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White Tea: A Review on Composition Characteristics, Extraction Techniques, and Application Potentials

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Abstract White tea has gained significant popularity worldwide due to its health benefits. As the least processed type of tea, white tea is known for preserving a high level of bioactive phytochemicals from fresh tea leaves. However, the composition of white tea can vary widely depending on factors such as harvest season, processing methods, and storage conditions. To effectively utilize the bioactive compounds in white tea, the extraction process plays a crucial role, and researchers have been actively exploring optimal parameters and innovative techniques to improve extraction efficiency. Additionally, extensive research is being conducted to uncover the diverse functionalities of white tea, leading to new discoveries and insights into its applications in the food and therapeutic industries. This review provides an overview of the compositional profiles of different white teas, highlights advances in the optimization of white tea extraction, and provides up-to-date literature on the diverse functional properties of white tea.

Keywords White tea; Composition characteristics; Extraction techniques; Bioactivity

Background

Aside from water, tea, typically made from leaves of the plant *Camellia sinensis*, is the most consumed beverage with worldwide popularity (Bortolini et al., 2021). Depending on the processing techniques, six types of tea can be clearly distinguished in order of increasing degree of fermentation/oxidation: white, green, yellow, oolong, black, and dark tea (Hinojosa-Nogueira et al., 2021). White tea, an important and minimally processed subclass of tea, is made primarily from newly grown buds and young leaves with downy, silvery hairs–the reason it is called "white" tea (Kosińska and Andlauer, 2014). For premium qualities in appearance and taste, white tea is plucked only once a year in the early spring, and tea quality is positively correlated with the freshness of the harvest (Li et al., 2020). In addition to plucking, the optimal temperature and altitude for the development of tea shoots are 18 °C-30 °C and 1,500 m above sea level, respectively (Sanlier et al., 2018). Due to history and cultural traditions, the vast majority of white tea is produced in China while a small portion is grown by other countries, including India and Sri Lanka.

In recent years, Chinese white tea production has increased dramatically from 22,000 tons in 2015 to 74,500 tons in 2020 (Figure 1), likely due to its unequaled flavor and health benefits. As the least processed type of tea, white tea is immediately dried to inhibit oxidation to prevent the loss of components responsible for the three basic and characteristic flavors of white tea: bitterness, umami, and sweetness (Zhang et al., 2017a). In general, white tea has a light, delicate, and sweet/umami taste and fresh/green aroma, which is perceived as more preferable than the second least processed green tea, especially for the brew prepared in cold water from whole leaves (Castiglioni et al., 2015). In addition to its distinctive sensory properties, the growing popularity of white tea is also attributed to its health benefits, in line with the trend of increased health awareness among tea consumers. There is a growing body of evidence supporting the preventive and therapeutic effects of white tea, including antioxidant capacity, anti-inflammatory activity, anticarcinogenic properties, etc. (Hinojosa-Nogueira et al., 2021; Sonawane et al., 2021; Zhou et al., 2023).

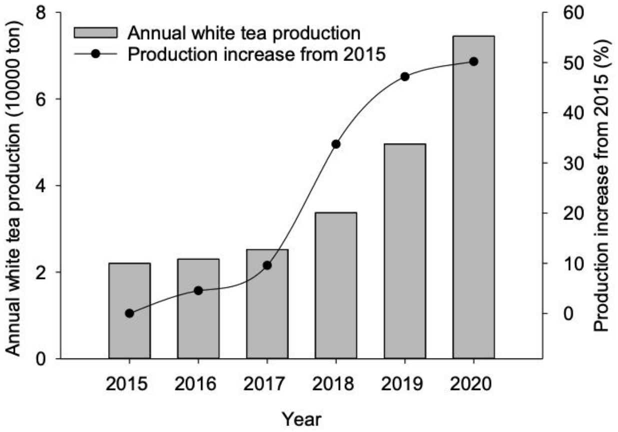

Figure 1 White tea production in China from 2015 to 2020 (Source: https://mp.weixin.qq.com/s/t6xOjNQTdaRw4Zob7vjgYA)

Efficient extraction of bioactive compounds is the basis for optimal utilization of the health-promoting phytochemicals in white tea, such as polyphenols, caffeine, theogallin, gallic acid, theaflavin, flavonol glycosides, and catechins, especially epigallocathechins (EGC), epigallocatechins gallate (EGCG), and epicatchin gallate (ECG). There are generally two main purposes for white tea extraction: one is for human consumption as a type of beverage, which involves the conventional aqueous brewing/infusion practice to produce household or commercial tea drinks (Zhang et al., 2017b); the other one is for food preservation or nutrient supplementation as natural antioxidants, which involves solvent extraction coupled with novel techniques to produce functional ingredients (Kowalska et al., 2021). The extraction parameters are important because they would determine not only the extraction efficiency but also the chemical composition of white tea extract (WTE). It is inevitable that the freshly prepared phytochemicals in WTE would usually go through the storage phase before use, during which time they are susceptible to degradations. Therefore, it is important to understand the stability of WTE during storage and develop effective stabilization strategies to maximize its health benefits.

With the growing global awareness and booming production of white tea, recent research has been conducted to explore efficient extraction methods for WTE production and to investigate stabilization approach for its feasible applications. However, the knowledge of white tea is relatively new and less well known compared with other teas, such as green tea. To fill this gap in the literature, the present review attempts to provide a comprehensive summary of published research on the extraction, stabilization, and bioactivities of white tea. Specifically, efficiency comparison between different extraction techniques, recent advances in stabilizing bioactive components, antioxidant or antimicrobial functions of white tea extract in food preservation, and health benefits proven by animal experiments or clinical trials will be discussed.

1 Varieties and Phytochemical Compositions

1.1 Classifications and compositions

Originating from China, white tea has traditionally been defined by the subspecies of *Camellia sinensis* harvested from: Fuding and Zhenghe Big White Da Bai, found only in Fujian Province (Hilal and Engelhardt, 2007). With the increasing worldwide recognition and popularity of white tea, it is now grown not only in other parts of China but also in other countries, leading to the international definition by plucking standard. White tea mainly consisting of the silvery buds and young leaves of the plant are hand-picked, steamed and dried without further processing, which gives the whitish appearance (Mao, 2013). Based on the origin, leaf composition, and processing protocols, white tea can be classified into several major categories (Table 1). There are four main varieties of white tea from China: Silver Needle (Yin Zhen), White Peony (Bai Mu Dan), Longevity Eyebrow (Shou Mei), and Tribute Eyebrow (Gong Mei). Each of the sub-varieties has its own physical appearance: the silver needle consists mostly of tea buds covered with fine white hairs; White Peony is a mixture of buds and small or broken leaves; Longevity Eyebrow is made from ground tea leaves (Pan et al., 2018). Moreover, new white tea can be processed into the compressed aged white tea, which has lower amounts of amino acids, soluble sugar, tea polyphenols, ester catechin, and gallic acid, but the umami and astringency tastes are less intense (Chen et al., 2020a).

In general, the main constituents of white tea are proteins, polysaccharides, phenolic compounds, amino acids, and methylxanthines (Dias et al., 2019), among which phenolics, amino acids, and methylxanthines are the three most important tea quality determinants (Hinojosa-Nogueira et al., 2021). Tea catechins and their derivatives can account for up to 30% of the dry weight of the leaf, the most important being gallocatechin (GC), epicatechin (EC), epigallocatechin (EGC), epicatechin gallate (ECG), gallocatechin gallate (GCG), and epigallocatechin gallate (EGCG). Among them, EGCG is the most abundant (about 59% of total catechins) and the most studied. The other two important functional components, theanine and caffeine, represent around 4% and 2%-5% of the dry weight of tea, respectively (Dias et al., 2019, Paiva et al., 2021) (Table 2).

The content of bioactive compounds in white tea is determined by both tea sub-types and grades. The contents of EGCG, theanine, and caffeine in hot tea infusions prepared from three types of Fuding white tea followed the order silver needle < longevity eyebrow < white peony (Pan et al., 2018). Similar results were reported with white pony water extract containing higher total catechin content up to 8 times than the silver needle white tea from the same company (Unachukwu et al., 2010). However, there was variation among teas from different companies with a wide range from 14.40 to 369.60 mg/g of dry plant material. In another study, the chemical content of EGCG and caffeine in white tea leaves followed the order silver needle > white peony > longevity eyebrow, while silver needle and white peony had similar and higher theanine content than the longevity eyebrow (Yang et al., 2018). Within the same subtype, the component quality can still vary between different grades. When the metabolites in super, first, second, and third grade white peony were analyzed and compared, a gradual decrease was observed in the flavonoids including EGCG across four different grades of white tea (Yue et al., 2019). Similar results were also reported in another study where the contents of total catechins and caffeine decreased as the grade level decreased (Ning et al., 2016).

Table 1 Representative subvarieties and properties of white tea

White tea	Grade and pluck standards	Characteristics	Major cultivar
Silver Needle (Yin Zhen)	First grade. Only top buds leaf shoots) of the *Camellia sinensis*	Generally whiter appearance and a lighter body with shorter withering time than Zhenghe (Fuding) Longer withering process, deeper color and a fuller body than Fuding (Zhenghe)	China
White Peony (Bai Mu Dan)	Second grade. One leaf shoot and two immediate young leaves one bud two leaf ratio)	Fuller flavor and greater potency than silver needle (Sanlier et al., 2018)	
Tribute Eyebrow (Gong Mei)	Third grade. One bud with two or three leaves	Processed more than silver needle and white peony teas, offering a dark brew with an earthy taste (Ahmed and Stepp, 2013)	
Longevity Eyebrow (Shou Mei)	Fourth grade. More than two leaves, with or without bud	By-product of silver needle tea production, darker in color, making a darker brew with more depth	
Darjeeling	Unfurled buds with two or three soft leaves	Similar to silver needle, the high elevation and low temperatures results in its unique flavor development	India
Ceylon	Slightly curved and unopened buds	A very light coppery brew with pine and honey flavor	Sri Lanka

Table 2 The contents of bioactive constituents in different types of white tea

Bioactive compounds	Content by weight (%)				
	Overall	Silver needle	White peony	Tribute eyebrow	Longevity eyebrow
Phenolic acids					
Gallic acid	0.21 – 0.35	0.12 – 0.44	0.20 – 0.50	0.22	0.17 – 0.35
Ellagic acid	0.23 – 0.24	-	0.17 – 0.35	-	-
Catechins					
(+)-catechin	0.10 – 0.62	0.53	0.30 – 0.50	-	0.39
(−)-epicatechin	0.05 – 1.10	0.22 – 0.30	0.15 – 0.28	-	<0.05 – 0.11
(−)-epigallocatechin	0.05 – 2.6	0.16 – 0.31	0.25 – 0.81	0.84	0.05 – 0.70
(−)-epigallocatechin gallate	0.21 – 9.5	5.8 – 6.7	3.2 – 6.4	0.06	0.56 – 3.0
(−)-epicatechin gallate	0.27 – 1.4	2.2 – 2.8	1.2 – 1.9	0.31	0.44 – 1.7
Total catechins	1.3 – 17	8.5 – 9.8	4.4 – 9.2	-	1.2 – 4.6
Total polyphenols	8.5 – 76	16 – 18	12 – 16	-	7 – 13
Amino acids					
L-theanine	0.01 – 1.2	0.83 – 1.27	0.47 – 1.5	-	<0.01 – 0.67
γ -aminobutyric acid	0.011 – 0.17	-	0.006 – 0.008	-	-
Total amino acids	1.1 – 3.8	-	2.8 – 3.4	-	0.15 – 1.5
Metilxanthines					
Theobromine	0.05 – 0.09	0.04 – 0.15	0.04 – 0.08	-	0.06 – 0.13
Caffeine	1.9 – 5.7	4.5 – 4.9	3.6 – 4.6	2.7	2.2 – 3.8
Reference	Hilal and Engelhardt 2007; Horanni, 2013; Tan et al., 2017; Bortolini et al., 2021	Tan et al., 2017; Yan et al., 2020	Tan et al., 2017; Ma et al., 2022	Tang et al., 2019	Ning et al., 2016; Tan et al., 2017; Yan et al., 2020

1.2 Compositional comparison of white tea with other tea types

As one of the least processed types of tea, white tea retains high levels of antioxidative compounds from fresh tea leaves. Therefore, it is believed to contain maximum polyphenols, whereas black tea is fully fermented through enzyme-mediated oxidation of polyphenols into oligomeric and polymeric flavanols theaflavins, thearubigins and other oligomers (Senapati, 2021). White tea brew contained 0.8 mg/mL of total catechin, whereas black tea infusion prepared from the same tea variety had merely 0.24 mg/mL (Carloni et al., 2013). The loss of antioxidant activity is mainly due to the oxidation process during which catechins and other polyphenols undergo catalysis by polyphenol oxidases in fermented teas. Therefore, there is a negative correlation between phenolic content and the degree of tea oxidation. Green tea is another type of minimally processed tea whose processing inactivates oxidative enzymes by heating but does not ferment, so the amount of tea polyphenols has little change (Wong et al., 2022). However, when comparing the antioxidative compounds found in white tea to those found in green tea, the results have been controversial. Some researchers claimed that green tea was a richer source of polyphenols because it undergoes minimal degree of oxidation due to enzyme inactivation during heat treatment (Sanlier et al., 2018). Compared to the 1.9 mg/mL total catechin content of green tea, white tea of the same variety had only 0.8 mg/mL (Carloni et al., 2013). Contrary results have been found that certain white teas have comparable amounts of total catechins to some green teas but lower antioxidant capacity, suggesting that white teas have fewer non-catechin antioxidants (Unachukwu et al., 2010). Nonetheless, another study showed that white tea had significantly higher levels of flavonoid compounds than green tea (Zhou et al., 2022). This apparent discrepancy may be due to variations in tea samples, as chemical constituents vary significantly depending on the harvest season, cultivars, growing conditions, and manufacturing process (Vastrad et al., 2021). In fact, Hilal and Engelhardt (2007) reported that the total polyphenol content of white tea was in the range of 16%-26% and that of green tea was 14%-35%, indicating that the compositional comparison between these two types of tea may have all kinds of results. Interestingly, in a study where the freshly plucked leaves of a single tea plant variety were processed into six typical tea types, green tea had the highest total catechin content of 131 mg/g, while white tea contained 75 mg/g of total catechin (Wang et al., 2018).

In terms of caffeine and theanine, the caffeine content is similar among different tea varieties, while the theanine content of black tea is usually slightly lower than that of white tea. Specifically, the mean caffeine content of white, green, oolong, and black teas were 17, 16, 19, and 18 mg/g, respectively, and theanine content values were 6.3, 6.6, 6.1, and 5.1 mg/g (Boros et al., 2016). In contrast, another study reported a much higher caffeine content in white tea (4.9%) than green tea (2.9%) and a higher theanine content of white tea (1.9%) than that in black and green teas (Hilal and Engelhardt, 2007). The higher amount of theanine could be attributed to fresh young shoots used for white tea production, which are known to be rich in functional compounds like theanine (Sonawane et al., 2021). However, less theanine was detected in white tea than in green and black teas produced from the same batch of tea leaves when a prolonged withering process (36 h) was used (Dai et al., 2017). Similar results were reported by Wang et al. (2018), who found that comparing teas made from the same batch of tea leaves, the theanine content in white tea retained 63% of theanine in fresh tea leaves after 48 h withering, which was significantly lower than that of green tea (95%) and black tea (82%). In addition to the inherent variation among teas, the compositional inconsistency among different tea types may also result from diverse extraction procedures and assay protocols used to determine certain tea components.

2 White Tea Composition Affected by Harvest, Processing, and Storage

From the fresh plant material to the white tea ready for consumption or other uses, tea leaves would go through processing and storage. Both steps determine the chemical composition and quality of white tea. Traditional research techniques and recent advances in the metabolomic approach have enabled compositional analysis of the enormous number of tea components and their changes (Li et al., 2022).

2.1 Phytochemical composition of white tea harvested from different seasons

Tea leaves harvested in different seasons possess distinctive chemical profiles and various levels of bioactive molecules in white tea. Higher total phenolic content was observed in white tea harvested in the summer and early fall than in spring. Conversely, contrasting results were obtained for total flavonoid content, with higher values in spring than in summer (Paiva et al., 2021). Similarly, Fang et al. (2017) reported that in fresh tea shoots consisting of one apical bud and two adjoining leaves, the abundance of epicatechins and catechins were lower in March than September, with EGC content mostly influenced by the time of harvest. Interestingly, the same study found that theanine content was lower in May compared to March and September, and tea leaves contained richer caffeine in March than September. In contrast, catechins, theanine, and caffeine concentrations were reported to be higher in early spring silver needle tea than in late spring white peony tea and fall longevity eyebrow tea (Tan et al., 2017). The Xinyang white tea plucked in spring had higher levels of EGCG and theanine while fall tea had a remarkably higher level of caffeine (Ma et al., 2022).

2.2 Constituent transformation of white tea during processing

The production of white tea involves only two steps: withering and drying. As the least processed type of tea, white tea retains most of the phytochemicals of *Camellia sinensis* L.. After the plucking, white tea undergoes wilting or withering, which usually takes place in the sun or on a rack in a heated room for 4-5 h to remove moisture, whereas oolong and black teas are withered for at least twice as long (Kosińska and Andlauer, 2014). The loss of moisture and resulting cell wall breakdown would lead to the release of oxidases and initiation of 5% oxidation catalyzed by oxidases, i.e., phenol oxidase and peroxidase (Hinojosa-Nogueira et al., 2021). Therefore, although white tea is considered as a type of non-fermented tea, it is actually slightly fermented through oxidation. In this process, polyphenol oxidase and native microflora initiate and catalyze the aerobic oxidation of tea catechins. They can dimerize, oligomerize, and even polymerize to a variety of derivatives, including theaflavins, theacitrins, theasinensins, theanaphthoquinones, and thearubigins (Dai et al., 2017). It was reported that the total polyphenol content in white tea decreased from 33% after 4 h to 28% after 93 hours of withering, while thearubigin slightly increased from 3.1% to 3.9% during the same period (Maulana et al., 2020). In addition to oxidation, the weakened biosynthesis may also contribute to the decrease in flavonoid levels (Chen et al., 2020b). The other step that white tea undergoes is the drying process, which can also alter heat-sensitive tea catechins if conducted at elevated temperatures (Wong et al., 2022).

Withering would also change the levels of other important biomolecules in white tea, namely theanine and caffeine. Chen et al. (2020) found that even though the total free amino content increased during withering, theanine content slowly decreased because it could not be supplied by the proteolysis or transported from tea roots to leaves, whilst the metabolism of theanine continued. Similar results were also confirmed by Dai et al. (2017) and Zhou et al. (2022). In the same metabolomic studies, it was reported that the caffeine content increased significantly, which could be attributed to the abundant nucleosides and nucleotides provided by ribonucleic acid (RNA) degradation, precursors of caffeine synthesis.

2.3 Phytochemical degradation of white tea during storage

It is widely believed in China that the aging for at least three years could greatly improve the health benefits of white tea, which is marketed at higher prices than teas produced and sold in the same year (Zhao et al., 2022). However, chemical analysis showed that some major bioactive molecules in white tea tend to decrease over storage time. The theanine content of longevity eyebrow reduced drastically from 6.4 mg/g to 0.43 mg/g over the storage period from 3 to 16 years, while the total catechin concentration decreased from 8.1 mM to 1.9 mM from 3 to 6 years but increased slightly to 3.2 mM on the 16th year (Ning et al., 2016). During storage, new chemicals are formed by using original white tea components as starting materials. Dai et al. (2018) reported that new compounds, 8-C N-ethyl-2-pyrrolidinone-substituted flavan-3-ols (EPSFs), were constantly formed from theanine and catechins during white tea storage for up to 16 years. Due to the loss of white tea catechins and other functional components, negative correlations were found between the antioxidative activities and their inhibitory effects on key enzymes related to diabetes mellitus type 2 (T2DM), at storage time of 1, 3, and 5 years (Xu et al., 2019). Similar results were reported by Xie et al. (2019), who found that the amount of EPSFs was a good predictive parameter for the storage time of white teas. Although some bioactive molecules of white tea are lost during storage, it is likely that the sensory development during aging contributed to its high market price. It was reported that the decrease and transformation of abundant flavonoids, tannins and amino acids were related to the reduced astringency, umami and increased browning of tea infusions (Fan et al., 2021).

3 Extraction of Active Biomolecules from White Tea

White tea is a rich source of catechins, which have been widely used in the food industry as natural antioxidants to inhibit lipid oxidation. The specific chemical structure of tea catechins can neutralize oxidative stress by scavenging free radicals to delay the onset of lipid oxidation and by chelating metal ions to interfere with the catalysis of oxidative reactions (Musial et al., 2020). As natural antioxidants, tea catechins have the advantages of having higher potency, better safety, and more potential health benefits than their synthetic counterparts. The catechins, especially EGCG, have been found to have more than 4 times the relative potency of butylated hydroxyanisole, which is a synthetic antioxidant often added to foods to preserve fat or oil (Vuong et al., 2010). In addition to the strong antioxidant capacity of tea catechins, safety concerns about synthetic antioxidants and customers' demand for natural ingredients have driven the food industry to favor the use of plant-derived phenolic antioxidants, e.g., tea catechins. Catechins, along with other active biomolecules in tea, such as caffeine and theanine, usually provide additional nutraceutical value to white tea extract (WTE) applications in foods.

3.1 Conventional extraction solvent properties, extraction times, temperature, etc.

The chemical functionalities and health benefits of WTE depend on the content and composition of bioactive compounds. Thus, to produce high quality WTE, it is crucial to optimize the extraction conditions and understand the effects of various steps in the process. In general, the conventional extraction methods can be divided into two categories: water-mediated brewing and organic solvent-assisted solvent extraction (Table 3).

Table 3 Optimization for conventional white tea extraction

Extraction methods	White tea to liquid ratio	Conditions	Results	Reference
Aqueous extraction (brewing)	2 g tea leaves or a tea bag and 150 mL mineral water	60 °C-98 °C, 3-15 min	Brewing at 98 °C for 7 min was the best condition to obtain a high content of antioxidant polyphenols and pleasant sensory properties	Pérez-Burillo et al., 2018
	0.5 g tea and 20 mL mineral water	Cold tea: 20 °C-25 °C, 120 min; Hot tea: 70 °C, 7 min	The cold infusion contained more bioactive compounds than the hot tea	Damiani et al., 2014
	0.5 g whole or milled tea leaves and 20 mL mineral water	Cold tea: 20 °C-25 °C, 15-120 min; Hot tea: 70 °C or 90 °C, 7 min	For whole tea leaves, the brewing conditions to reach the highest antioxidant activity was 120 min for cold tea and 90 °C for hot tea; Tea infusions prepared from milled leaves had the greatest antioxidant activity but a more bitter and astringent taste	Castiglioni et al., 2015
	Tea g to pure water at ratios from 1:30 to 1:60	80 °C-100 °C, 3-7 min	Brewing at 100 °C for 7 min and water ratio of 1:30 extracted the most active compounds; Brewing at 100 °C for 3 min and water ratio of 1:50 produced tea with the best sensory qualities	Zhang et al., 2017b
	1 g tea and 10 mL distilled water	98 °C, 5 min	The antioxidant properties of the six categories of teas tested were in decreasing order of green, yellow, oolong, black, dark, and white tea	Zhao et al., 2019
	5 g tea and 500 mL distilled water	65 °C-95 °C, 5-240 min	With elevated temperature, the extraction rate of each substance was accelerated in the first 50 min	Lin et al., 2017
	2 g tea and 100 mL distilled water	28 or 100 °C, 5 min or 2 h	Antioxidant properties were affected by time but not temperature	Hajiaghaalipour et al., 2016
	2 g tea and 200 mL distilled water with or without 5 mL lemon juice	80 °C, 5-30 min	The extraction of phenolics from white tea by water was accelerated by lemon juice; There was no significant difference in phenolic content between white and green tea extracts after 5 min	Rusak et al., 2008
	Hot extraction: 2 g tea and 100 mL distilled water, magnetic stirring; Cold extraction: 0.5 g tea and 20 mL distilled water, stirred manually every 30 min	80 °C, 450 s (hot extraction); 20 °C-25 °C, 2 h (cold extraction)	The cold extraction resulted in a beverage with more total phenolic compounds but less total flavonoids	de Carvalho Rodrigues et al., 2015

Continued Table 3

Extraction methods	White tea to liquid ratio	Conditions	Results	Reference
Solvent extraction	2 g tea and 200 mL ethanol 10%-70%	80 °C, 5-30 min	Ethanol at 40% was the most effective among the solvents tested in the prolonged extraction of catechins, especially in the extraction of EGCG	Rusak et al., 2008
	Ethanol infusion 0-100%	40 °C-90 °C, 5-90 min	The best conditions to maximize the extraction of total polyphenols were ethanol at 50% for 47.5 min; Although the yield of polyphenols was optimal at 65 °C, the maximum antioxidant capacity was achieved at 90 °C	Peiró et al., 2014
	100 mg ground tea and 0.5 mL extracting solutions, including methanol, methanol:water 1:1 (v:v), methanol:acetonitrile 1:1 (v:v), ethanol, ethanol:acetonitrile 1:1 (v:v) and water	32 °C, 21 min with ultrasonication	Methanol possessed the highest extraction efficiency of volatile components	Sereshti et al., 2013
	1 g tea and 50 mL ethanol solution 10%-30%	30 °C-70 °C, 5-15 min	Optimum conditions were 10 min, 66 °C and 30% ethanol solution	Zielinski et al., 2016
	0.5 g tea and 5 mL solvents ethanol, methanol, and ethanol/methanol combination	5-15 min, with various ultrasound intensities 40%, 70% and 100%	Optimal conditions were 70% sonication intensity, 15 min, and methanol as the solvent	Ahmadi et al., 2022

3.1.1 Water extraction (brewing)

The extraction efficiency of brewing can naturally be affected by the characteristics of white tea leaves. The phytochemical composition of white tea varies over a broad range, which could be affected by white tea varieties, geoclimatic growing environment, processing methods, and leaf morphology. It has been reported that silver needle, which is harvested earliest, has higher total phenolic compounds than white pony and longevity eyebrow tea (AlHafez et al., 2014). However, the infusion of silver needle had lower concentrations of bioactive compounds (catechins, caffeine, theanine, and free amino acids) than that of the other two tea types (Pan et al., 2018). This discrepancy was explained by the unique leaf traits of silver needle: the shape of the rolled leaves slows the diffusion of components through the water-repellent white hairs on the leaf surface, preventing efficient water contact. Interestingly, these patterns were not found in other studies where different types of white tea infusions were prepared (Damiani et al., 2014; Lin et al., 2017). The various extraction conditions are likely responsible for the inconsistency.

The efficiency of extraction is largely influenced by brewing conditions, mainly temperature and time. Compared to high-temperature, and short-time brewing (70 °C, 7 min), low-temperature and long-time brewing (20 °C-25 °C, 2 h) dramatically increased the content of extracted phenolic compounds and caffeine by up to four and three times, respectively (Damiani et al., 2014). Certain phenolic components in white tea may be degraded or transformed at high temperatures, contributing to the observed lower levels (Venditti et al., 2010). Moreover, the longer infusion time in cold brew preparation allows sufficient time for active components to migrate into the beverage, although the effect of extraction time would reach a maximum at some point. For example, no significant increase in the phytochemical content was found after 5 min (the recommended infusion time for hot tea preparation) brewing at 90 °C for bagged white tea (Shannon et al., 2018). In contrast, the optimal extraction time was found to be over 40 min, when intact tea leaves were used (Lin et al., 2017). Thus, the size of white tea materials may also be an important parameter for the best brewing efficiency, with smaller ones being easier to extract. For a certain type of white tea, the extraction process is quite sensitive to temperature, even for hot tea brewed at more than 80 °C. When the brewing temperature of Fuding white tea increased from 80 °C to 100 °C (5 min), the EGCG, caffeine, and theanine contents increased dramatically from 78, 226, and 48 mg/L to 139, 388, and 75 mg/L, respectively, presumably because higher temperatures disrupted cell wall structures and facilitated the water penetration, along with diffusion of tea components (Zhang et al., 2017b). It is noteworthy that extraction at high temperatures above 85 °C for a prolonged time could induce two types of structural transformations, degallation and epimerization: the former hydrolyzes EGCG to gallic acid (GA) and the non-galloylated catechins, while the latter converts catechins from epi-catechins (EC, EGC, ECG, EGCG) to their corresponding trans-isomers (C, GC, CG, GCG) (Lin et al., 2017).

Another important but relatively less recognized factor affecting brewing kinetics is water quality. Along with many other tea catechins, the EGCG content was the highest at 116 mg/L in the Fuding white tea infusion prepared with pure water with the lowest ionic level, compared to only 84 mg/L for tap water with the highest ionic level, and 101 mg/L for spring water with a medium ionic level (Zhang et al., 2017a). The common minerals in water, i.e., Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}, are known to lower the mass transfer rate from solid tea leaves to bulk liquid water in the brewing process (Murugesh et al., 2017). A lower pH favors the extraction of white tea polyphenols, which can be achieved naturally by adding lemon juice (Rusak et al., 2008). At higher pH, the stability of tea catechins may be compromised by the occurrence of degallation (Cao et al., 2021) and epimerization (Xu et al., 2017). In addition, the rate of auto-oxidation increases with pH, with the pyrogallol moiety on the B ring of EGC and EGCG being more susceptible to oxidation than the catechol moiety of EC and ECG (Murugesh et al., 2017).

Since the white tea infusions are made ready-to-drink after the brewing process, the sensory attributes, including color, aroma, and taste, should be considered in addition to the physiochemical properties. Brewing conditions are particularly important determinants of the sensory properties of white tea, which does not contain flavor compounds produced by fermentation, but only natural chemical components of tea leaves (Pastoriza et al., 2017). Several studies have reported a positive relationship between the content of phenolic compounds and sensory characteristics. For example, since EGCG is the major contributor to bitterness, white tea drinks brewed with hard water containing less galloylated catechins had lower overall sensory acceptability and a darker color (Cao et al., 2021). In contrast, pure weakly acidic water with low concentration of dissolved ions produced white tea infusions with the highest catechin content and superior color, aroma, and taste (Zhang et al., 2017a). In terms of the temperature and time combination, brewing at 98 °C for 7 min was found to be the best condition to obtain a high content of antioxidant polyphenols while maintaining pleasant sensory properties (Pérez-Burillo et al., 2018).

The water extraction technique has the advantages of low cost, toxin-free, and relatively simple setups. However, its efficiency may be limited due to poor selectivity for target bioactive molecules and loss of heat sensitive compounds during exposure to high temperature for a prolonged period.

3.1.2 Solvent extraction

Organic solvents and their aqueous formulation have been studied for extraction of bioactive compounds from white tea with various efficiencies. It was reported that 40% aqueous ethanol was more effective in extracting tea phenolics and flavonoids than the 10% and 70% ethanol solvents at extraction times of 15 and 30 min, although the opposite trend was found for 5 min (Rusak et al., 2008). Similarly, 50% ethanol was reported to be the optimal concentration to maximize the extraction of total polyphenols, at an extraction time of 47.5 min and temperature of 65 °C (Peiró et al., 2014). The optimal solubility of white tea biomolecules plays a major role in their extractability and extraction efficiency. EGCG, the major white tea flavonoid, has a higher solubility in aqueous ethanol solutions than in water and pure ethanol, which may contribute to the higher extraction efficiency in the mixed water-ethanol solvent system (Hu et al., 2016). Under ultrasound assisted extraction, methanol was found to be the optimal solution for the extraction of white tea polyphenols with the highest radical scavenging activities (Ahmadi et al., 2022). Compared with ethanol (50% and 100%), and 50% methanol, pure methanol possessed the highest extraction yield with more than twice the amount of volatile compounds than the other solvents (Sereshti et al., 2013).

Different from the conventional brewing method, solvent extraction usually has higher extraction efficiency and lower energy consumption required by heating. However, utilization of organic solvent may introduce concerns in operation safety, presence of toxic residues, and requirement for additional purification process.

3.2 Assisted extraction

Conventional extraction methods are a simple process of soaking a pulverized white tea sample in the appropriate solvent in a closed system, followed by constant or sporadic agitation. However, these techniques have some specific drawbacks, such as time consuming, solvent requirement, low extraction selectivity, and decomposition of thermolabile compounds (Manousi et al., 2019). To address these issues, some innovative assisted extraction techniques have been developed, such as high-pressure assisted extraction, microwave-assisted extraction, and ultrasound-assisted extraction (Table 4).

Table 4 Assisted extraction methods for white tea

Assisted extraction method	Parameters tested	Results	Reference
High pressure	Pressure: 200 MPa and 500 MPa; Time: 5 and 10 min	Most efficient phenolic extraction from white peony was under the pressure of 200 MPa for 5 min	Šeremet et al., 2021
	Pressure: 300, 400, and 500 MPa; Solid to liquid ratios: 1, 2, and 3%; Time: 120, 360, and 600 s	The optimal extracting conditions were 300 MPa, 2.2% solid to liquid ratio, and 10 min	Uzuner and Evrendilek, 2019
Microwave	Power level: 114, 229, and 399 W; Time: 0.3-3.7 min; Ethanol concentration: 0-100%; Liquid/solid ratio: 15.9-184.1 mL/g	Conditions for the highest amounts of total phenolics were 229W, 38.8% ethanol, 184 mL/g liquid/solid ratio, and 3 min of extraction	Rehder et al., 2021
Ultrasound	Ultrasound intensity: 40%, 70%, and 100%; Time: 5, 10, and 15 min; Solvent: ethanol, methanol, and combined ethanol/methanol	The highest total phenolic content and free radical scavenging activity were obtained at 70% sonication intensity, 15 min, and methanol as solvent	Ahmadi et al., 2022
	Temperature: 25-55 °C; Time: 10-60 min; Volume of preconcentration solvent: 20-50 µL; Salt concentration: 5-15%	The optimal extraction conditions for volatile compounds were 21 min, 32 °C, 27 µL extraction solvent, and 7.4% salt	Sereshti et al., 2013

3.2.1 High pressure assisted extraction

The high pressure can trigger various phenomena that induce a reaction in the direction of promoting volume decrease, which leads to the improvement of extraction efficiency (Khan et al., 2019). The highest total phenolic content (3,136 mg/L) was determined in the ethanolic (50%) extract of white peony under the pressure of 200 MPa for 5 min, while the highest EGCG (1,446 mg/L), ECG (354 mg/L) and caffeine (863 mg/L) contents were determined at the same pressure level but with a longer pressure holding time of 10 min (Šeremet et al., 2021). In another study, the optimal conditions were achieved using 300 MPa, 2.2% solid to liquid ratio, and 10 min brewing time, which resulted in 92% total antioxidant activity, 1,949 mg/L total phenolic content, and 17.5% total caffeine content (Uzuner and Evrendilek, 2019). High-pressure assisted extraction appears to be a promising alternative novel technique to minimize caffeine content while maximizing the amounts of total amino acids and phenolic compounds in cold-brewed white tea.

3.2.2 Microwave assisted extraction

Microwaves are nonionizing electromagnetic waves within the frequency range of 300 MHz to 300 GHz, of which 915 MHz is considered the most useful for industrial applications due to its greater penetration depth, while 2,450 MHz frequency is generally used in domestic microwave ovens and for extraction applications (Routray and Orsat, 2012). It was reported that a microwave oven with a frequency of 2,450 Hz and a power of 229 W extracted the highest amounts of total phenolic and flavonoid compounds from a white tea blend with the predicted optimal conditions of 38.8% ethanol concentration, 3 min of extraction, and a 184 mL/g liquid/solid ratio (Rehder et al., 2021).

3.2.3 Ultrasound assisted extraction

Ultrasound-assisted extraction of target compounds from a given matrix is a complex mechanism involving mass transfer and a variety of possible chemical reactions that affect yield and associated biological activities. In general, the effect of ultrasound on mass transfer is directly related to the sound energy introduced into the extraction system and the ultrasound frequency (Tiwari, 2015). The highest total phenolic content (68 mg/g) and free radical scavenging activity (78%) were observed for the following optimal conditions: 70% sonication intensity, 15 min sonication time and methanol as solvent (Ahmadi et al., 2022).

Assisted extractions are promising alternatives for the conventional methods, but they may also have some drawbacks. For example, the usage of specific equipment complicates the extraction process whilst increases the energy consumption and cost expenditure.

Even though several attempts have been made to improve the extraction efficiency of white tea, the literature is still limited regarding the combination of multiple techniques and the effects of both equipment settings and extraction conditions. Moreover, other techniques should be explored in the future, such as enzyme-assisted extraction, supercritical fluid extraction, accelerated solvent extraction, and subcritical water extraction (Raghunath et al., 2023).

3.3 Stability of white tea extract and stabilization techniques

3.3.1 Storage stability

It is commonly observed that bioactive compounds in the extracted white tea tend to be destabilized during storage but the packaging material may play an important role in slowing down this process. The antioxidant activity of WTE decreased by 20%-50% after 3 months of storage at room temperature, regardless of the method used to measure the antioxidant activity (Pastoriza et al., 2017). However, extending storage to 6 months did not induce additional changes in the same study, possibly due to the oxidation of the sensitive phenolic compounds during the first 3 months, which protected the other antioxidants for longer periods. It was also reported that tea catechins degraded by at least 50% during the first month of storage in canned commercial soft drinks and accompanied by a decrease in biological activities (Zeng et al., 2017). Cold storage of tea beverages in polyethylene terephthalate bottles at 4 °C was reported to ensure a slower decline in catechin content in white, black, and green teas (Nekvapil et al., 2012).

3.3.2 Stabilization techniques

To address the inherent drawbacks of tea polyphenols TPPs, e.g., low stability and bioavailability, the encapsulation of TPPs is desired to improve their stability against harsh environment for shelf-life extension and bio-efficacy enhancement (Yin et al., 2022). Polymeric nanoparticles (NPs) prepared by nanoencapsulation of WTE based on poly ε-caprolactone and alginate released 20% of the polyphenols in simulated gastric medium, and 80% after 5 h at pH 7.4, showing a good ability to control the delivery of polyphenols (Sanna et al., 2015). Furthermore, NPs protected tea polyphenols from degradation so that WTE retained its antioxidant activity. An increase in the thermal stability of liposomal WTE samples was registered according to the physical stability of the WTE-loaded liposomes and the SEM image showed that the particle diameter of the liposomes did not change significantly after 6 months of storage (326.27 nm), although the microencapsulation efficiency decreased to 52% (Ahmadi et al., 2022). It is noteworthy that the addition of cholesterol to the liposomal formulations can enhance the stability by preventing the phase transition of phospholipids. The encapsulation technologies would open new perspectives for the exploitation of WTE-loaded nanoparticles for nutraceutical applications.

4 Application Potential of White Tea in Food and Therapeutic Industries

The abundance of bioactive phytochemicals in white tea ensures its application potential in human nutrition and disease treatment. White tea has been widely used in foods and therapeutics as an antimicrobial/antioxidant and disease treatment agent (Table 5; Table 6). A variety of other health benefits of white tea have also been reported and recently reviewed by Zhou et al. (2023) and Hinojosa-Nogueira et al. (2021). The following sections aim to provide a specific update on the recent discoveries of the applications of white tea in food and nutraceutical fields.

Table 5 Food applications of white tea

Food applications	Effects	Reference
Films	Active edible furcellaran/whey protein films with white tea extracts WTEs exhibited antioxidant and antimicrobial activities	Pluta-Kubica et al., 2020
	Chitosan films with white tea showed strong antibacterial activity against *Pseudomonas aeruginosa*	Stefanowska et al., 2023
Beef	White tea powder effectively inhibited lipid oxidation in beef mince during refrigerated storage for 7 days	Kırmızıkaya et al., 2021
Candies	WTE was used as a base ingredient to produce candies with antioxidant and microbial stability	Šeremet et al., 2020
	Total phenolic content and antioxidant capacity of white tea based candies notably decreased by the end of storage for 4 months and the gelatine formulation exhibited slightly better retention of bioactive compounds	Mandura et al., 2020
Popsicle	The popsicles formulated with animal proteins and WTE showed the highest antioxidant activity	Santos et al., 2020
Kombucha	Kombucha made with white tea in the first week of fermentation had the lowest fluoride content, which is a desirable trait in terms of food safety and preventing fluoride exposure	Jakubczyk et al., 2021

4.1 Food applications

4.1.1 Antimicrobial activity

Pathogenic and spoilage microorganisms are known to pose a major threat to human health and food quality. To inhibit their growth, antimicrobial agents are commonly added to foods to prevent and control foodborne pathogens and spoilages. However, due to growing concerns about the safety of chemical additives, the use of natural antimicrobial compounds as alternatives to conventional synthetic chemicals has attracted considerable interest from both consumers and the food industry (Hou et al., 2021). Common examples of food outbreaks are the *Staphylococcus aureus* food poisoning and the *Salmonella typhimurium* infection, which cause toxic symptoms and gastrointestinal infection. The main spoilage microbes in food products include bacteria, such as *Enterobacteriaceae*, *Lactobacilli*, and *Pseudomonas* species, yeasts and molds, such as *Saccharomyces*, *Aspergillus*, and *Penicillium* species (Takó et al., 2020). The major bioactive components in white tea, i.e., polyphenols, have been described to exhibit antimicrobial activity through multiple mechanisms, including destruction of cell membrane structure, changing bacterial cell morphology, and metal ion complexation (Zhang et al., 2021).

Table 6 Therapeutic activities of white tea

Bioactivities	Effects	Reference
Diabetes	The antidiabetic potential of WTE in α–amylase inhibitory assay showed that the IC50 value of methanolic extract of white tea was 68.73 μg /mL whereas that of a standard drug was 39.07 μg/mL	Kalauni and Sharma, 2018
	A regular consumption of WTE for two months improved the oxidative status of lung tissues of rats with prediabetes	Silveir et al., 2021
	White tea significantly improved the structural changes of the kidneys in mice with T2DM mellitus and markedly ameliorated the glucose intolerance when used in combination with Jiaogulan tea	Xia et al., 2021
	WTE extracted by citric acid increased α-glucosidase inhibition	Shiyan et al., 2020
	The inhibitory effects of α-Amylase and α-Glucosidase by WTE decreased with the prolongation of storage time from 1 to 3 years	Xu et al., 2019
	Crude polysaccharides from white tea showed the inhibitory activity of α-glucosidase	Guo et al., 2021
	WTE effectively ameliorated hyperglycemia and hyperlipidemia in Streptozotocin-induced diabetic rats	Amanzadeh et al., 2020
Cardiovascular disease	1.6% WTE supplemented in a diet high in fats and sugars for 20 weeks prevented the development of metabolic syndrome-associated hypertension in rats	de la Fuente Muñoz et al., 2022
	WTE was efficient in stimulating the uptake of low-density lipoprotein-cholesterol LDL-c in hepatic cells	Luo et al., 2020
Obesity	White tea was the most effective tea type in reducing the body weight and fat accumulation in high fat diet induced obese mice	Liu et al., 2019
	WTE significantly inhibited weight gain of obese mice receiving high fat diet by reducing their food and energy intake	Mao et al., 2021
Fatty liver disease	Daily feed of 1000 mg/kg and 500 mg/kg body weight WTE alleviated hepatic steatosis and liver injury in a mouse model of non-alcoholic fatty liver disease	Li et al., 2022
Plague	Mouth rinses of steeped 2.5% white tea twice daily for four days was effective in reducing *Streptococcus mutans* and plaque accumulation on teeth	Damhuji et al., 2022
	0.1 mg/mL white tea mouth rinse was found to be a potent antiplaque agent when used twice daily for ten days	Nagar et al., 2018
	Ethanol- and water- based WTEs were effective against two cariogenic oral bacteria *Streptococcus mutans* and *Streptococcus sobrinus*	Kusumawardani et al., 2019
	Enamel samples were hardened significantly after being immersed in a solution containing both white tea and xylitol	Auerkari et al., 2018
	White tea mouthwash significantly inhibited the growth of *Streptococcus mutans* and *Lactobacillus acidophilus*, the effect of which was more evident when the concentration increased from 20 μL to 40 μL	Jeevanandan, 2019
	White tea was useful for inhibiting the growth of pathogens involved in the development of caries and/or periodontal diseases	Auerkari and Suhartono, 2018
Intoxication	WTE exerted significant protection against neurotoxicity mediated by tert-butyl hydroperoxide and hydrogen peroxide in cells	Li et al., 2019
	Compared with black, red, and green teas, white tea exerted the strongest protective effect on bone tissue and hyaline cartilage against co-exposure of heavy metals, Cd and Pb, to rats	Tomaszewska et al., 2018

Continued Table 6

Bioactivities	Effects	Reference
Intoxication	White tea enhanced the liver histology, immunohistochemistry and biochemistry against acrylamide induced toxicity in rats	Hamdy et al., 2022
	1% WTE effectively reduced the activities of biomarkers under conditions of inflammatory, oxidative and liver stress in rats with benzo(a) pyreneinduced hepatotoxicity and lung toxicity	Rangi et al., 2018, Dhatwalia et al., 2019
	Polyphenol extract from white tea effectively lowered biochemical parameters of liver function and hepatocyte damage in mice with CCl_4 induced liver injury	Cao et al., 2020
	White tea exhibited antioxidant and hepatoprotective activities in mice with acute alcohol-induced liver injury	Yi et al., 2020
Alzheimer's disease	White tea exerted significant protection against Aβ hallmark (Alzheimer's protein) evoked neurotoxicity by modifying Aβ amyloid into an amorphous and punctate aggregate morphology	Li et al., 2019
	White tea infusions effectively inhibited the activity of acetylcholinesterase, the administration of which inhibitors is the most common treatment of Alzheimer's disease	Baranowska-Wójcik et al., 2020
Aging	White tea was effective in reducing wrinkles by lowering dermal extracellular matrix degradation, inflammation, and skin barrier damage	Sonawane et al., 2021
	In vivo sun protection factor (SPF) testing of white tea cream product revealed an average SPF of 1	Campa and Baron, 2018
	Silver needle white tea was proved to be effective in preventing D-galactose/lipopolysaccharide-induced aging in mice through antioxidative and anti-inflammatory mechanisms	Chong et al., 2021
	WTE had a significant inhibitory effect on the formation of amyloid mediated by aging and high-fat diet	Wan et al., 2021
Memory deficits	Ischemia impaired spatial learning in rats was avoided by white tea supplementation 10 days before ischemia stroke or sham surgeries	Martins et al., 2017
Cancer	WTE inhibited proliferation of cancer cells via induction of apoptosis	Liu et al., 2018
	The viability of the cancer cells decreased with increasing white tea concentrations	Haghparasti and Mahdavi Shahri, 2018

The antimicrobial activities of white tea against a variety of pathogens, molds, or fungi have been reported in several studies, and the efficacy of white tea (unfermented) is higher than that of semi-fermented or fermented tea due to its abundance of tea catechins, among which EGCG and EGC are the major ones responsible for the antimicrobial activity (Dias et al., 2019). Ethanol-based and water-based WTEs showed significant antibacterial activity against *Streptococcus mutans* and *Streptococcus sobrinus*, whereas ethanol-based and water-based black tea extracts were effective only against *Streptococcus mutans*. (Kusumawardani et al., 2019). Compared to green, purple, and black teas, WTE exhibited the highest antimicrobial effect with the largest inhibition zone for *Escherichia coli* and *Staphylococcus typhimurium* (Koech et al., 2014). However, the antifungal activity of white tea was reported to be lower than green tea and higher than black tea against an aflatoxigenic mold, *Aspergillus parasiticus* (Orak et al., 2013). The phenolic content in tea extract is likely to be responsible for its antimicrobial capacity, as green tea extract was reported to contain the highest number of phenolic compounds in this study.

The application of WTE as an antimicrobial agent in foods systems has been shown to be effective in inhibiting microbial growth, maintaining food quality, and prolonging shelf life. Biopolymer films based on furcellaran-whey protein isolate incorporated with WTE successfully inhibited yeast and mold growth during storage for cheese (Pluta-Kubica et al., 2020). In another study, white tea kombucha and chitosan-kombucha films incorporated with WTE showed inhibition zones of 22 and 20 mm, respectively, against *Pseudomonas aeruginosa*, a foodborne pathogen (Stefanowska et al., 2023).

4.1.2 Antioxidant activity

In the food industry, tea polyphenols as natural antioxidants have shown great potential in preventing food oxidation to inhibit undesirable changes in the physicochemical and sensory attributes, such as the formation of rancid flavors and discoloration (Gutiérrez-del-Río et al., 2021). Several mechanisms may be involved in the antioxidant activity of polyphenols, including radical scavenging, metal chelation, and enzyme regulatory activities (Yan et al., 2020). The antioxidant activity of white tea is frequently compared to other tea categories without common agreement, although the phenolic content has been found to be positively correlated with the antioxidant activity. Teas from the same cultivar but processed into different tea types, had an antioxidant profile that followed the order: green > white ≥ black tea, which was likely due to the higher degree of phenolic oxidation of white and black tea than the green tea (Carloni et al., 2013). However, in another study, the inherently higher polyphenols content of silver needle white tea led to its highest radical scavenging activity, followed by green and then black tea (Kaur et al., 2019). Another study demonstrated that green and white teas had similar but higher levels of total phenol and flavonoids than black tea, and thus better free radical scavenging activity (Pereira et al., 2014).

The antioxidant efficacy of white tea varies according to the harvest season, extraction conditions, and storage time. Compared with summer and fall, white tea harvested in the spring season was reported to possess relatively higher amount of catechins, including EC, EGC, ECG and EGCG, corresponding to its highest antioxidant capacity (Ma et al., 2022). The extraction procedure of tea leaves would significantly affect the antioxidant activity of tea extract, as the chemical profile of WTE is largely dependent on the extraction conditions. Cold infusions of white tea (20 °C-25 °C, 2h) had a higher phenolic content 4.77-7.63 mmol/L gallic acid equivalents (GAE) compared to 1.43-4.02 mmol/L GAE in hot infusions (70 °C, 7 min) and the same trend was observed for the antioxidant activities (cold: 17.09-34.23; hot: 5.26-17.07 mmol/L trolox equivalents) (Damiani et al., 2014). Compared to the cold infusion prepared at room temperature (20 °C-25 °C) for a long time (2 h), the conversion of polyphenols to other compounds at the higher brewing temperature (70 °C) could be responsible for this phenomenon. Interestingly, under hot brewing conditions with a temperature range of 60 °C-98 °C and a time of 3-15 min, WTE prepared at 98 °C for 7 min had the highest phenolic content and antioxidant capacity (Pérez-Burillo et al., 2018). The storage time of white tea may affect the antioxidant efficacy of the derived WTE, as its chemical composition can change over time. Xu et al. (2019) found that for white tea aged 1, 3, and 5 years, longer storage time decreased the polyphenol content, which led to a decrease in the antioxidant activity of WTE against several free radicals. To achieve the best antioxidant capacity, it is critical to optimize the steps of converting white tea leaves into WTE in order to retain the maximum amount of tea polyphenols.

The antioxidant activities of white tea can effectively preserve the oxidative stability of foods and act as a bioactive ingredient for the development of novel functional foods. After 7 days of refrigerated storage of ground beef, white tea powder (1%) effectively inhibited the formation of TBARS (secondary metabolites of lipid oxidation) formation by 89% compared with the untreated control (Kırmızıkaya et al., 2021). An active edible furcellaran/whey protein film with WTE was developed and effectively prolonged the shelf life of fresh soft rennet curd cheese (Pluta-Kubica et al., 2020). The WTE-containing film exhibited strong antioxidant activity and the sensory quality of cheese was rated the best at the end of a three-week storage period. In addition to food preservation, WTE is also formulated into functional foods to provide *in vivo* antioxidant activity, offer potential health benefits, and meet customer demand for naturally derived ingredients.

4.2 Therapeutic activities

A myriad of studies on the therapeutic applications of WTE are found in the scientific literature (Table 6). The health benefits of white tea have been correlated with its bioactive compounds such as L-theanine, gamma-aminobutyric acid (GABA), and polyphenols (Bag et al., 2022).

4.2.1 Metabolic diseases

Metabolic diseases are disorders that negatively affect a wide range of normal metabolic processes, the prevalence of which has increased significantly in recent decades and poses a serious threat to human health (Anaeigoudari et al., 2021). White tea has been shown to be effective in the treatment of some of the most common metabolic diseases, including diabetes, obesity, cardiovascular disease, and non-alcoholic fatty liver disease. Two major mechanisms are involved in these therapeutic functions: the regulation of glucose and lipid metabolisms.

Recent animal and cell studies suggest that white tea may be particularly effective in ameliorating abnormal lipid metabolism. A tea cocktail containing white tea partially prevented hyperlipidemia, reduced serum high-density lipoprotein levels, insulin resistance, and increased C-reactive protein levels, while completely preventing left ventricular hypertrophy in mice fed with a high-fat diet (Ferreira et al., 2020). Another study found that WTE ameliorated obesity, lipid accumulation, hepatic steatosis, and liver injury in a mouse model of nonalcoholic fatty liver disease (Li et al., 2022). Compared with the other tea types, WTE showed the best anti-obesity effects in reducing the body weight and white fat accumulation in obese mice (Liu et al., 2019). Recent *in vivo* and *vitro* gene ontology and pathway analysis revealed that white tea can regulate pathways related to lipid metabolism and energy expenditure. A cell-based study found that WTE reduced very-low-density lipoprotein production by downregulating gene expression of apolipoprotein B, microsomal triglyceride transfer protein, and triglycerides synthesis, while stimulating low-density lipoprotein cholesterol uptake by targeting the low-density lipoprotein receptor (Luo et al., 2020). *In vivo* evidence showed that WTE can improve the lipid metabolism by regulating pathways associated not only with lipid synthesis but also with energy expenditure, such as respiratory electron transport, oxidative phosphorylation, ATP metabolism, and other energy metabolism pathways (Li et al., 2022). The superior anti-obesity effect of white tea may be due to both increased energy expenditure and inhibition of fatty acid synthesis, whereas the other teas were only able to regulate the latter (Liu et al., 2019).

White tea has been shown to be effective in regulating glucose metabolism and a typical example is the treatment of T2DM. T2DM is a severe endocrine metabolic disorder that causes serious complications in various organs, either as a result of excessive glucose or in response to the altered hormone levels (Zhao et al., 2019). WTE treatment for 30 days significantly decreased serum glucose levels in diabetic rats suffering from hyperglycemia (Amanzadeh et al., 2020). White tea-treated T2DM mice showed significantly lower glycemic responses to glucose administration than the control group and significantly attenuated the accumulation of renal advanced glycation end products in T2DM mice, thereby inhibiting the structural changes of the kidneys (Xia et al., 2021). The ability of white tea to regulate hyperglycemia may be due to its inhibitory effects on α-amylase and α-glucosidase, which are key dietary enzymes related to T2DM *in vitro* and break down carbohydrate before absorption (Xu et al., 2019).

4.2.2 Oral health

The active components in WTE are well known to help maintain oral health and prevent dental problems such as plaque and caries. Dental plaque contains highly organized microbial communities that adhere to the surface of hard dental tissues and is a major cause of various oral and pharyngeal diseases (Digel et al., 2020). In a clinical study, mouth rinsing with steeped 2.5% white tea steeped twice daily for four days significantly improved the plaque index, indicating a reduction in plaque accumulation on teeth (Damhuji et al., 2022). A similar study reported that white tea mouthwash was a potent antiplaque agent when used for 10 d, although less effective than chlorhexidine, a gold standard for plaque (Nagar et al., 2018). Furthermore, white tea has the potential to fight caries, as human enamel and rat jawbone samples with or without the demineralization-remineralization treatment were hardened after immersion in a white tea-xylitol solution (Auerkari et al., 2018).

The effective elimination of harmful oral bacteria by white tea is responsible for its functions in maintaining oral hygiene. White tea mouthwash can significantly inhibit the growth of several bacteria that contribute to dental caries and/or periodontal disease, including *Streptococcus mutans*, *Streptococcus sobrinus*, *Lactobacillus acidophilus*, *Porphyromonas gingivalis* and *Actinobacillus actinomycetemcomitans* (Auerkari et al., 2018, Jeevanandan, 2019; Kusumawardani et al., 2019). It is noteworthy that the antimicrobial activity of WTE against oral pathogens is dose dependent. Increasing the white tea mouthwash treatment from 20 μL to 40 μL increased the zone of inhibition by 2% for *Streptococcus mutans* and *Lactobacillus acidophilus*, while increasing to 60 μL increased the antibacterial efficacy by up to 3% (Jeevanandan, 2019). More inhibition with increasing WTE concentration from 0 to 40% was also observed for *Porphyromonas gingivalis* and *Actinobacillus actinomycetemcomitans* (Auerkari and Suhartono, 2018).

The widely reported remineralization functionality of WTE also contributes to its effect in fighting caries. WTE treatment increased the microhardness value by respective 36% and 62% for demineralized dentin and enamel, indicating its remineralization functionality through cross-linking of the collagen network (Sayed and Roushdy, 2023; Roushdy and El-Sayed, 2023). Both the antioxidant and anti-collagenolytic activities of WTE were likely responsible for this functionality because it exhibited strong anti-elastase and anti-collagenase capacity (Daokar et al., 2020). Enhanced microtensile bond strength in demineralized dentin was observed when WTE was used as a natural remineralization agent, and its action potential was gradually stabilized with time from 0 to 3 months (Roushdy et al., 2022). Interestingly, for dentin without preceding demineralization, WTE alone reduced its hardness whereas combined WTE and xylitol clearly increased the hardness, regardless of their concentrations (Auerkari et al., 2018). The WTE concentration, complexation with other reagents, and application duration are important factors to consider when using WTE to treat caries.

4.2.3 Intoxication

The versatile bioactive components in WTE have encouraged researchers to investigate its potential against various toxins, and several mechanisms have been discovered. Benzo(a)pyrene (BaP) is a well-known toxin generated from incomplete combustion of organic compounds, which can be absorbed by humans through the oral, inhalation, and dermal exposure routes (Verma et al., 2012). In rats with BaP-induced pulmonary toxicity, WTE was effective in restoring BaP-induced oxidative and inflammatory stress and lung histoarchitecture, with the efficacy similar to pure EGCG (Dhatwalia et al., 2019). Similarly, the biomarkers in conditions of inflammatory, oxidative, and hepatic stress were decreased after treatment with WTE in BaP-intoxicated rats, and the hepatic histoarchitectural changes also showed improvement (Rangi et al., 2018). WTE also exhibited protection in rats against the intoxication induced by with mutagenic, genotoxic, and carcinogenic toxins. In the same study, the effectiveness of WTE was better than black, red, and green teas (Tomaszewska et al., 2018). Furthermore, Hamdy et al. (2022) reported that white tea can act as a potent anti-inflammatory, antioxidant, and anti-apoptotic agents to protect rat liver injury from acrylamide, a potential carcinogen produced in a variety of foods during cooking.

5 Conclusions

The chemical composition of white tea exhibits significant variation attributed to differences in subtypes, harvest time, and storage duration. While it is often claimed that white tea possesses a distinct phytochemical profile compared to other tea types, definitive conclusions regarding specific components cannot be drawn with certainty. The substantial variation in compositional underscores the importance of efficient extraction of white tea as it enhances the overall utilization rate of the tea. Of the two major extraction strategies, namely aqueous and solvent extraction, aqueous extraction brewing provides ready-to-drink tea beverages, whereas solvent extraction allows further exploration of white tea applications. Several factors, including liquid properties, solid-to-liquid ratio, temperature, and extraction time, have been reported to play a crucial role in extraction efficiency. Given that extraction efficiency is influenced by the properties of white tea materials, it is essential to determine the optimal conditions for each specific tea sample of interest. Furthermore, continued research into novel extraction techniques to improve the extraction efficiency of white tea is warranted. It is worth noting that the application of white tea in food is relatively limited compared to other common teas, and therefore the antioxidant and antimicrobial effects of white tea in a variety of food systems should be evaluated and its efficacy compared to other teas should be investigated. With regard to therapeutic applications of white tea extract, current studies rely primarily on cell- or animal-based model systems, with limited information on the practical functions of white tea in humans. Thus, the promotion of clinical trials is necessary to uncover and better understand the health potential of white tea.

Authors' contributions

GAQ carried out the investigation and drafted the manuscript. FHF provided technical support for result analysis. JP conceived the study, supervised the findings of this work, and revised the manuscript. LY and CXN contributed to the design of the research. All authors read and approved the final manuscript.

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