuigu, Huangyezao, Zhenghe Dabai, Fujian Shuixian	Fresh	70% methanol	UHPLC-MS	5 identified	Compounds	20
Volatile compounds								
Total volatiles	Leaf	Not specified	Fresh	SDE/SAFE	GC-MS	>600	Compounds	38
Total volatiles	Flower	Not specified	Fresh	HS-SPME	GC-MS	63	Compounds	5
1-Phenylethanol	Flower	Longjing 43, phase III	Fresh	SDE	GC-MS	12.5–45.8	μg g^{-1}	45
Spermidine derivatives								
Tri-coumaroyl spermidine	Flower	Not specified	Fresh	70% methanol	UPLC-MS	92–181	μg g^{-1}	1
Spermidine derivatives	Leaf	Not specified	Fresh	70% methanol	UPLC-MS	Not detected	—	52

Table 2 (Contd.)

Component	Matrix	Cultivar/season	Processing state	Extraction/preparation	Analytical method	Range/mean ± SD	Unit	Source
Organic acids								
Gallic acid	Leaf	Not specified	Fresh	70% methanol	HPLC	0.5–2.0	mg g^{-1}	74
Gallic acid	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	2.83 ± 0.42	mg g^{-1}	5
Gallic acid	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	3.65 ± 0.55	mg g^{-1}	5
Gallic acid	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	4.95 ± 0.72	mg g^{-1}	5
Gallic acid	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	3.21 ± 0.48	mg g^{-1}	5
Citric acid	Flower	Baiye No.1, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	9.99 ± 1.5	mg g^{-1}	5
Citric acid	Flower	Huangjinya, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	12.45 ± 1.8	mg g^{-1}	5
Citric acid	Flower	Yujinxiang, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	15.16 ± 2.1	mg g^{-1}	5
Citric acid	Flower	Jiukeng, phase III	Hot-air dried (60 °C)	70% ethanol	UHPLC-MS	11.82 ± 1.6	mg g^{-1}	5
Minerals								
Aluminum	Leaf	Not specified	Dried	HNO_3 digestion	ICP-MS	200–1000	mg kg^{-1}	13
Aluminum	Flower	Not specified	Dried	HNO_3 digestion	ICP-MS	233.0 ± 15.5	mg kg^{-1}	72
Manganese	Leaf	Not specified	Dried	HNO_3 digestion	ICP-MS	500–2000	mg kg^{-1}	13
Manganese	Flower	Not specified	Dried	HNO_3 digestion	ICP-MS	1542.3 ± 89.2	mg kg^{-1}	18

[a] Values are expressed as mean ± standard deviation (SD) where replicate data are available, or as range (minimum–maximum) where individual dispersion metrics are not reported. Abbreviations: DW, dry weight; HPLC, high-performance liquid chromatography; UHPLC-MS, ultra-high-performance liquid chromatography-mass spectrometry; GPC, gel permeation chromatography; GC-MS, gas chromatography-mass spectrometry; SDE, simultaneous distillation-extraction; SAFE, solvent-assisted flavour evaporation; HS-SPME, headspace solid-phase microextraction; ICP-MS, inductively coupled plasma mass spectrometry; MW, molecular weight; TFP, tea flower polysaccharide; and n.d., not detected.

methylated xanthine subtypes, a group of secondary metabolites derived from purine nucleotides, most prominently found in tea.[42] It acts as a stimulant for the central nervous system. Tea leaves have relatively high levels of caffeine compared with other caffeine-containing plants, with caffeine making up to 3% of the dry weight of tea leaves. Unlike tea leaves, the blossoms contain smaller amounts of caffeine, making up close to 0.3–1.1% of the dry weight of tea flowers.[33] The three methylxanthine compounds (caffeine, theobromine, and theophylline) found in these flower samples were examined, of which caffeine had the most significant concentration, between 3.29 and 4.97 mg g^{-1}.[36] The caffeine content was estimated to be between 0.13% and 0.07%.[46] Caffeine exhibits both beneficial and adverse physiological effects depending on dosage and individual sensitivity. While moderate intake is associated with improved alertness and cognitive function, excessive consumption may lead to adverse effects such as jitteriness, anxiety, increased heart rate, and insomnia. Emerging evidence also suggests that caffeine has potentially protective roles in neurological and metabolic disorders; however, these findings are primarily derived from epidemiological and preclinical studies and require further validation. Tea flowers, which are often considered an underutilized by-product, represent a promising renewable source of bioactive compounds, including caffeine. Their utilization could support the development of value-added products and reduce reliance on conventional tea leaf-based resources.[44]

3.3.4 **Flavonols.** Flavonols play a key role in identifying tea concentrates and their antioxidant properties in the leaf blades. The main flavonol glycones found in tea leaves are kaempferol, myricetin, and quercetin. Tea leaves contain mono-, di-, and triglycosides of flavonols, which are now seen.[45] Flavonols, along with flavonol glycosides, make up approximately 2–3% of the dry weight of tea leaves. A novel flavonol glycoside named chakaflavonoside has been discovered in *C. sinensis* florets. Tea flowers contain five key quercetin glycosides, three key myricetin glycosides, and five key kaempferol glycosides.[46] Previous studies have reported that a total of eighteen flavonols have been extracted from *C. sinensis* florets.[47,48] Using ultra-high-performance liquid chromatography-mass spectrometry (UHPLC-MS), twelve kinds of flavonoid glycosides were identified and quantified from tea flowers of five different cultivars of tea plants (Meizhan, Shuigu, Huangyezao, Zhenghe Dabai, and Fujian Shuixian).[49]

3.3.5 **Volatile flavor compounds.** Phenylpropanoids, often referred to as benzenoids, contribute to aroma and color, and their purpose in the plant is to attract pollinators and repel herbivores and pathogens.[50] Products made from tea leaves have been said to contain more than 600 volatile compounds.[43] The majority of these aromatic compounds are either generated or intensified during processing. Relatively fewer aromatic compounds are found in fresh tea leaves, originating from one of the two pathways, *i.e.*, the terpenoid and shikimate mechanisms, or through subsequent oxidative degradation of carotenoids and fatty acids.[43] The shikimic acid pathway is a central metabolic pathway in bacteria, archaea, fungi, algae, and some protozoa and higher plants, which aids in the production of folates and aromatic amino acids (tryptophan, phenylalanine, and tyrosine). The composition and abundance of volatile compounds vary depending on extraction methods, cultivar, and the developmental stage of the flower. Notably, glycosidically bound volatiles reach their highest levels during the intermediate flowering stage (phase III). Among the identified compounds, acetophenone and 1-phenylethanol (1-PE) are characteristic constituents of tea flowers and are present at higher levels than in tea leaves. Their accumulation increases during flower development and is primarily localized in the anthers. Several glycosidically bound derivatives of 1-phenylethanol have been identified in tea blossoms, highlighting the complexity of aroma precursor compounds in this plant.[51,52]

A diverse range of volatile compounds has been identified in tea flowers during blooming, including alcohols, aldehydes, esters, ketones, and heterocyclic compounds, with alcohols and aldehydes generally predominating. The composition and relative abundance of these compounds vary across different flowering stages.[53] As flower development progresses, the proportion of alcohols and esters tends to decrease, while heterocyclic compounds increase, reaching their highest levels at the full bloom stage. Although numerous volatile compounds have been detected, a subset is consistently present across developmental stages, while others are stage-specific, indicating dynamic changes in aroma composition during flower maturation.[53]

3.4 Other bioactive compounds

3.4.1 Saponins. Saponins are among the major bioactive constituents of tea flowers, representing the second most abundant group after soluble sugars. Their content in tea blossoms (0.47–4.23% dry weight) is substantially higher than that reported in tea leaves. A wide range of terpenoid saponins has been identified in tea flowers, including floratheasaponins, chakasaponins, and assamsaponins, indicating considerable chemical diversity.[44,54] It has been observed that saponins accumulate in large quantities when petals account for more than 50% of the net floral mass among the four tea varieties (Baiye 1, Longjing 43, Jiaming 1, Yingshuang) from the Zhejiang Province in China.[55] Saponins identified in the buds of tea blossoms exhibit multiple biotic roles, encompassing anti-hyperlipidemic and anti-hyperglycemic properties, preservation of the gastric mucosa, hypoallergenic effects *in vitro*, anti-obesity effects, modulation of stomach motility in murine animals, and enhancement of bowel passage.[56] Floratheasaponins A–F, especially B and E, are potent anti-allergic agents that inhibit β-hexosaminidase release from RBL-2H3 cells. Chakasaponins I–III inhibit the increase in plasma triglycerides and glucose, at least in part, by inhibiting gastric emptying.[45] The variation in biological activity is likely due to the differences in the saponin composition and content among cultivars. The bioactivities exhibited by tea flower-derived saponins include surfactant, anti-inflammatory, antimicrobial, anticancer, neuroprotective, gastroprotective, and anti-allergic properties, with potential applications in agriculture, the chemical industry, and medicine. Saponins from the flowers can also inhibit cancer cell proliferation.[57]

3.4.2 Spermidine derivatives. Ultra-performance liquid chromatography (UPLC) combined with mass spectrometry revealed remarkably dissimilar metabolic profiles between tea leaves and blossoms at various developmental phases.[45] This is due to the presence of unique components, such as spermidine derivatives, which are exclusive to *C. sinensis* blossoms. Tea flower extract profiling revealed four spermidine derivatives, and they were found to be tricoumaroyl spermidine, feruoyldicoumaroyl spermidine, coumaroyl diferuloyl spermidine, and triferuloyl spermidine, which are established in *C. sinensis* flowers, but are yet to be observed in tea leaves.[58] The net concentration of tri-coumaroyl spermidine in tea blossoms is in the range of 92 $\mu g\ g^{-1}$ to 181 $\mu g\ g^{-1}$ (unprocessed mass), which is significantly higher than in other flora.[59] Phenolic acid and spermidine complexes are a broadly dispersed category of secondary plant byproducts that accumulate mainly in floral organs and serve a variety of functions, including protection against wounding, pathogens and insects, and the production of flowers. They are also implicated in sex-specific differentiation, root growth, cell division, and cytomorphogenesis. Not all flower organs are equally involved in metabolite production, and spatial differences within a flower are common. These four spermidine derivatives have shown inhibitory activity against HIV-1 protease.[45]

3.5 Other minor bioactive compounds

Tea consists of almost 30 organic acids, mainly quinic acid, oxalic acid, malic acid, acetic acid, citric acid, tartaric acid, and ascorbic acid, which constitute about 3% of the total dry weight. Organic acids are among the most important factors influencing tea quality.[41] Experiments have reported quantities of these organic acids in tea flowers, namely quinic acid (1.05–2.18 mg g^{-1}), malic acid (7.37–8.40 mg g^{-1}), citric acid (9.99–15.16 mg g^{-1}), gallic acid (2.83–4.95 mg g^{-1}), and succinic acid (1.13–1.40 mg g^{-1}).[58] Apart from gallic acid and quinic acid, which contribute to astringency, citric acid, malic acid, and succinic acid act as souring agents that are commonly used to impart taste to foods. Research has shown that during the early stages of flowering, many compounds are oxidized in the tricarboxylic acid (TCA) cycle to supply energy for flower development. Higher levels of succinic acid, citric acid, and chlorogenic acid in tea flowers compared to young shoots may be explained by the accelerated TCA cycle during tea flower growth.[59] The vitamin content of tea flowers is relatively underexplored, with limited available information. However, some studies have reported the presence of vitamin B2 and vitamin C. The vitamin content varies among different tea flower cultivars and maturation stages. Vitamin B2 was identified as the predominant vitamin, with levels ranging from 0.14 to 0.20 mg per 100 g dry weight across different cultivars.[60,61]

Minerals present in *C. sinensis* are closely associated with metabolic processes. Elements such as phosphorus, potassium, sulfur, manganese, and zinc play important roles in metabolic pathways during tea flowering. The mineral composition of tea

Table 3 Comparative extraction methods for bioactive compounds from tea flowers (*Camellia sinensis*): process parameters, yields, greenness metrics, and scale-up constraints[a]

Target compound	Solvent system	Solid-to-liquid ratio (w/v)	Temperature (°C)	Time	Particle size	pH	Yield (%)	Marker compounds (mg g^{-1} extract or mg g^{-1} dry weight)	Greenness metric	Scale-up constraints	Source
Polysaccharides (TFPs)	Hot water extraction (HWE)	01 : 20	90	120 min	NR	6.0–7.0	3.5	Total sugars: 685; uronic acid: 96	Moderate (water: safe, *E*: 2.4 kWh kg^{-1}, CO_2: 20.3 kg kg^{-1})	Long extraction time; high thermal energy; batch variability 8–12%	89
Polysaccharides (TFPs)	Boiling water extraction (BWE)	01 : 20	100	60 min	NR	6.0–7.0	4.2	Total sugars: 712; acidic polysaccharides: ↑15%	Moderate (water: safe, *E*: 2.2 kWh kg^{-1}, CO_2: 17.6 kg kg^{-1})	Risk of polysaccharide hydrolysis; Maillard reaction products	89
Polysaccharides (TFPs)	Enzyme extraction (EE)	01 : 25	50	180 min	40 mesh	5.0 (optimal)	5.1	Total sugars: 745; protein: ↓40%	Good (water: safe, *E*: 1.8 kWh kg^{-1}, CO_2: 14.4 kg kg^{-1}, enzyme cost factor)	High enzyme cost ($50–200 per kg); activity loss > 45 °C; batch variability 12–18%	89
Polysaccharides (TFPs)	Traditional water extraction (TWE)	01 : 30	100	360 min (6 h)	NR	6.5	4.5	Total sugars: 698; theanine: 12.5	Poor (water: safe, *E*: 4.5 kWh kg^{-1}, CO_2: 36 kg kg^{-1})	Excessive time; thermal degradation risk; not scalable	88
Polysaccharides (TFPs)	Microwave-assisted extraction (MAE)	01 : 20	200–230	2 min	NR	6.0–7.0	4.3	Total sugars: 720; low M_w fragments: ↑25%	Moderate to good (water: safe, *E*: 0.9 kWh kg^{-1}, CO_2: 7.1 kg kg^{-1})	High capital cost; uneven heating; catechin degradation > 180 °C	83
Polysaccharides (TFPs)	Ultrasound-assisted extraction (UAE)	01 : 25	60	30 min	60 mesh	6.0–7.0	5.3	Total sugars: 778; uronic acid: 132	Good (water: safe, *E*: 1.0 kWh kg^{-1}, CO_2: 8.0 kg kg^{-1})	Cavitation erosion equipment; scale-up acoustic challenges	88
Catechins	70% ethanol	01 : 30	60	120 min	40 mesh	5.0–6.0	8.2	EGCG: 12.96; EC: 4.89; total catechins: 28.02	Moderate (ethanol: class 3 solvent, *E*: 2.8 kWh kg^{-1}, CO_2: 22.4 kg kg^{-1})	Solvent recovery costs; flammability; residual solvent < 50 ppm required	5
Saponins	70% ethanol	01 : 30	70	180 min	40 mesh	6	13.5	Total saponins: 135.02; chakasaponin II: 45.3	Moderate (ethanol: class 3 solvent, *E*: 3.2 kWh kg^{-1}, CO_2: 25.6 kg kg^{-1})	Long extraction time; foam formation; emulsion stabilization issues	5
Catechins + caffeine	Water (distilled)	01 : 50	80	30 min	NR	6.5	6.8	Caffeine: 4.97; EGCG: 8.5; EC: 3.2	Good (water: safe, *E*: 1.5 kWh kg^{-1}, CO_2: 12 kg kg^{-1})	Low catechin selectivity; concurrent protein extraction; microbiological risk	5
Volatile compounds (1-phenylethanol)	Ethanol glycoside hydrolysis	01 : 40	40	1440 min (24 h)	NR	4.5 (acidic)	0.8	(*R*)-1-Phenylethanol: 2.4; (*S*)-1-phenylethanol: 1.8	Poor (ethanol + acid, *E*: 4.0 kWh kg^{-1}, CO_2: 32 kg kg^{-1})	Extremely time-consuming; acid hydrolysis artifacts; not industrially viable	58

Table 3 (*Contd.*)

Target compound	Solvent system	Solid-to-liquid ratio (w/v)	Temperature (°C)	Time	Particle size	pH	Yield (%)	Marker compounds (mg g^{-1} extract or mg g^{-1} dry weight)	Greenness metric	Scale-up constraints	Source
Flavonol glycosides	50% methanol	01 : 20	25 (RT)	60 min	60 mesh	6	4.5	Quercetin glycosides: 15.3; kaempferol glycosides: 12.7	Poor (methanol: class 2 solvent, toxic, *E*: 2.5 kWh kg^{-1})	Methanol toxicity; strict residue limits (200 ppm); environmental H&S concerns	95
Kombucha bioactives	*C. sinensis* flower + SCOBY fermentation	1 : 10 (starter)	25	10 080 min (7 days)	NR	2.5–3.5 (initial)	NR	Theaflavins: 8.2; D-saccharic acid-1,4-lactone: 4.5	Good (biological process, *E*: 0.3 kWh kg^{-1}, CO_2: 2.4 kg kg^{-1})	Long fermentation; contamination risk; batch variability 15–25%; pH monitoring critical	5
Saponins (chakasaponins I–III)	Methanol → *n*-butanol partition	1 : 10 (MeOH)	25 (RT)	2880 min (48 h)	NR	7	2.8	Chakasaponin I: 18.5; II: 22.3; III: 19.7	Poor (methanol/chloroform toxic, *E*: 5.5 kWh kg^{-1}, CO_2: 44 kg kg^{-1})	Multiple solvent steps; chloroform use prohibited in food; not scalable	40
Saponins (anti-cancer)	Methanol → *n*-butanol	01 : 15	25	120 min	NR	7	3.2	TFS total: 89.5; cytotoxic activity: IC_{50} 1.5 µg mL^{-1}	Poor (methanol toxic, *E*: 4.2 kWh kg^{-1}, CO_2: 33.6 kg kg^{-1})	Pharmaceutical-grade only; solvent residue compliance challenging	78
Volatile compounds (aroma)	HS-GC-MS (headspace)	NA (direct analysis)	120 (oven)	20 min incubation	350 µm (freeze-dried)	NA	NA	Linalool ACI: >27; acetophenone ACI: 57.35 (TF-S2 only); total volatiles: 250.74×10^6 (TF-S1), 543.04×10^6 (TF-S2), 308.64×10^6 (TF-S3)	Excellent (solvent-free, *E*: 0.05 kWh kg^{-1}, CO_2: 0.4 kg kg^{-1})	Analytical-scale only; not preparative; requires freeze-drying pre-treatment; batch variability in flower stage selection	94
Catechins, caffeine, TPC	Oven drying (40 °C) *vs.* freeze-drying	NA (drying study)	40 (oven)/ −55 (freeze)	6 h (oven)/ 48 h (freeze)	NR	NA	NA	Caffeine: 7.6 ± 0.1 (TRI 2023) to 5.5 ± 0.1 (TRI 3031) mg g^{-1}; catechins: 30–50% higher in oven-dried *vs.* freeze-dried; TPC: unchanged	Moderate (thermal energy for oven drying, *E*: 1.2 kWh kg^{-1}, CO_2: 9.6 kg kg^{-1})	Drying method critical for catechin preservation; oven drying 30–50% better than freeze-drying for catechins; cultivar variation significant; ≤10% incorporation recommended for black tea	5

[a] Abbreviations: TFPs, tea flower polysaccharides; TWE, traditional water extraction; HWE, hot water extraction; BWE, boiling water extraction; EE, enzyme extraction; MAE, microwave-assisted extraction; UAE, ultrasound-assisted extraction; RT, room temperature; M_w, molecular weight; TFS, tea flower saponins; TPC, total phenolic content; SCOBY, symbiotic culture of bacteria and yeast; HS-GC-MS, headspace gas chromatography-mass spectrometry; ACI, aroma characteristic index; NR, not reported; and NA, not applicable. Greenness metrics: *E*, energy consumption (kilowatt-hours per kilogram dry matter); CO_2, carbon dioxide equivalent emissions (kilograms per kilogram dry matter). Solvent classes per ICH Q3C(R8): class 2 (limited toxicological concern), and class 3 (low toxicological concern). Yield expressed as percentage of dry weight unless specified. Scale-up constraints reflect reported limitations for industrial translation. Note: greenness assessment based on solvent safety (GHS classification), energy consumption, and carbon footprint. "Good" = aqueous or biological process with $E < 1.5$ kWh kg^{-1}; "moderate" = class 3 solvents or thermal processing with *E* 1.5–3.0 kWh kg^{-1}; "poor" = class 2 solvents or high-energy multi-step processes with $E > 3.0$ kWh kg^{-1}. Batch variability expressed as the coefficient of variation (%).

flowers includes aluminum, boron, calcium, copper, iron, potassium, magnesium, zinc, manganese, phosphorus, and sulfur.[62,63] These elements contribute to various physiological functions, including enzyme activation, photosynthesis, respiration, and cellular metabolism. The pigments found in tea flowers predominantly comprise carotenoids and anthocyanins, which contribute to flower coloration and plant health. While tea flowers are generally white, certain mutations exhibit pink or red coloration.[63,64] Carotenoids such as neoxanthin and β-carotene have been identified, with their levels decreasing during flower maturation. Anthocyanins also contribute to color variation, with their accumulation influenced by developmental stage and gene expression. Despite their importance, the mechanisms governing pigment accumulation in tea flowers remain incompletely understood and require further investigation.[65] A comprehensive summary of the extraction of different classes of compounds is presented in Table 3.

4 Economic and operational efficiency framework

According to the IEA Bioenergy Task 42 recommendations for the evaluation of a biorefinery, the functional unit considered for the assessment of the biofuel production from tea flowers is one ton of dry matter, and the scope of the study covers the geographical location of Assam, India, which spans a total of 312 210 hectares and produces 672 140 tonnes of tea flowers every year.[66]

4.1 Mass balance

Fresh flower yields from field surveys range between 4500 and 14 800 kg per ha per year. At 70–80% moisture content, this amounts theoretically to 900–4440 kg per ha per year of dry matter. Allowing for field losses of 15–25%, spoilage of 55–10%, and drying inefficiencies of 15–30%, the amount of recoverable dry matter is in the region of 600–3000 kg per ha per year, with a median of 1800 kg. This would put the potential for Assam at approximately 187 000 to 937 000 tonnes of dry tea flower per year, which largely remains an untapped resource.[67] The processing of one tonne of dry tea flower at a 1 : 10 w/v ratio with 70% ethanol yields 80–120 kg of crude extract, corresponding to a recovery of 8–12%.[68] The high-value purified fractions of saponins or polysaccharides make up 15–25 kg. Co-products comprise over 850 kg of lignocellulosic residue for animal feed or bioenergy, while 0.5–2 kg is made up of essential oil. The amount of wastewater generated is around 9500 L, with a biochemical oxygen demand amounting to 3–8 g L^{-1}. Literature-reported yields include polyphenols at 11.6% of dry weight,[30] saponins between 0.47% and 4.23%,[69] and polysaccharides up to 34%.[30]

4.2 Carbon balance

Tea flowers contain approximately 45% carbon after drying. Of the carbon in the dry tea flowers per ton, the bioactive portion in the final product amounts to 35–55 kg, or 8–12% of the total dry carbon, whereas the residue retains 320–380 kg, or 71–84%, of the total carbon. During the extraction process, 15–25 kg of carbon is lost as energy-related emissions, and 20–40 kg are lost during the biodegradation of wastewater. Most of the carbon is conserved in the products and co-products, *i.e.*, 80–90%, whereas 10–20% of the carbon is lost during the process. Comparing the above information with the synthetic polyphenol process, in which 5–15 kg CO_2 is emitted per kg of product, we see that tea flower extraction has advantages in the form of reduced emissions, especially from field decomposition and the formation of methane gas.[70]

4.3 Techno-economic assessment (TEA)

Capital requirements for a facility processing around 5 tonnes per day would be between approximately USD 700 000 and 1.28 million. These operating expenses would include drying (about 150k–250k), extraction (200k–400k), and concentration/drying (280k–480k), which would be consistent with benchmarks for an herbal extraction facility.[71] Current operating expenses on a kilogram basis for the extract would comprise raw materials (15–25%), energy (20–30%), which might be reduced by biogas,[71] solvent (10–15%), 95% ethanol recovery,[65] labor (15–20%), and waste treatment/depreciation (20–30%). With revenue per tonne of dry flowers, we can expect several product streams as follows: (i) crude polyphenol extract, 100 kg, at 15–40 USD per kg, or 1500–4000 USD. (ii) Purified saponins, 20 kg at 200–500 USD per kg, equivalent to 4000–10 000 USD. (iii) Essential oil, 1 kg, costing between 500 and 1500 USD per kg. Residual cake, 850 kg at 0.10–0.30 USD per kg; 85–255 USD. The total potential revenue is approximately 6000–16 000 USD per ton of dried flowers. For the operation to be viable, a minimum of about 2000 tonnes is required annually, with payback time frames of approximately 4–7 years, depending on the purity of the extract and market accessibility.[71–73]

4.4 Life cycle assessment

Under ReCiPe 2016, the key impact category affected by extraction is climate change, which ranges from 2 to 12 kg CO_2e per kg of extract, contingent upon the energy mix, from a renewable-optimized mix to a coal-grid baseline.[74] The impacts of fossil scarcity can be reduced by using bio-based solvents and greater integration of renewable electricity into the energy supply.[75] Eutrophication can be controlled by using closed-loop water systems and anaerobic digestion for wastewater treatment. It should be noted that the expanded systems credit the avoided methane emissions that would have resulted from the decomposition of biomass in the field.[76] It is clear from the side-by-side comparisons that the global warming potential would be reduced by 50–70 percent by using a solar biomass dryer and extracting biogas from waste processing by 2013.[77,78]

5 Implications for health

Tea flowers contain numerous bioactive metabolites, indicating their diverse biotic role. Various *in vitro* experiments demonstrate that the florets exhibit a range of health-enhancing properties, including anti-inflammatory, antioxidant, and immunostimulant effects, which are largely attributed to their catechins, polysaccharides, and saponins. Fig. 2 presents the bioactive molecules in tea flowers and their associated health benefits (Table 4).[1,30,35,77,83,106]

5.1 Antioxidant properties

Research has demonstrated that the tea flowers exhibit antioxidant activity that increases from the bud stage, peaks at phase III (Fig. 1), and declines to its lowest level at full bloom. This is likely associated with fluctuations in the contents of caffeine, catechin, and other biocomponents throughout the development of the flower. The antioxidant activity primarily stems from the existence of polyphenols and polysaccharides, including catechins like EGCG and ECG, and flavonol glycosides found in *C. sinensis* blossoms.[79,80] Tea flower extracts are obtained using distilled water or 70% ethanol, followed by fractionation with solvents like chloroform, ethyl acetate, and *n*-butanol. The ethyl acetate fraction from the ethanol extract of *C. sinensis* florets exhibits the highest scavenging activity (59.60 μg mL^{-1}) against DPPH-independent radicals. Simultaneously, the ethyl acetate fraction of *C. sinensis* florets exhibits the maximum hydroxyl radical quenching activity, with a 50% scavenging concentration (SC_{50}) of 11.6 (g mL^{-1}), followed by the ethanol extract of *C. sinensis* blossoms (SC_{50}, 19.7 μg mL^{-1}).[81] These differences correlate with variations in catechins, flavones, and polyphenols. Additionally, tea floret extracts demonstrate dose-dependent antioxidant activity against DPPH radicals.[82] Likewise, hydro-soluble polysaccharides derived from tea blossoms exhibit antihepatotoxic effects by shielding against oxidative deterioration in mice, induced by carbon tetrachloride.[83] Furthermore, TFPs have antioxidant activity that surpasses that derived from *C. sinensis* seeds.[84] Consumption of *C. sinensis* blossom extract, which contains carbohydrates, phenolic compounds, proteins, and saponins, amplifies liver function by improving the quantity of SOD levels, myeloperoxidase, catalase, and reduced glutathione while reducing levels of amino transferase and malondialdehyde.[85] Overall, antioxidant activity is one of the most consistently reported properties of tea flowers, supported by both *in vitro* assays and some animal studies. However, the majority of the evidence is derived from chemical and experimental models, and clinical validation in humans remains limited.

5.2 Anticancer effects

Tea flower extracts display selective antiproliferative activity in various cancer models, although the therapeutic potential has yet to be established. In animal models, tea flower polysaccharides (TFPs) at 150–300 mg kg^{-1} increased plasma IL-2, IFN-γ, and

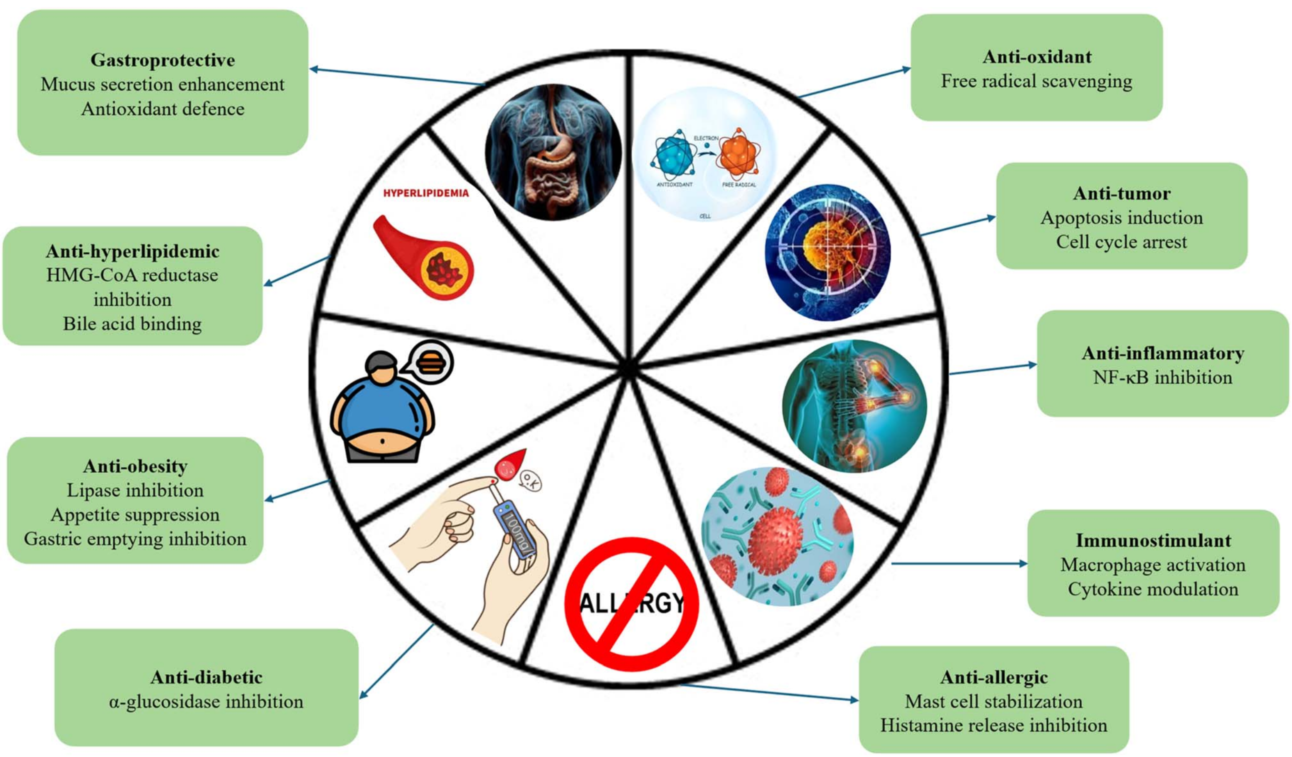

Fig. 2 Multifunctional health benefits of *Camellia sinensis* flower bioactive compounds and their underlying mechanisms. The diagram illustrates nine major bioactivity categories: antioxidant (free radical anti-tumor (apoptosis induction, cell cycle arrest), anti-inflammatory (NF-κB inhibition), immunostimulant (macrophage activation, cytokine modulation), anti-allergic (mast cell stabilization, histamine release inhibition), anti-diabetic (α-glucosidase inhibition), anti-obesity (lipase inhibition, appetite suppression, gastric emptying inhibition), anti-hyperlipidemic (HMG-CoA reductase inhibition, bile acid binding), and gastroprotective (mucus secretion enhancement, antioxidant defence). Central icons represent target organs and pathological conditions: hyperlipidemia, obesity, diabetes, and allergy. Abbreviations: Nrf2, nuclear factor erythroid 2-related factor 2; NF-κB, nuclear factor kappa B; HMG-CoA, 3-hydroxy-3-methylglutaryl-coenzyme A.

Table 4 Volatile compounds present in the tea (*Camellia sinensis*) flower

S. no.	Compound/class	Range/concentration	Ref.
1	Total volatile compounds	63 identified	93 and 108
2	Hydrocarbons	30.9%; 0.22–3.42%	93 and 108
3	Esters	18.40%; 5.68–11.52%	93 and 108
4	Aldehydes	14.3%; 16.42–27.58%	93 and 108
5	Ketones	11.10%; 2.08–13.26%	93 and 108
6	Alcohols	9.5%; 21.26–37.13%	93 and 108
7	Acids	6.30%; 1.51–2.67%	93 and 108
8	Heterocyclic compounds	21.97–41.06%	108
9	Hexanoic acid	14.1%; 2.35–7.58%	93 and 108
10	Phytol	8.70%	93
11	Linalool	5.20%; 27.24–59.66%	93 and 108
12	Geranyl acetone	4.80%	93
13	Nonanal	4.20%; 6.70–8.30%	93 and 108
14	Aromatics	0.08–1.70%	108
15	Alkenes	0.15–0.33%	108

CD4+/CD8+ T-cell ratios against sarcoma-180 cancer, while purified fractions (TFPs-1, TFPs-2, TFPs-3) inhibited gastric cancer BGC-823 cell growth.[86,87] Purified tea flower saponins (TFS; floratheasaponins A/D) inhibited cisplatin-resistant A2780/CP70 ovarian cancer cells at 1.5–2.5 μg mL^{-1} with reduced toxicity to non-cancerous IOSE-364 cells, indicating partial selectivity.[88] Mechanistic studies confirmed S-phase arrest (increase in p21, reduction in cyclin A2/CDK2/Cdc25A) and p53-dependent intrinsic/extrinsic apoptosis (DR5/Fas/FADD, mitochondrial cytochrome *c* release, caspase-9/3/7 activation) rather than viability loss through ATM-Chk2 DNA damage response and AKT–MDM2–p53 modulation.[89] Purified saponins (PTFSs; chakasaponins I/IV) also inhibited A2780/CP70 and OVCAR-3 cells at an IC_{50} of ∼2.6–2.7 μg mL^{-1}, inducing autophagy (0.5–1.5 μg mL^{-1}) *via* ROS/ERK signaling.[90] Tea flower extract exhibited greater anti-proliferative and apoptotic activities against MCF-7 breast cancer cells compared to five other *Camellia* species (*C. japonica*, *C. tenuifolia*, and *C. synaptica*), due to EGCG and EGC content unique to tea flowers.[91,92]

Nevertheless, the application is hindered by the lack of selectivity data, the absence of pharmacokinetic validation for systemic bioavailability, and the use of cell line and animal models (0.5–3.5 μg mL^{-1} saponins; 150–300 mg kg^{-1} polysaccharides). It is worth noting that the crude extracts (25–1000 μg mL^{-1}) were non-cytotoxic, suggesting that the anticancer properties are restricted to purified fractions with low yield (≥0.34% saponins), which pose significant bioavailability and scalability issues.[93] Therefore, anticancer effects should be considered preliminary, as the evidence is largely limited to *in vitro* systems and animal models, with no clinical validation available.

5.3 Anti-inflammatory effects

Pharmaceutical experiments have clearly indicated that tea blossom extract substantially reduces ear oedema induced by croton oil and paw oedema induced by carrageenan. It also mitigates liver inflammation brought about by *Propionibacterium acnes* and lipopolysaccharides (LPS). The controlled oral delivery of *C. sinensis* floret extract effectively reduces nitric oxide in mRNA, tumor necrosis factor (TNF)-α, and interleukin (IL)-1β from the livers of murine animals.[92] *In vitro*, ethanolic extracts of tea florets at concentrations of 50 and 100 μg mL^{-1} subdue nitric oxide production in LPS-activated RAW 264.7 cells (rodent macrophages), a property attributed to its catechin content.[94] These findings are supported by both *in vitro* cell-based assays and *in vivo* animal models; however, their direct translation to human inflammatory conditions remains unclear.

5.4 Immuno-stimulant effects

TFPs have demonstrated significant immunostimulant properties both *in vitro* and *in vivo*. TFPs from traditional water extraction (TWE) at a 3.0 μg mL^{-1} accumulation had a more substantial impact on splenic lymphocyte multiplication in rodents than polysaccharides from tea leaves.[95] Current investigations indicate that a refined segment from TFPs can mitigate immunosuppression induced by cyclophosphamide in BALB/c rodents.[41] The polysaccharides from *C. sinensis* remain unassimilated in the human digestive system, allowing for their easy passage to the colon where they are broken down by the gut microbiota that colonizes the far end of the gut. Hence, we can conclude that TFPs impact the gut microbiome and contribute to the host's immunological response.[96] Treatment with TFPs at a controlled dose of 200 mg per kg body weight per day successfully altered 69 of 80 unstable genera and 17 of 20 altered bacterial operating KEGG pathways, while also enhancing short-chain fatty acid synthesis in cyclophosphamide-induced immunodeficient mice. TFPs initiate the TLR4/MyD88/NF-κB p65 and JAK2/STAT3 pathways, leading to an increased expression of genes such as claudin-1, claudin-5, and occludin-1 at the mRNA level in colonic tissues.[92] Histological analysis showed that TFP augmentation reinforces the intestinal barrier. TFPs also elevate the blood levels of cytokines, including TNF-α, IFN-γ, IL1β, IL-2, and IL-6. TFPs could be utilized to regulate enteric equilibrium and stimulate the immune system when combined with other bioactive compounds. Consuming tea flower extracts at a controlled dose of 200 mg per kg body weight per day increases immune system activity in cyclophosphamide-induced rats.[24] Previous research on tea leaves suggests that polyphenol–polysaccharide complexes may be responsible for immunoreactions. The net catechin concentration in tea leaf extracts influences the immunostimulatory potential of polysaccharides.[30] Additionally, a composite amalgam of tannins, polyphenols, and polysaccharides can prevent tumors and cancer in murine animals (*in vivo*) and rodent cells (*in vitro*). Tea flower extract has the same effect but is less effective than TFPs for immunological activation at the same dosage, which was found to be 200 mg per kg body weight in a day.[30]

The effects of ultrasonic treatment on the structural and functional characteristics of Golden Flower Tibetan Tea Polysaccharides (GFTPS)[97] were investigated, with an emphasis on the antioxidant capacity, digestibility, and prebiotic potential of GFTPS. The findings demonstrated that ultrasonication significantly reduced molecular weight from 16 036.94 Da to 10 642.35 Da at 200 W and raised uronic acid concentration to

274.28 mg g^{-1}, which may have been caused by cavitation-driven breaking of glycosidic bonds and polysaccharide–protein dissociation. Colonic fermentation of ultrasonication-modified GFTPS at 200 W increased the formation of short-chain fatty acids (SCFAs) and enhanced populations of *Bacteroides*, *Lachnospira*, and *Klebsiella*. This was correlated with a decrease in pH and a buildup of butyrate (7.63 mg g^{-1} after 48 hours). The pathways involved in the metabolism of carbohydrates and the production of SCFA may be elevated, according to functional annotation.[97] Notably, these observations are primarily based on *in vitro* simulated digestion and animal studies, and their relevance to human gut microbiota modulation requires further validation.

5.5 Antidiabetic effects

Polysaccharides and saponins derived from tea blossoms are vital in terms of hypoglycemic impact. Polysaccharide hypoglycemic efficacy mainly depends upon the biochemical constitution, molecular weight, shape, anatomy, extraction, and removal processes. Evidence from chemically-induced (alloxan, streptozotocin) and diet-induced diabetic models shows different mechanisms for molecular weight fractions, although critical translational knowledge gaps remain. The polysaccharide fraction TFP-2 (1.12×10^4 g mol^{-1}; 75–300 mg per kg per day, oral, 3 weeks) decreased fasting blood glucose in alloxan-induced diabetic mice through α-glucosidase inhibition ($IC_{50} \leq 2$ mg mL^{-1}) rather than insulin sensitization. Applying the FDA body surface method (divide by 12.3 to go from mice to human) resulted in TFP-2 and metabolites being in the range of 6.1–24.4 mg per kg per day, or 365 mg per day to 1.46 g per day in a 60 kg human. It is important to note that clinical pharmacokinetic data have not validated the bioavailability of TFP-2 and its metabolites.[98] Saponins (chakasaponins I–III; 50–100 mg per kg per day, single dose) acutely inhibited postprandial glucose and triglyceride excursion in sucrose- and olive oil-loaded mice through gastric emptying inhibition (37–52% delay at 50 mg kg^{-1}; HED approximately 243–486 mg per day for 60 kg human), a mechanism different from acarbose's intestinal enzyme inhibition.[45] However, none of the studies compared efficacy against metformin, acarbose, or GLP-1 receptor agonists, and the crude extract preparations varied in polysaccharide (3–15%, w/w) and saponin (0.47–4.23%, w/w) content, making dose standardization impossible. Critical translational issues include the lack of characterization of human oral pharmacokinetics for bioactive compounds, the use of type 1 diabetes models (β-cell destruction) rather than type 2 (insulin resistance), and the small safety margins between effective doses (50–500 mg per kg per day) and the NOAEL (4 g per kg per day) compared to metformin's well-established therapeutic window.[99] Overall, antidiabetic effects are moderately supported by animal studies but remain unverified in human clinical settings.

5.6 Anti-obesity potential

Obesity is an alarmingly increasing global public health issue. The evidence is mainly from diet-induced obesity (DIO) models with limited comparative data. In high-fat diet (HFD)-fed C57BL/6 mice, methanolic tea flower extract (250–500 mg per kg per day, oral) inhibited body weight gain and visceral fat accumulation for 9–14 days, while similar effects were also seen in Tsumura Suzuki Obese Diabetic (TSOD) mice, a polygenic model of metabolic syndrome.[99] The *n*-butanol-soluble fraction (enriched in saponins) and its major compound chakasaponin II (25–50 mg per kg per day) decreased food intake and hypothalamic neuropeptide Y (NPY) mRNA expression, with concomitant increases in plasma cholecystokinin (CCK) and GLP-1 levels, indicating vagal afferent-mediated appetite suppression.[100] Mechanistically, chakasaponin II stimulated serotonin release from isolated ilea and inhibited gastric emptying (GE)—actions partially reversed by capsaicin pretreatment, implicating TRPV1 + sensory neurons.[99] None of the studies compared effects with FDA-approved anti-obesity drugs (*e.g.*, orlistat, liraglutide, semaglutide) or with botanical controls; dose translation: 500 mg per kg per day in mice corresponds to a human equivalent dose (HED) of ≤40.5 mg per kg per day based on body surface area scaling (FDA guidance), approximately 2.4 g per day for a 60 kg human, which is impractically high for tea flower consumption. Activity was specified to define saponin markers (chakasaponin II, floratheasaponins A–C), although crude extracts required 100–200-fold higher doses to produce similar effects, and weight loss was partially due to reduced food intake rather than increased energy expenditure, making direct comparisons with thermogenic anti-obesity drugs difficult. In gut microbiota modulation, it was found that TFPs (200 mg per kg per day, 14 days) increased the *Bacteroidetes*/*Firmicutes* ratio in cyclophosphamide-immunosuppressed mice—a ratio that has been associated with improved energy metabolism in obesity models—but not in healthy mice, suggesting context-dependent prebiotic activity.[96]

5.7 Hypoallergenic potential

β-Hexosaminidase, an enzyme in the secretory granules of basophils and mast cells, acts as a marker for degranulation. Its presence makes it a frequently used indicator for assessing the effectiveness of anti-allergic compounds in animal studies.[100] Floratheasaponins A–F, the primary components of the methanolic extract of tea blossoms, have been shown to hinder the release of β-hexosaminidase from rat basophilic leukemia (RBL) 2H3 cells. Notably, floratheasaponins B and E exhibit powerful inhibitory effects, with rates of 59.8% and 52.3% at 3 μM, respectively. These activities are significantly more potent than those of the widely known allergy-preventing biomolecules ketotifen fumarate (obstruction rate 27.6% at 100 μM) and tranilast (obstruction rate 22.4% at 100 μM).[85] This evidence is limited to *in vitro* cellular models, and *in vivo* or clinical confirmation is lacking.

5.8 Antihyperlipidemic, antihyperglycemic, and anti-hypolipidemic potential

The methanolic extract from tea blossoms and their *n*-butanol-soluble fraction have been found to inhibit the elevation of serum triglycerides in olive oil-treated rodents.[91] Within the *n*-butanol-soluble fraction, floratheasaponins A–C exhibited more potent inhibition of serum triglyceride elevation than saponins E1 and E2, which are derived from the seeds of the tea shrub. The influence of chakasaponins I–III on plasma triglyceride and blood sugar levels in mice fed sucrose and olive oil was investigated. Chakasaponins I–III (at doses of 50 and 100 mg kg^{-1}) significantly reduced plasma lipid and glucose spikes, partially due to the reduction of gastric emptying.[84] Furthermore, the methanolic extract and its *n*-butanol-soluble segments (impure saponin segment) from Chinese tea florets exhibit inhibitory action, hindering lipase drawn from the pancreas. Chakasaponins I–III, floratheasaponins A, B, and C, extracted from the floral portions of *C. sinensis*, primarily inhibit the elevated triglyceride levels at doses of 50 and 100 mg kg^{-1} in mice fed olive oil.[92] Notably, the potential of chakasaponins I–III to reduce blood triglyceride levels is attributed to their effects on intestinal emptying.[87] Moreover, various flavonoids in tea blossoms, such as kaempferol 3-*O*-Glc-(1→3)-Rha-(1→6)-Glc, kaempferol 3-*O*-Glc-(1→3)-Rha-(1→6)-Gal, and chakaflavonoside B, have successfully demonstrated hindering activity on oleic acid–albumin-induced lipid accumulation in HepG2 cells.[88]

5.9 Additional health implications

Methanolic extract and *n*-butanol-dissolvable fractions of tea blossoms (impure saponins) exhibit a strong hindering effect on intestinal mucosal ulcers in rats brought about by ethanol and indomethacin. Within these raw saponin segments, floratheasaponins A, B, and C have been identified as the primary contributors to significant gastrointestinal protection. Tea flower concentrate, primarily comprised of catechins, flavonoids, and polyphenols, has been shown to inhibit melanin synthesis in the case of B16–F10 melanoma cells. In particular, this concentration exponentially decreases the melanocyte content and tyrosinase action brought about by α-melanocyte-stimulating hormone in these cells. Melanoregulin and tyrosinase gene expression levels, key flag bearers of melanin synthesis, are notably affected by the extract.[89] Recent research has found that long-term ingestion of TFPs can benefit intestinal health in BALB/c mice.[90] In the *in vitro* analysis of the anaerobic fecal microbiota fermentation, it was observed that TFPs stimulate the generation of short-chain fatty acids and the relative abundance of good bacteria, such as *Bifidobacterium* and *Lactobacillus*, in artificially modified gut conditions for both fit individuals and patients bearing inflammatory bowel disease.[31] Fig. 3 presents a comprehensive overview of the various compounds responsible for health benefits.[30,35,40,42,77]

Overall, the health-promoting properties of tea flowers are supported predominantly by *in vitro* assays and animal studies, with very limited human evidence available. Among the reported activities, antioxidant and anti-inflammatory effects are relatively well supported due to consistency across multiple experimental models. In contrast, anticancer, antidiabetic, anti-obesity, and hypoallergenic effects remain preliminary, as they are largely based on controlled laboratory conditions using purified compounds or high-dose extracts. The lack of standardized formulations, pharmacokinetic data, and clinical

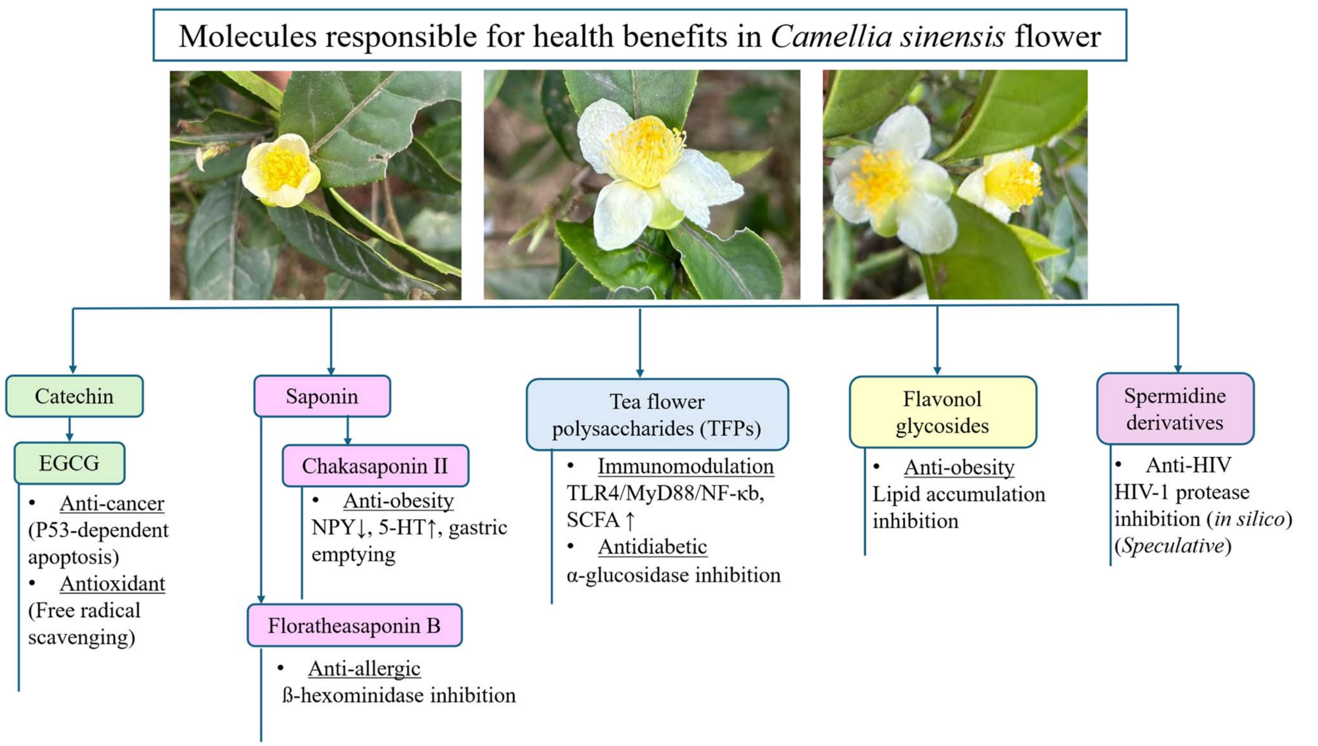

Fig. 3 Bioactive molecules in *Camellia sinensis* flowers and their associated health benefits. Major compound classes include catechins (EGCG), saponins (chakasaponin II, floratheasaponin B), tea flower polysaccharides, flavonol glycosides, and spermidine derivatives, with demonstrated activities in anticancer, antioxidant, anti-obesity, anti-allergic, immunomodulatory, antidiabetic, and anti-HIV pathways. Mechanistic pathways: NPY, neuropeptide Y; 5-HT, 5-hydroxytryptamine (serotonin); TLR4, toll-like receptor 4; MyD88, myeloid differentiation primary response 88; NF-κB, nuclear factor kappa-light-chain-enhancer of activated B cells; SCFA, short-chain fatty acids; Nrf2, nuclear factor erythroid 2-related factor 2; ARE, antioxidant response element; and *in silico*, computational prediction without experimental validation.

validation represents a major limitation in translating these findings into practical human health applications. Future studies should focus on well-designed clinical trials and bioavailability assessments to establish the efficacy and safety of tea flower-derived bioactives.

6 Applications of tea flowers

Tea flowers were previously discarded as crop residues in tea leaf production. Current research, however, reveals the potential of tea flowers as a valuable commodity in the production of nutraceuticals, functional foods, cosmetics, pharmaceuticals, and crops.[13] Recent discoveries have revealed the potential and efficacy of tea flowers, harboring similar amounts of bioactive phytochemicals as tea leaves, including polyphenols (15.01 ± 0.18 mg g^{-1}), catechins, caffeine (55.13 ± 2.01 μg g^{-1}), and L-theanine (up to 6.51 ± 0.82 mg g^{-1}), thus making tea flowers viable materials for a variety of commercial uses.[101,102] For nutraceuticals, tea flowers are promising natural sources of antioxidants as well as other potential ingredients in health supplements. The terpenoids show marked variation with flowering stages (Fig. 1),[32,111] with optimal values of 184.51–249.27 mg g^{-1} in fully bloomed flowers, which can be used as an indicator of optimal harvesting times. The antioxidant potential, as indicated by 83.90–87.53% DPPH scavenging, as well as effective superoxide scavenging, qualifies these flowers as a good addition to formulations aimed at combating oxidative stress and associated diseases. This is in accordance with the overall indications from various studies related to the prevention and management of non-communicable diseases, *e.g.*, cardiovascular, metabolic, and neurodegenerative disorders.[91,93]

In the realm of functional foods and drinks, tea flowers can be used as a functional ingredient and can provide bioactivity and aroma to food and beverage systems. The high L-theanine content (varying from 1.04 to 6.51 mg g^{-1} depending on the developmental stages) can be used to provide natural relaxation and cognitive benefits when used along with caffeine, and has shown synergistic effects in enhancing attention, memory, and executive functions, and can be applied to reduce fatigability in the brain. Also, research has shown that the bioactive compounds present in tea flowers, such as catechins and flavonoids, offer antibacterial properties to the system, such as inhibiting *E. faecalis*, *S. aureus*, and *E. coli*, which can be considered for natural food preservative systems.[95,96] In the cosmetic and dermatology domain, the Cosmetic Ingredient Review (CIR) organization assessed tea flower extract for its safety in cosmetic formulations. The flower extract is used because of its variety of applications, which include antioxidant, antimicrobial, skin conditioning, and anti-aging properties. The tea flower extracts have various applications in the cosmetic arena, including astringents and skin protectants, and humectants; these are utilized in various skincare products, including for hydration and protection against environmental factors. The tea flower is rich in polyphenols and catechins, which enhance its use in anti-aging products by scavenging free radicals and inhibiting lipid peroxides. These compounds can affect various cell signal pathways related to skin health, such as inflammation and photoprotection.[96,98] On the one hand, the pharmaceutical and therapeutic aspects of tea flower-based products have been explored for their unique bioactivity. The antioxidant properties of tea flower compounds, such as improved diastolic functions and decreased LDL cholesterol oxidation, have supported the therapeutic research and development of tea flower-based treatments for various cardiometabolic conditions. The presence of antiviral agents in tea flower-based compounds, such as the action of EGCG on viruses, suggests the possibility of supportive treatments against various viruses. The hepatoprotective, antidiabetic, and neuroprotective potentials associated with the bioactivity of tea compounds suggest good prospects for therapeutic interventions. The presence of unique GABA-related compounds such as L-theanine suggests the possibility of tea flower-based treatment and formulation potentials for stress-relieving and brain-enhancement agents.[100] Tea flowers have helped promote eco-friendly methods in the field of agriculture and industries by maximizing the utilization of what was previously discarded as a waste product. Varying the concentrations of bioactive-containing compounds has helped in optimizing the collection period, with a focus on specific varieties. Unopened buds have a statistically higher quantity of each of the bioactive compounds when compared to other stages, helping with precision agriculture techniques for optimal extraction.[101] The effect of the "flowering" process (fermentation mediated by *Aspergillus cristatus*) on the quality of Shaanxi Fu brick tea was examined in this research. Additionally, their hypolipidemic and antioxidant properties were assessed *in vitro*. Tea polyphenols (13.09%) and free amino acids (38.24%) significantly decreased ($p < 0.05$) during blooming, although caffeine and flavonoids were not significantly altered. These results highlight how crucial the blooming process is in determining the functional metabolite composition and bioactivity of Fu brick tea.[102] White teas were made from the fresh leaves (WT), flowers (WTF), and seeds (WTS) of *Camellia sinensis* cv. *Fuding Dabaicha* in order to assess the potential of tea flowers and seeds. Taste components and their influence on pleasantness were examined using molecular simulations, targeted metabolomics, and sensory assessment. WTF had the greatest pleasantness score (6.60), with WTS (6.36) and WT (6.10) following closely after. D-Fructose, glucose, D-galactose, and D-xylose all increased pleasantness in a dose-dependent manner. These sugars established a persistent binding network with the CHRM1 receptor (-60.04 kcal mol^{-1}), with D-fructose being the main contributor, according to molecular simulations. ARG123 was shown to be a crucial binding residue by alanine scanning. The high-value use of tea flowers and seeds is supported by this research.[103]

7 Safety and risk

Tea flowers, along with other edible flower products, are vulnerable to particular safety considerations, mainly because of their exposed reproductive organs, environmental exposure and concentrated bioactive compounds. Mutagenicity studies indicated low toxicity and no mutagenicity in rats ($LD_{50} > 12$ g

kg^{-1}; NOAEL 4 g per kg per day), with no dose-related subchronic effects, indicating that an acceptable human daily intake would be 24 g of dry flower per day for a 60 kg human, using an extrapolation factor of 10 m, which exceeds estimated exposure in the functional food scenario. However, pollen protein may persist after processing, which can trigger IgE-inducing reactions or pollen cross-reactivity in immune-compromised individuals, warranting a safety label.[45] Edible flowers are also exposed to pesticides, heavy metals and pathogenic microbes, such as *Salmonella*, *Bacillus*, *Enterobacter*, and *Staphylococcus* species, and mycotoxin-forming mold during the inadequate drying of flower products or products that are minimally processed.[104] The routine usage of pesticides and insecticides on tea plantations harbors further risks of contamination, as the chemicals applied to the foliage may translocate to other parts of the tea shrub or may even deposit in the tea flowers, which may be the reason for the detection of trace residues in the leaves.[105] Naturally occurring contaminants should also be considered, as they pose a risk for cross-contamination during harvest, which may introduce pyrrolizidine or tropane alkaloids. Tea plants can accumulate aluminum and fluoride, which could extend to the flowers. Tea flowers contain high contents of polyphenols, saponins and other bioactive compounds, which may reduce non-heme iron absorption and can interact with anticoagulant drugs. This warrants the use of good agricultural practices, adequate and hygienic processing, and intense microbial testing to ensure the safety of edible flower products.[105]

7.1 Limitations

This review summarizes the investigation and valorization of tea flowers. Studies have been based on thematic relevance rather than a systematic protocol and may be subject to selection bias and may not include all relevant evidence. Also, differences in study design, methods and results precluded a quantitative meta-analysis; therefore, the conclusions are based on the qualitative results. Despite the promising research, the evidence on the bioactive potential of tea flowers is still gaining attention as an underutilized powerhouse of functional phytochemicals, but unfortunately, there are still several hindrances to the feasibility of the research on this underutilized resource. All of the trials done so far are mainly focused on *in vitro* studies or animal models, with only a few well-controlled human clinical trials, which makes it difficult to apply these antioxidant, anti-inflammatory, and other health benefits directly in the case of humans.[106] Inconsistencies in extraction solvents, extraction procedures, and the usage of crude and processed raw material are also known to cause variations in the extract yield and purity of the tea flower. The variability in growth stages, maturity stages, cultivars, geographic origin, harvest season and post-harvest processing also leads to irregularities in the composition of various leading phytochemicals like saponins, catechins, flavonoids, *etc.*[107] The discrepancies in the analytical and bioactivity assays make comparisons among the studies much more difficult, which further leads to inconsistent results and highlights the need for standardization methods and planned clinical trials to validate these claims on the health benefits of tea flowers.[108]

7.2 Analytical method heterogeneity

There is significant variation in how tea flower studies are conducted, which makes it more difficult to compare numbers across the board. A great deal of work was carried out using non-specific spectrophotometric tests such as Folin–Ciocalteu "total phenolics," aluminum chloride "total flavonoids," and vanillin/sulfuric acid "total saponins." All of these tests, however, can be easily contaminated and will not necessarily show objective outcomes. The Folin–Ciocalteu reagent will react with any available reducing agent, including sugars, proteins, and other non-phenolic compounds. The vanillin–sulfuric acid test cannot distinguish between triterpenoid and steroidal saponins; in addition, it also reacts to sugar. Both assays give "total" amounts that are only rough estimates. When possible, we rely on LC-MS/MS and UHPLC-MS datasets used by others for comparison, as these techniques can provide structural confirmation and quantitative determinations of individual constituents such as catechins, chakasaponins, floratheasaponins, flavonol glycosides, and other compounds. Unfortunately, the body of tea flower research does not have a standard chromatographic method to facilitate a more rigorous meta-analysis validation process.[109]

7.3 Antioxidant assay limitations and biological relevance

Arguments about antioxidants in tea flower literature largely result from *in vitro* tests carried out using chemical tests such as DPPH, ABTS, and FRAP. These tests are only approximations and have little practical relevance in day-to-day life. These tests use synthetic free radicals, operate under unnatural pH, and are unable to forecast bioaccumulation and alterations in phase II metabolism. In addition, they cannot forecast the prevention of disease, but rather are approximations for what actually occurs in the human body.[109] Furthermore, these tests do not take into account bioavailability. For instance, tea catechins have high levels of phase II metabolism, particularly in the small intestine and the liver. As a result, less than 5% of the original catechins manage to achieve bioavailability. The bulk, approximately 70%, is absorbed in the colon, where microbial enzymes act on it, resulting in phenyl-γ-valerolactones and phenolic acids. These contribute to its biological effects, but chemical assays do not detect these.[110] Therefore, the antioxidant potencies calculated by such chemical tests were not taken as an indication of actual effectiveness or protection against diseases. There is interest in evidence that links antioxidants to valid cellular pathways (such as, *e.g.*, Nrf2/ARE pathways), but mechanistic work on tea flowers is still limited.[111]

8 Conclusion

Tea flowers are a significant biomass source with considerable untapped potential, at around 4.6 billion kilograms per year in Assam. The agronomic advantages of tea flowers are well-documented, with the potential for around 30% post-harvest yield improvement. The chemical composition is well-established, with catechin levels in the range of 24.85–28.02 mg g^{-1}, polysaccharides at around 34% of dry weight, and saponins at levels of 0.47–4.23%. Protein levels of 30–50% and theanine constituents are also well-documented. Safety in rodents is well-established at levels above 12 g kg^{-1}; however, there have been no human trials. Bioactivity, as related to antioxidant, anticancer, antidiabetic, antiobesity, and immunomodulatory potential, has only been demonstrated *via in vitro* studies using unknown clinical doses, without any clinical validation or human studies published to date. To establish credibility, there are seven priority investigations to be conducted: standardized LC-MS/MS fingerprinting studies, evaluation of shelf life and sensory stability in food matrices, bioavailability in humans and metabolomics of phase II metabolites and microbial biotransformation products, allergen profiling and toxicity studies for 90 days, one human pilot study using a validated biomarker, standardization of cultivars and process, and supply chain analysis. Novel food approval in the European Union, including equivalence to tea leaves, will be required, with only general function health claims being allowed in the absence of human data to support health or antioxidant claims. There is a GRAS evaluation required in the US and compliance with India's FSSAI for quality specifications. Therefore, it is recommended that tea flowers be viewed as new food ingredients with traditional use precedent, as opposed to evidence-based functional foods, until human efficacy data become available.

Conflicts of interest

The authors declare no conflict of interest in this work.

Data availability

No new data were created or analyzed in this study. This article is based on previously published literature, and all relevant data are cited within the manuscript.

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