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New insights into chemical compositions and health benefits of white tea and development of new products derived from white tea

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ABSTRACT

This study reviews the health benefits of white tea and the development of new products derived from white tea. The core processing procedures such as withering and drying play a pivotal role in shaping the unique characteristics of white tea. In the withering phase, water gradually diminishes, and endogenous polyphenol oxidase induces a slight oxidation of polyphenols which leads to a delicate fermentation process. This not only helps preserve the integrity of most components but also imparts an exclusive flavor and taste to white tea. Additionally, white tea stands out as a rich source of polyphenols, polysaccharides, and saponins. These bioactive components which can be extractable during brewing are conferring a myriad of health benefits. These benefits include antioxidant, anti-inflammatory, anti-aging, anti-radiation, anti-hyperglycemia, anti-hyperlipidemia, neuroprotection, and cardiovascular-protection properties. Innovative applications range from ready-to-drink infusions to skincare products. The review proposes white tea as a raw material for supplements, meal replacements, and confectionery. Various studies suggest its potential in enhancing gut health, supporting endurance, and contributing to photoprotection in skincare. The article concludes by highlighting white tea's adaptability, its role as a bridge between tradition and modernity, and its potential to shape the future of functional foods and beverages. Overall, white tea emerges as a versatile resource with applications extending beyond traditional consumption, offering a holistic approach to health and wellness.

1. Introduction

Various types of tea are crafted from fresh leaves of the *Camellia sinensis* (L.) O. Kuntze plant. Among these, the widely recognized variations include fermented black teas, partially fermented oolong teas, and non-fermented green teas. White tea stands apart in its production process, distinct from other teas. Unlike oolong or black tea, it undergoes neither fermentation nor enzyme deactivation akin to green tea. Instead, white tea exclusively experiences withering and drying. Initially categorized as a non-fermented type, a precise definition for white tea remains elusive, lacking unanimous agreement within the tea community[1]. In recent years, white tea has captured increasing interest, blending cultural heritage with emerging recognition for its potential health benefits. Originating from China's southwest region, white tea boasts a rich history spanning over two millennia. Initially consumed by chewing fresh tea leaves and later sun-drying them for prolonged storage, the Tang dynasty marked a turning point with the development of green tea[2-3]. Recent studies have delved significantly into white tea's chemical compositions, particularly focusing on polyphenols. These investigations identify

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and quantify specific polyphenolic compounds, unraveling their potential health benefits and contribution to the tea's flavor profile. Advancements now spotlight amino acid profiles, notably theanine, contributing to an understanding of the unique taste and potential health effects linked to white tea consumption[4]. Research continues into other bioactive components in white tea, such as polysaccharides and saponins, enriching our understanding of its chemical composition and potential health-promoting properties. Transitioning to contemporary research, the review explores white tea's cutting-edge health benefits, emphasizing antioxidant properties, novel anti-inflammatory mechanisms, and recent discoveries related to neuroprotection and cardiovascular health[5]. Evolving processing technologies, including traditional withering and drying methods, modern techniques enhancing flavor and aroma, and the integration of technology to maintain bioactive compounds, signify the dynamic evolution of white tea[6].

This review further navigates the integration of white tea into functional foods and beverages, from the development of infused products to the study of bioavailability and its dynamic interplay with consumer preferences and market trends. As the review concludes, it sets the stage for future directions and research gaps, inviting further exploration in areas that beckon the scientific community and the tea industry.

The scope of this review extends beyond the existing literature on white tea, which predominantly focuses on its chemical composition and health benefits. While there is abundant research on these aspects such as Zhou et al.[7] and Piyasena et al.[8], there is a noticeable gap in the literature regarding the potential product developments stemming from white tea, specifically those that introduce and highlight its health benefits to meet consumer needs. This review breaks new ground by offering a holistic examination of white tea, weaving together its chemical compositions, health benefits, and the largely unexplored arena of product development. By adopting an integrated approach, the review goes beyond the traditional silos of research and opens avenues for cross-disciplinary insights.

The novelty of this review lies in its pivotal role as a bridge between traditional knowledge and modern advancements. It not only delves into the historical and traditional aspects of white tea but also integrates cutting-edge research to create a comprehensive narrative. This synthesis makes review a valuable resource for both scientific and industry communities, offering a balanced perspective that combines age-old practices with contemporary scientific understanding. Furthermore, the review addresses a practical need within the industry by providing actionable insights for professionals involved in the tea sector. It equips them with knowledge that can enhance the quality, efficiency, and innovation of white tea-related product development. This practical orientation sets the review apart, making it a valuable guide for those seeking to navigate the intersection of tradition and innovation in the tea industry. In response to the prevailing global interest in health and wellness, the review strategically positions white tea as more than just a beverage with antioxidant properties. It emphasizes the diverse health-promoting attributes of white tea, aligning with the preferences of health-conscious consumers. This aspect of the review adds contemporary relevance to the traditional aspects of white tea, making it a timely and significant contribution to the existing body of knowledge in this field.

2. Chemical compositions of white tea

As for white tea, a range of beneficial compounds has been identified and isolated, acid (6%–9%), peptides, alkaloids (2%–5%), volatile compounds (0.047%), organic acids, minerals, nucleosides, and so forth[7]. The major bioactive components of tea are polyphenols, including catechins, flavones, flavanols, phenolic acids, and proanthocyanins[9]. Besides, tea is a good source of amino acids, vitamins, minerals, caffeine, polysaccharides, alkaloids, organic acids, pigments, and saponins[10]. Unlike deeply fermented black tea or dark tea, white tea is slightly fermented during the withering process, and therefore, most of the bioactive components in the fresh leaves are retained without being converted by the endogenous polyphenol oxidase (PPO) and peroxidase (POD).

2.1 Tea polyphenols in white tea

Tea polyphenols is a category of polyhydroxy phenolic compounds, which is rich in unfermented green tea or slightly fermented white tea[11]. During fermentation, it can be converted into theaflavins, thearubigins, and theabrownin thus form the unique color of fermented tea like black tea[12]. There are mainly 8 kinds of catechins[13-15].

Generally, green tea, white tea, and black tea were non-fermented, slightly fermented, and fully fermented, respectively. During fermentation, catechins would be polymerized into polymers such as theaflavins, theasinensins, and thearubigins[14]. Oppositely, the oligomeric procyanidins would be depolymerized into cyanidins. Consistent with the research of Dai et al.[16], green tea showed the highest level of procyanidins and catechins, while black tea contained the highest amount of theaflavins and theasinensins, and white tea were in the middle. Specially, the methylated catechins epicatechin gallate (EGC) 3-methylgallate and epicatechin (EC) 3-*O*-(3-*O*-methylgallate) showed the highest level in white tea[16].

2.2 Flavonoid glycosides in white tea

White tea is a minimally processed tea rich in bioactive compounds, especially flavonoids, which have antioxidant properties and various health benefits. The presence of flavonoid glycosides, such as quercetin and kaempferol, enhances its health-promoting qualities[17]. When compared to green and black teas, white tea contains the highest levels of kaempferol glycosides, a type of flavonol glycoside. Green tea has more glucosylated quercetins but fewer galactosylated quercetins than white tea. Additionally, white tea has a higher content of myricetin-3-galactoside but lower levels of myricetin-3-glucoside compared to green tea. Green tea also has the highest levels of apigenin-*C*-monoglycosides, while white tea features the highest levels of apigenin-*C*-diglycosides[16]. Regular consumption of white tea, coupled with a balanced diet, may enhance intake of flavonoid glycosides, potentially offering health benefits associated with antioxidant and anti-inflammatory effects[18].

2.3 Amino acids in white tea

White tea, derived from the *C. sinensis* plant, stands out for its unique amino acid profile, contributing to both its distinctive flavor and potential health-promoting properties. In a comparative analysis

with other tea varieties such as green, black, oolong, and Pu-erh teas, white tea exhibited the highest content of amino acids, particularly theanine[19]. Theanine, known for its relaxing and mood-enhancing effects, constituted a significant portion of the total amino acids in white tea, ranging from 30% to 50%. The most prevalent amino acid in tea is *L*-theanine (representing about 4% of leaf dry weight), which contributes to the pleasant and relaxing effects of the tea. This amino acid not only contributes to the pleasant taste of white tea but also offers potential benefits for stress relief and mental well-being[20].

Gamma-aminobutyric acid (GABA) is a notable amino acid that distinguishes white tea from other tea varieties. A comparative analysis revealed that white tea has a GABA content of 50.5 mg/100 g, which is higher than that found in green, black, and oolong teas. Interestingly, GABA levels in white tea increase during the withering process, unlike in other tea types. These findings suggest that white tea could be a promising candidate for GABA-enriched products, enhancing its health benefits and market potential[21]. GABA is known for its calming effects and has been studied for promoting relaxation and reducing anxiety. The study also examined the relationship between amino acids and the fermentation degree of tea, identifying arginine as correlated with the fermentation process. Significant differences in arginine content were found between fermented and unfermented teas, highlighting how processing methods influence amino acid composition[22].

2.4 *Alkaloids in white tea*

White tea contains alkaloids, with caffeine as the most abundant (2.23%−4.94%). Caffeine levels vary by harvest season, with early spring silver needle white tea averaging 4.71%, late spring White Peony at 4.14%, and autumn ShouMei at 3.18%. White tea also contains theobromine (0.04%−0.15%), which does not significantly vary with seasons[23]. These alkaloids contribute to the characteristic taste and physiological effects of white tea, providing a unique profile of bioactive compounds that contribute to the overall sensory experience and potential health benefits of consuming white tea[24].

3. Health benefits of white tea

The pharmacological activities of white tea include antioxidative effects, anti-inflammatory effects, anti-microbial effects, anti-hyperglycemic effects, anti-hypertensive effects, anti-hyperlipidemia effects, and anti-tumor effects[10]. Fig. 1 illustrates the different beneficial effects of white tea for human health.

3.1 *Anti-oxidative activities*

Polyphenolic compounds in white tea exhibit significant antioxidative properties, effectively neutralizing reactive oxygen species (ROS) to reduce cellular oxidative damage and protect against chronic diseases associated with oxidative stress[25]. Among these compounds, catechins play a crucial role as the primary type of tea polyphenols, offering antioxidant effects. They enhance the activity of superoxide dismutase in serum, a critical enzyme in the body's defense system, which aids in scavenging ROS and mitigating oxidative stress[26]. Moreover, catechins can chelate with mineral catalysts such as calcium, copper, and iron, effectively inhibiting

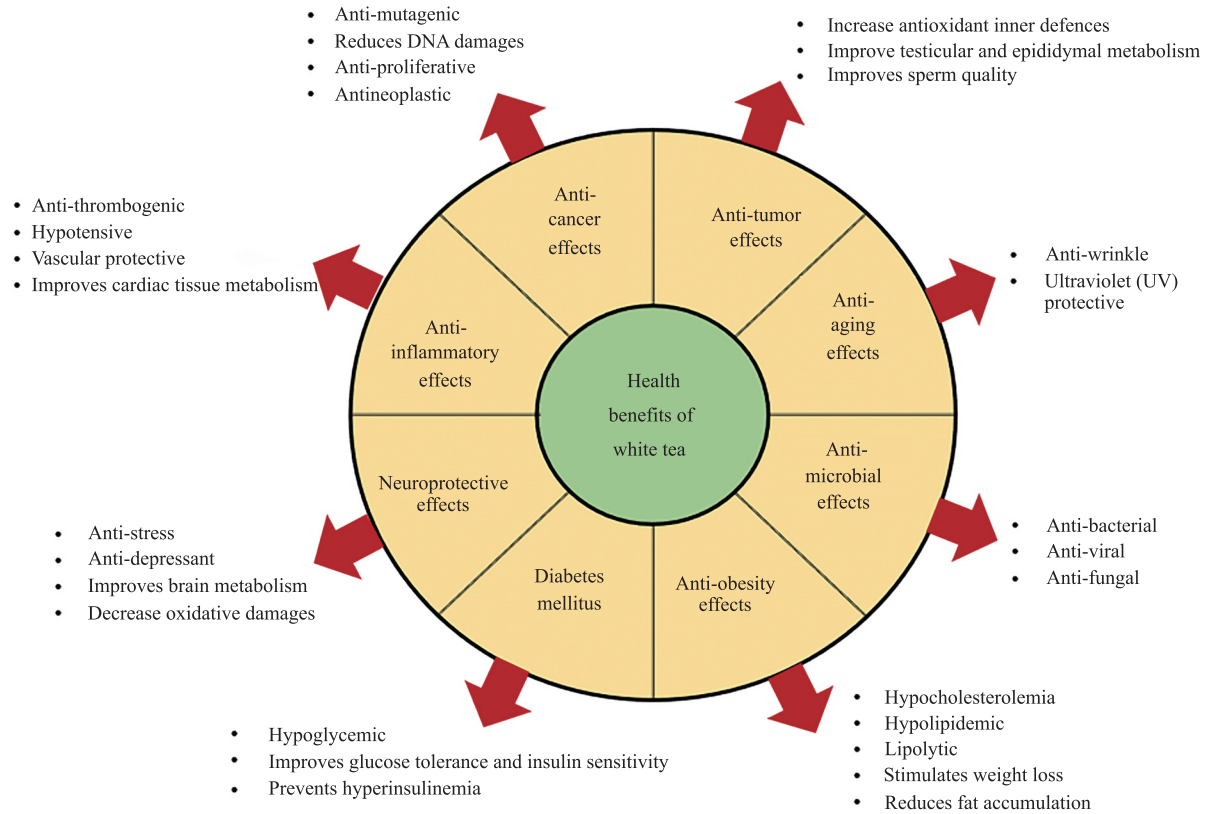

Fig. 1 Beneficial effects of white tea for human health.

catalytic oxidation reactions and preventing further cellular damage[25]. This chelation not only reduces oxidative stress but also protects biomolecules like proteins and lipids from oxidative degradation. Together, these antioxidative mechanisms underscore the potential of white tea polyphenols in maintaining cellular health and preventing oxidative-related diseases. In a study, 8 g of dried white tea leaves were steeped in 100 mL of boiling water for a duration of 5 min. Following this, the infusion underwent a filtration process using filter paper. The antioxidant capacity of the white tea infusions was subsequently evaluated using the ferric-reducing antioxidant power (FRAP) assay. The *in vitro* results unveiled that white tea, similar to green tea and catechin, exhibited a superior antioxidant capacity when compared to *Pelargonium purpureum*. This highlights the robust antioxidant properties of white tea, suggesting its potential as a source of beneficial compounds that contribute to oxidative stress mitigation[27]. In a study involving mice, white tea did not significantly affect plasma antioxidant capacity, or the antioxidant capacity of various organs (heart, lung, spleen, liver, kidney, and brain) compared to the control group. While white tea showed antioxidant properties *in vitro*, its impact *in vivo* was not prominently observed under the study's conditions[28]. In a 12-month study with Sprague-Dawley rats, researchers examined the antioxidant mechanism of white tea by administering different doses of white tea extract (WTE) alongside adriamycin (ADR) to induce oxidative stress. Four groups were established: Control, Control + ADR, white tea Dose 1 + ADR, and white tea Dose 2 + ADR. After treatment, antioxidant capacity was assessed in the liver, heart, and brain using various analytical methods[29]. The study found that white tea consumption, even at non-pharmacological doses, reversed oxidative damage from ADR in proteins and lipid metabolites in the liver, heart, and brain. It highlighted varying antioxidant potential among organs, with the heart needing a higher dose for optimal recovery. An inverse relationship between hydrophilic antioxidant activity and oxidative metabolites supported white tea's protective effects against acute oxidative injury. Overall, long-term white tea intake showed potential antioxidative benefits, suggesting its use in acute oxidative stress scenarios[30]. Polyphenols in white tea serve as a strong first line of defense against oxidative stress from ADR without requiring new antioxidant enzyme activation. Their complex, synergistic actions effectively reduce oxidative damage and restore tissue redox status. The study suggests that WTE activates the NRF2/ARE response, aiding in ADR detoxification[31].

Long-term consumption of WTE triggers the NRF2/ARE response, aiding in xenobiotic detoxification and reducing oxidative damage from ADR[32]. Its antioxidant activity modulates key enzymes like catalase, superoxide dismutase, and glutathione reductase. The quantity and quality of polyphenols and catechins were sufficient to neutralize free radicals without needing to increase enzyme levels. The study suggests further research on specific polyphenols could shed light on the regulatory mechanisms of nutritional factors[33].

3.2 Anti-inflammatory activities

Inflammation involves up-regulation of inflammatory genes and mediators in response to damage[25]. Xia et al.[34] found that WTE reduce acute and subacute inflammatory responses in mice by down-regulating interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), cyclooxygenase-2 (COX-2), inducible nitric oxide synthase (iNOS), while inhibiting the nuclear factor kappa-B (NF-κB) pathway. Additionally, a study on white tea oligopeptides, particularly BaiMudan (BMD) and ShouMei (SM), revealed they are readily absorbed and effectively inhibit inflammatory indicators, with BMD showing superior effects against IL-6. Synthesized peptides like EVFAG also demonstrated varying anti-inflammatory actions. The study underscores the importance of white tea oligopeptides in combating inflammation, suggesting further research on their mechanisms[35].

3.3 Anti-tumor activities

Emerging research suggests that white tea possesses potent anti-tumor properties, offering a natural avenue for cancer prevention and treatment. This article explores the multifaceted evidence supporting the anti-tumor potential of white tea. A comprehensive analysis pooling data from human subjects across 12 cohort studies highlights a noteworthy correlation between tea consumption and a reduced risk of bladder cancer[36]. Notably, this study provides compelling evidence that includes white tea as a key player in the tea-family's cancer-fighting prowess. Groundbreaking research by Liu et al.[37] delved into the anti-proliferative effects of water extracts from white tea. Focusing on Hela cells and BEL-7402 liver cancer cells, the study demonstrated a robust inhibition of cancer cell proliferation. The key mechanism at play was identified as the induction of apoptosis, a programmed cell death process crucial for preventing unchecked cell growth[37].

White tea's anti-tumor effects are deeply rooted in its ability to induce apoptosis in cancer cells. Apoptosis serves as a natural safeguard, ensuring the orderly elimination of damaged or potentially harmful cells. White tea's capacity to trigger apoptosis in cancer cells provides a promising strategy for impeding tumor growth and progression[38]. The evidence amassed from both cohort studies and *in vitro* experiments positions white tea as a formidable contender in the fight against cancer. Its dual action of reducing the risk of bladder cancer in populations and directly inhibiting the proliferation of specific cancer cell lines underscores its potential therapeutic relevance[39]. The collective findings from epidemiological studies and laboratory research emphasize the anti-tumor potential of white tea, opening doors to future investigations into its specific bioactive compounds and their mechanisms of action. As research unfolds, white tea may well become a valuable asset in our arsenal against cancer, offering a natural and accessible approach to promoting health and well-being.

3.4 Anti-aging activity

White tea, renowned for its delicate flavor and subtle aroma, extends its allure beyond the teacup to offer a profound array of anti-aging properties. At the heart of its potency lies a rich reservoir of polyphenols, antioxidants, and catechins, which collectively engage in a formidable defense against the ravages of aging. White tea flavonoids (WTF) can delay aging of mice model through antioxidative and anti-inflammatory activities[40]. These antioxidants act as guardians, neutralizing free radicals that contribute to oxidative stress which is a major culprit in the aging process. By mitigating oxidative stress, white tea helps minimize the appearance of fine lines

and wrinkles, promoting a more youthful complexion. Furthermore, the enchanting elixir of white tea doesn't merely halt at defense; it actively participates in skin rejuvenation. White tea is known to stimulate collagen production, a pivotal protein responsible for maintaining skin elasticity and firmness. The rejuvenating touch of white tea extends beyond the surface, working from within to encourage the skin's natural resilience. In the realm of inflammation, white tea emerges as a soothing balm. Its anti-inflammatory properties offer a calming embrace to irritated skin, alleviating redness and contributing to a harmonious complexion[41]. This dual action–combating oxidative stress and promoting skin regeneration–renders white tea a holistic ally in the pursuit of ageless beauty. WTF down-regulates the expression of pro-inflammatory genes of liver, thus reduce the release of inflammatory factors. Meanwhile, WTF increase the activities and amounts of serum antioxidative enzymes, relieving the oxidative damage of lung, kidney, and liver. So, the anti-aging effects of WTF is attributed to its anti-inflammatory and antioxidative properties. Whether savored in a steaming cup or incorporated into skincare routines through extracts and formulations, white tea stands as a testament to the artistry of nature in combating the visible signs of aging[42].

3.5 Anti-microbial activities

The anti-microbial activities of white tea have been shown to exhibit potent properties that combat various microorganisms. The primary components contributing to white tea's anti-microbial prowess are its polyphenols, catechins, and antioxidants. At the forefront of white tea's defense against microbial invaders are its polyphenols, which have been found to inhibit the growth of bacteria and fungi[43]. These polyphenols disrupt the integrity of the microbial cell membranes, hindering their ability to thrive and reproduce. Catechins, a subtype of polyphenols abundant in white tea, have been particularly notable for their antimicrobial effects. Studies indicate that catechins can interfere with the cellular processes of bacteria, leading to their eventual demise[44]. Epigallocatechin-3-gallate (EGCG) is one of the major catechins in white tea. The anti-microbial properties of EGCG have been applied by Wang et al.[45] in fishery products. The treatment of EGCG played the role of immune booster and apoptosis inhibitor, thus reduced the mortality of shrimp caused by the infection of pathogenic virus and bacteria[45]. Renzetti et al.[12] summarized the possible anti-bacterial mechanisms of catechins from green tea, and besides, EGCG, ECG, and theaflavin digallate were found to have the most potent anti-bacterial activity. Catechins could either bind to the bacterial toxins thus change its conformation and thereby its activity, or, it could promote the decomposition and inhibit the secretion of toxins[46-47]. Catechins could inhibit the formation of bacterial extra-cellular matrix and thus the movement and communication of bacteria[48].

Furthermore, the antioxidants present in white tea play a crucial role in bolstering the immune system. By scavenging free radicals and reducing oxidative stress, white tea aids in fortifying the body's natural defenses against microbial infections. This holistic approach not only targets the microorganisms directly but also enhances the overall resilience of the host[49]. Recent research has illuminated the specific antimicrobial potential of white tea against common pathogens. Its inhibitory effects on the growth of bacteria like *Staphylococcus aureus* and *Streptococcus mutans*, as well as fungi such as *Candida albicans*, highlight its broad-spectrum efficacy. The versatility of white tea in combating both Gram-positive and Gram-negative bacteria further underscores its potential as a natural antimicrobial agent[50]. In practical terms, incorporating white tea into daily routines, whether through consumption or topical applications, may offer a gentle yet effective strategy to ward off microbial threats.

3.6 Anti-obesity activity

White tea, renowned for its delicate flavor and numerous health benefits, has emerged as a potential ally in the quest against obesity. Research suggests that white tea possesses anti-obesity effects, offering a natural and holistic approach to weight management[51]. White tea's anti-obesity properties are its rich polyphenols, catechins, and antioxidants. These bioactive compounds have been shown to influence various mechanisms associated with weight regulation. One notable aspect is white tea's ability to enhance metabolism. Studies suggest that the catechins in white tea may contribute to increased fat oxidation and energy expenditure, potentially aiding in weight loss[52]. Moreover, white tea may play a role in inhibiting the differentiation and proliferation of adipocytes, or fat cells. By modulating adipogenesis, white tea may help prevent excessive fat accumulation. This anti-adipogenic effect could be attributed to specific compounds in white tea that interfere with the adipocyte maturation process. WTE potently reduced the weight of obese mice induced by high fat diets. It not only decreased the synthesis of fat, but also facilitated the decomposition of fat. Besides, WTE down-regulated the inflammation-promoting factor IL-6, thereby inhibited the inflammation of liver tissue[53]. White tea's impact on appetite regulation is another facet of its anti-obesity effects. Some research indicates that WTE may influence appetite-regulating hormones, promoting a sense of satiety and reducing overall food intake. This modulation of appetite can be crucial in managing calorie consumption and, consequently, body weight[54]. The anti-inflammatory properties of white tea may also contribute to its anti-obesity effects. Chronic inflammation is associated with obesity and related metabolic disorders, and white tea's ability to mitigate inflammation may play a role in promoting overall metabolic health[55]. While white tea is not a standalone solution for obesity, incorporating it into a balanced diet and a healthy lifestyle may contribute positively to weight management efforts. As research continues to unravel the intricacies of its bioactive compounds, white tea holds promise as a gentle and sustainable approach to promoting a healthier body weight[53].

3.7 Anti-high blood pressure

White tea has shown promise in contributing to the management of high blood pressure. Research suggests that white tea possesses anti-hypertensive effects, offering a natural approach to support cardiovascular health. The potential anti-high blood pressure effects of white tea are attributed to its rich content of polyphenols, particularly catechins and flavonoids[56]. These bioactive compounds have been associated with various cardiovascular benefits, including vasodilation and the improvement of blood vessel function. White tea's ability to promote vasodilation, the widening of blood vessels,

can lead to a reduction in blood pressure. Studies have indicated that the catechins in white tea may enhance the production of nitric oxide (NO), a molecule that helps relax and dilate blood vessels, facilitating improved blood flow and potentially lowering blood pressure[5]. Moreover, white tea's antioxidant properties play a role in protecting blood vessels from oxidative stress. By scavenging free radicals and reducing inflammation, white tea may contribute to maintaining the health of the endothelium which is the inner lining of blood vessels and preventing damage that could lead to hypertension. Luo et al.[57] revealed that EGCG was one of the effective components of white tea which improved lipids metabolism by downregulating the production of low-density lipoprotein, while reducing the accumulation of intracellular triglyceride. The *in vitro* research of Luo et al.[57] revealed that the WTE reconstructed the homeostasis of lipids metabolism by regulating relevant genes. The human liver cancer HepG2 cells were treated by WTE, and after that, the production of low-density lipoprotein is decreased, while the uptake of low-density lipoprotein cholesterol is increased, and besides, the intracellular accumulation of triglycerides was down-regulated[57]. A randomized controlled clinical trial executed by Chatree et al.[58] found that, although the intake of EGCG had no effect on obesity reduction, the consistent supplement (150 mg/time, twice per day) for 8 weeks significantly reduced the blood pressure and fasting plasma triglyceride of obese subjects. Incorporating white tea into a balanced and heart-healthy lifestyle may offer a complementary strategy for individuals looking to manage or prevent high blood pressure[58].

3.8 Antihyperglycemic effect

White tea, recognized for its delicate flavor and rich health-promoting properties, has shown potential ameliorative effects on diabetes mellitus, offering a natural approach to managing this metabolic disorder. Research suggests that white tea may exert positive influences on various aspects related to diabetes, contributing to overall glycemic control and metabolic health[59]. The beneficial effects of white tea on diabetes can be attributed to its bioactive compounds, including polyphenols, catechins, and antioxidants. These components have been associated with several mechanisms that can positively impact individuals with diabetes[60]. Studies have suggested that the polyphenols in white tea can improve insulin sensitivity, enhancing the body's ability to utilize insulin effectively. This may contribute to better glucose control, which is crucial for individuals with diabetes. Some research indicates that white tea may stimulate insulin secretion from pancreatic beta cells. This could be particularly beneficial for individuals with type 2 diabetes, as impaired insulin secretion is a characteristic of this form of the condition[61]. In a randomized controlled clinical trial, researchers from Iran found that the consumption of white tea infusions together with aerobic exercises significantly ameliorated the glycemic parameters of females with type 2 diabetes mellitus (T2DM)[62]. The antioxidants present in white tea may help combat oxidative stress and inflammation, both of which play a role in the progression of diabetes and its complications. By reducing inflammation and oxidative damage, white tea may contribute to overall metabolic health. Diabetes can lead to various complications, and white tea's antioxidant properties may offer protection against diabetic complications such as cardiovascular issues and kidney damage. The anti-inflammatory effects of white tea could also be beneficial in preventing diabetes-related complications[7]. α-Amylase and α-glucosidase play crucial roles in glycometabolism by breaking down starch into disaccharides and then monosaccharides. Consequently, suppressing the activities of these enzymes is considered an effective approach in treating T2DM. In a study by Xu et al.[15], the inhibitory impact of white tea on α-amylase and α-glucosidase was investigated *in vitro*. The research revealed that white tea demonstrated excellent inhibitory effects on both enzymes, even surpassing the efficacy of acarbose, a common inhibitor. However, it was observed that this inhibitory effect gradually diminished during the storage of white tea[15]. Incorporating white tea into a balanced diet, along with a healthy lifestyle, may serve as a supportive measure for individuals with diabetes. However, it is essential to emphasize that white tea should not replace prescribed medications or medical advice. Individuals with diabetes should consult with healthcare professionals for personalized guidance, and any dietary changes should be made in consultation with a registered dietitian or healthcare provider.

3.9 Ameliorative effect on kidney damage

The ameliorative effects of white tea on kidney damage underscore its potential as a natural remedy in supporting renal health. Kidney damage is a complication of diabetes mellitus due to persistent hyperglycemia. The research of Xia et al.[34], demonstrated the renal protective effects of white tea on the type 2 diabetes mice. The intake of white tea reverses the abnormal metabolism of glycemia and serum lipids. White tea inhibits the production of pro-inflammatory factors, and besides, improves the antioxidative capacity of serum and kidney tissue, thereby preventing kidney damage of type 2 diabetes mice[34]. The renal toxicity caused by the anti-tumor drug *cis*-platin is one of the widely concerned problems. Saral et al.[63] found that the infusions of white tea could reverse the nephrotoxicity in rats caused by cisplatin, and the kidney protecting effects of white tea was attributed to its anti-inflammatory features.

Rich in polyphenols and antioxidants, white tea has exhibited properties that may be beneficial in mitigating damage to the kidneys. Research suggests that the antioxidants present in white tea play a crucial role in reducing oxidative stress, a factor implicated in the development and progression of kidney damage. By scavenging free radicals and alleviating oxidative burden, white tea may contribute to preserving the structural and functional integrity of the kidneys[63]. Additionally, white tea's anti-inflammatory properties may offer protection against inflammation-induced kidney damage. Chronic inflammation is recognized as a contributor to various renal disorders, and white tea's ability to modulate inflammatory responses could potentially mitigate the risk of kidney injury. The potential reno-protective effects of white tea may extend to its impact on blood pressure regulation[25]. As research continues to unveil the intricacies of white tea's impact on kidney health, it stands as a potential, natural component in the holistic approach to supporting renal well-being.

3.10 Anti-irradiation effect

The anti-irradiation effect of white tea underscores its potential as a protective agent against the detrimental effects of radiation exposure. Abundant in polyphenols, catechins, and antioxidants,

white tea exhibits promising properties that could counteract the adverse impacts of ionizing radiation on cells and tissues. The antioxidative nature of white tea plays a pivotal role in mitigating radiation-induced oxidative stress[64]. Ionizing radiation produces free radicals that can result in cellular damage, and the scavenging activity of white tea's antioxidants helps neutralize these free radicals, thereby reducing oxidative damage and promoting cellular resilience. Research suggests that white tea's radioprotective effects extend to its ability to modulate the expression of specific genes involved in cellular responses to radiation. By influencing these genetic pathways, white tea may contribute to enhanced cellular repair mechanisms, aiding in the mitigation of DNA damage caused by radiation exposure[65]. Furthermore, the anti-inflammatory properties of white tea may play a role in alleviating inflammation associated with radiation exposure. Chronic inflammation is often linked to radiation-induced tissue damage, and the anti-inflammatory effects of white tea could contribute to a reduction in inflammatory responses. The review paper by Saric and Sivamani[66] evaluated the anti-ultraviolet (UV) radiation effects of polyphenols originating from plants. Drawing on previous studies, Saric and Sivamani[66] concluded that polyphenols may protect the skin from UV radiation, thereby conferring beneficial effects on skin health. In practical terms, incorporating white tea into the diet or using it as a topical application may offer a natural and accessible strategy to mitigate the harmful effects of radiation. While more research is necessary to fully comprehend the extent of white tea's radioprotective effects, its antioxidative and anti-inflammatory properties position it as a potential supplement to existing radiation protection measures.

3.11 Neuroprotective effects

The neuroprotective effects of white tea illuminate its potential as a natural ally in promoting brain health. Laden with polyphenols, catechins, and antioxidants, white tea exhibits properties that may safeguard the nervous system and support cognitive function. White tea's robust antioxidative capacity plays a pivotal role in neuroprotection by neutralizing free radicals and reducing oxidative stress[7]. The combined effects of caffeine's stimulation and theanine's sedation make white tea a viable option for addressing depression, anxiety, and various other mental health issues. Additionally, the neuroprotective benefits of white tea are attributed to the antioxidant properties of polyphenols and their derivatives, the neurotransmitter interactions involving amino acids like theanine and GABA, as well as the xanthine properties of caffeine. These attributes have been demonstrated in cell models, suggesting potential advantages of white tea white tea in managing neurodegenerative conditions such as Alzheimer's and Parkinson's disease[67].

Research suggests that the polyphenols in white tea may cross the blood-brain barrier, reaching the brain and exerting protective effects. These compounds have been associated with the enhancement of synaptic plasticity and the promotion of neurogenesis−the formation of new neurons−factors critical for maintaining cognitive function and preventing age-related cognitive decline[32]. Moreover, white tea's anti-inflammatory properties contribute to its neuroprotective effects. Chronic inflammation is recognized as a contributor to various neurological disorders, and white tea's ability to modulate inflammatory responses may help mitigate inflammation-induced damage to brain cells. White tea's impact on neurotransmitter activity and its potential to improve blood flow to the brain further contribute to its neuroprotective profile[68]. These mechanisms may enhance cognitive performance and protect against neurodegenerative conditions. As the understanding of white tea's impact on the nervous system continues to unfold, it stands as a promising candidate in the pursuit of maintaining cognitive vitality and preventing age-related neurological decline. Table 1 illustrates health effects of white tea with their mechanisms.

4. Innovative applications and product development with white tea

4.1 Ready-to-drink white tea infusions

Leveraging the distinctive flavor profile, health-promoting qualities, and versatility of white tea, product development opens a realm of possibilities. One promising avenue is the creation of ready-to-drink white tea infusions, featuring a medley of flavor combinations. Developing a ready-to-drink tea infused with white tea presents an exciting opportunity to provide consumers with a convenient and flavorful beverage option that capitalizes on the health benefits associated with white tea. This product could feature a carefully crafted blend of white tea leaves, chosen for their delicate flavor and antioxidant properties. Complementing the white tea base, the infusion could incorporate additional ingredients such as fruits, herbs, or botanicals to enhance the taste profile and nutritional value. The result would be a refreshing and ready-to-enjoy tea that not only satisfies thirst but also delivers a subtle and sophisticated white tea experience[69].

4.2 White tea in yogurt

A study found that incorporating tea extracts, including white tea, into yogurt did not significantly affect the viability of *Lactobacillus* spp., implying that the buffering capacity of tea potentially contributed to maintaining the stability of these beneficial bacteria. The pH values of yogurt with tea extracts were consistently higher than plain yogurt, suggesting a buffering effect, and post-acidification observed during storage was attributed to metabolic activity and proteolytic by-products. Despite these factors, the addition of tea extracts did not notably impact post-acidification, and all three types of tea-infused yogurts maintained high levels of bacterial counts throughout the storage period. This suggests potential health benefits for consumers. The study recommends further research to explore bacterial viability after simulated gastrointestinal digestion, providing insights into the potential effects of tea-infused yogurts on gut health[70].

4.3 White tea and synbiotics

The growth of probiotic strains is known to be influenced by specific prebiotics, and there is a hypothesis suggesting that a blend of prebiotics could collectively impact intestinal bacteria in a synergistic manner[71]. It is posited that optimizing the combination of prebiotics can be achieved through mixture design studies. In the context of white tea, the potential for *Lactobacilli* and *Bifidobacteria*

Table 1
Health effects of white tea with their mechanisms.

Health benefit	Research model	Mechanism	References
Anti-oxidative activities	Sprague-Dawley rats	White tea administration for 12 months significantly reduces oxidative damage induced by ADR in kidney tissue. This effect is attributed to the high polyphenol content of white tea, particularly EGCG, which enhances antioxidant enzyme activity and scavenges free radicals. Additionally, white tea attenuates inflammation and regulates gene expression related to oxidative stress response pathways, such as Nrf2, Ho1, and Nqo1	[29-30,33]
Anti-inflammatory activities	Cell culture (RAW 264.7 cells), zebrafish (*Danio rerio*)	Oligopeptides extracted from BMD and SM white tea exhibit potent anti-inflammatory activity both *in vitro* and *in vivo*. These oligopeptides significantly reduce the production of inflammatory mediators such as NO, IL-6, and TNF-α in LPS-induced RAW 264.7 cells. Furthermore, in a zebrafish model of bacterial inflammation, the oligopeptides effectively suppress neutrophil recruitment to the inflammatory site, indicating their ability to mitigate inflammatory responses	[35]
Anti-tumor	Cell culture (Hela and BEL-7402 cancer cell lines)	White tea aqueous extract (WTAE) from the eastern Chinese province of Fujian exhibits potent antioxidant activity and inhibits the proliferation of Hela and BEL-7402 cancer cells. The main bioactive ingredients of WTAE were analyzed to elucidate its health effects. WTAE effectively induced apoptosis in both cell lines, but the pro-apoptotic effects were more pronounced in Hela cells compared to BEL-7402 cells. The half maximal inhibitory concentration (IC_{50}) of WTAE for Hela cells (0.05 mg/mL) was lower than that for BEL-7402 cells (0.1 mg/mL)	[37]
Anti-aging	Mice models	WTF delay aging through antioxidative and anti-inflammatory activities, stimulate collagen production, and down-regulate pro-inflammatory genes, contributing to skin rejuvenation	[40]
Anti-microbial	*In vitro* experiments; studies on fishery products (juvenile shrimps)	White tea polyphenols disrupt microbial cell membranes and interfere with cellular processes of bacteria and fungi. EGCG exhibits immune-boosting and apoptosis-inhibiting properties. Catechins inhibit bacterial toxin formation and movement	[45]
Anti-obesity	Obese mice induced by high fat diets; *in vitro* experiments; randomized controlled clinical trial	WTE reduces weight and inhibit fat synthesis, down-regulates inflammation, and regulates lipids metabolism. Catechins enhance fat oxidation and decrease appetite, contributing to weight management	[54,58]
Anti-high blood pressure	*In vitro* experiments; human liver cancer HepG2 cells; randomized controlled clinical trial	White tea catechins improve blood vessel function, lipid metabolism, and reduce blood pressure	[57-58]
Antihyperglycemic effect	*In vitro* experiments; randomized controlled clinical trial; review papers	White tea polyphenols improve insulin sensitivity, stimulate insulin secretion, inhibit *α*-amylase and *α*-glucosidase, and regulate glycemic parameters	[15,62]
Ameliorative effect on kidney damage	Mice models; rats; *in vitro* experiments	White tea reverses abnormal metabolism, inhibits pro-inflammatory factors, and improves antioxidative capacity, protecting against kidney damage	[34,63]
Anti-irradiation effect	*In vitro* experiments	White tea's antioxidative and anti-inflammatory properties mitigate radiation-induced oxidative stress and inflammation and modulate gene expression involved in cellular responses to radiation	[64,66]
Neuroprotective effects	Cell models	White tea's antioxidative and anti-inflammatory properties protect against oxidative stress and inflammation, inhibit amyloid β-protein aggregation, and enhance synaptic plasticity and neurogenesis, contributing to neuroprotection	[32,67]

to ferment specific oligosaccharides and polysaccharides is crucial for the development of synbiotics. White tea phenolics serve as metabolic prebiotics and provide a matrix for probiotic strains, exerting significant effects on the intestinal environment by modifying the composition of the intestinal bacterial population. This underscores the potential of white tea in fostering a favorable symbiotic relationship between prebiotics and probiotics for enhanced gut health[72]. A separate study indicates that despite the initially low bio-accessibility in the duodenal stage, white tea extract demonstrated the highest duodenal and colonic bio-accessibility after *in vitro* gastrointestinal digestion when compared to green tea and black tea. Initially, green tea exhibited the highest total phenolic content (TPC) of 1 005.703 mg/g, followed by black tea (814.600 mg/g) and white tea (650.654 mg/g). However, during the colon stage (Pronase E + Viscozyme L stages), there was a substantial increase in TPC, particularly notable for white tea (522.981 mg/g), exceeding the values for both green tea (252.628 mg/g) and black tea (418.628 mg/g). White tea can be identified as a noteworthy candidate for enhanced colon bioavailability compared to green and black tea. This observation suggests that white tea polyphenols may undergo transformations or be more efficiently released in the colon, potentially due to the activity of gut microbiota[73].

4.4 White tea as a health supplement

There is a potential of white tea as a health-promoting supplement due to its rich content of amino acids, polyphenols (particularly catechins like EGCG), and methylxanthines. Despite the popularity of green tea supplements, the less-known white tea could become a valuable raw material for food supplements due to its interesting health properties. With a global trend in dietary supplements, the development of white tea-based supplements is proposed to achieve results comparable to studies conducted with high doses of white tea components. Further research is essential on therapeutic doses, potential side effects, and interactions with other compounds before widespread use[20].

White tea can be used to develop a weight loss supplement. A study suggests that an approximate intake of 0.22 mg of white tea could play a crucial role in promoting weight loss effects. The application of white tea in a specific dosage might enhance the process of fat burning. Some reports have demonstrated that the consumption of white tea catechins contributes to the reduction of diet-induced obesity, possibly due to catechins increasing energy expenditure[74]. The mechanism behind white tea-induced weight loss appears to be multifaceted. Recent research proposes that the rise in oxygen intake, attributed to sympathetic nerve-induced thermogenesis,

leads to the inhibition of catechol-*O*-methyltransferase activity induced by tea. Additionally, catechins are believed to inhibit small-intestine micelle formation and alpha-glucosidase activity in animals, resulting in reduced serum lipids and sugar absorption[75].

4.5 White tea in confectionery

White tea plays a pivotal role in the formulation of white tea-based pectin jelly with honey, offering a source of bioactive compounds and distinctive sensory characteristics. The study compares these jellies with gelatine-based candies, emphasizing factors such as total phenolic content, antioxidant capacity, and sensory attributes. While the pectin jellies demonstrate higher sweetness, acidity, and tea flavor, challenges arise in the stability of bioactive compounds during storage. Gelatine candies maintain better texture and color stability over time. The use of white tea contributes to the overall desirability and bioactive potential of the pectin jellies; however, careful attention to processing conditions and storage is essential to optimize its benefits in the final product[76]. Using white tea as a candy base offers numerous benefits, including an energizing effect from methylxanthine caffeine and various health advantages due to flavonoids, particularly flavan-3-ols, which contribute to neuroprotective, antimutagenic, and anticancerogenic activities. The candies are produced with vegan hydrocolloids (agar and pectin) and alternative sweeteners (steviol glycosides, sorbitol, and agave syrup), enriched with dietary fibers (inulin and psyllium). The study explores biaxially oriented polypropylene film with acrylic and poly (vinyl chloride) barrier coating as an effective packaging material. Candies made with pectin exhibit the longest shelf life, while gelatin candies show better bioactive quality parameters, highlighting the need for further optimization of agar and pectin formulations to achieve candies with optimal physicochemical properties, increased bioactive compound content, and enhanced microbial stability[77].

In another study, the utilization of white tea in popsicle formulation proves significant as it leads to a substantial increase in antioxidant compounds, irrespective of added protein. White tea's rich content of bioactive compounds, such as flavan-3-ols, contributes to potential health benefits, including neuroprotection and anticancerogenic effects. Popsicles with the optimized white tea extract, along with roasted mate and fermented rooibos, gained high consumer acceptance (88%), showcasing market potential. The compatibility of white tea with diverse ingredients like vegan hydrocolloids and sucrose alternatives allows for flexible formulations, catering to various dietary preferences. Additionally, the study highlights the extended shelf life of products, especially those made with pectin, emphasizing white tea's role not only in enhancing nutritional value but also in preserving product stability. Overall, the incorporation of white tea enhances the appeal, nutritional profile, and market potential of popsicles, making it a valuable ingredient in developing healthier and more attractive frozen treats[78].

4.6 White tea in liquid soap

A study focused on producing liquid soap infused with white tea extract, evaluating its various aspects. The pH values of soap formulations increased linearly with higher white tea concentrations, meeting quality standards. Microbial contamination, assessed through total plate number (TPN), adhered to acceptable limits. Antibacterial activity against *S. aureus* was observed in all treatments. Overall, the study concluded that white tea-infused liquid soap formulations met quality standards, displayed favorable sensory attributes, and demonstrated potent antibacterial effects[79].

4.7 White tea in kombucha

There was a study delves into the advantages of utilizing white tea in crafting kombucha, underscoring its rich polyphenol content, potent antioxidant properties, and health-enhancing characteristics. Noteworthy findings include the substantial rise in polyphenolic compounds during the fermentation of white tea, akin to green tea, featuring antioxidants like catechins, theaflavin, and tearubigin. White tea, particularly on the 1st and 14th days of fermentation, emerges as a commendable source of flavonoids, renowned for their antioxidant effects, vessel-sealing abilities, anti-inflammatory features, and immune system support. The study establishes a positive correlation between fermentation time and reductive potential, polyphenol content, and antioxidant potential, suggesting that prolonging the fermentation of white tea kombucha may amplify its health benefits. In conclusion, incorporating white tea into kombucha production offers myriad health benefits, emphasizing the pivotal role of tea selection, fermentation duration, and microbial content in optimizing the drink's health-promoting properties[80].

4.8 White tea-infused oils

The significance of oil infused with white tea is evident in a comprehensive study exploring its impact on soybean oil subjected to microwave heating, juxtaposed with olive leaves extracts. White tea-infused oils stand out for their potent antioxidant properties, effectively countering oxidative processes in soybean oil and enhancing overall oxidative stability. Notably, these extracts emerge as natural alternatives to synthetic antioxidants commonly used in the industry, aligning with the growing preference for minimally processed, natural ingredients. White tea-infused oils offer a dual functionality, serving as both a versatile culinary ingredient, imparting a unique flavor profile, and a potential source of health benefits associated with white tea consumption[81].

4.9 White tea capsules for endurance

The potential use of white tea in the development of a capsule for endurance can be explored based on the findings related to its impact on oxygen consumption, endurance exercise, and metabolic processes. A study highlights the interaction between white tea consumption and improvements in endurance capacity, which could be beneficial for individuals engaged in physical activities aiming for weight loss. It indicates that endurance exercise, such as swimming, increases NO and decreases superoxide dismutase, leading to vasodilation in the heart muscle. This results in enhanced oxygen flow to tissues, including muscle tissue, which, in turn, reduces lactic acid levels. Lower levels of lactic acid are associated with improved endurance. White tea consumption is suggested to increase oxidation activity in skeletal muscle and elevate the concentration of free fatty acids in the blood, contributing to a reduction in lactate levels and increased endurance[74]. Caffeine in white tea is mentioned as a factor

that can increase the use of free fatty acids and intramuscular triacylglycerol. This process may decrease the rate of muscle glycogenolysis, minimizing oxygen consumption and enhancing endurance during exercise. The study also refers to the positive effects of stimulant drinks, including white tea, in improving struggling abilities in mice. Furthermore, the research discusses the role of tea catechins in stimulating lipid catabolism, thereby increasing fat utilization during exercise. The study also notes that certain components in white tea, such as ECGC and *L*-theanine, are linked to the upregulation of genes involved in β-oxidation and lipid metabolism, as well as relaxation of the mind without inducing drowsiness[41]. In summary, the findings suggest that white tea may have positive effects on endurance and metabolic processes related to energy expenditure during exercise. These aspects make white tea an interesting candidate for further research and development.

4.10 Meal replacement shake with white tea

The meal replacement shake with white tea stands out as a comprehensive health solution, leveraging the antioxidant powerhouse that white tea is renowned for. Packed with compounds that combat oxidative stress, it fortifies the body's natural defense mechanisms, potentially lowering the risk of chronic diseases. Additionally, the infusion of white tea brings metabolic advantages, thanks to catechins known to boost metabolism. This not only supports weight management but also contributes to overall metabolic health. The anti-inflammatory properties of white tea further enhance the product's appeal, aiding in reducing inflammation and supporting joint health[82].

Moreover, the shake goes beyond mere nutritional fulfillment. The calming effects of *L*-theanine in white tea turn it into a stress-relieving elixir, creating a well-rounded product that not only nourishes the body but also promotes emotional well-being. The antioxidants in white tea contribute to healthier skin, making this shake a beauty-enhancing product that supports overall skin health[83]. As a functional product the shake will ensure a balanced nutritional profile, delivering essential vitamins, minerals, proteins, and the added benefits of white tea, making it suitable for weight management and overall nutritional enhancement. By incorporating white tea, the product becomes a holistic health support system, addressing antioxidant defense, metabolic health, and stress management[84]. The versatility of this functional product extends to various occasions, serving as a breakfast replacement.

4.11 Skincare and haircare products

In recent years, there has been a growing trend in the beauty and cosmetics industry towards incorporating tea extracts into skincare and haircare formulations. While green tea has been a popular choice, recent studies highlight the potential benefits of utilizing white tea extracts. White tea, known for its lighter color and delicate flavor, has demonstrated remarkable photo-protective properties and, when applied topically, has shown promising results in reducing UV-induced damage to the skin[85].

Research conducted by Camouse and co-workers has revealed that both white and green tea extracts exhibit significant photo-protective effects when applied to UV-irradiated skin. In a double-blind placebo-controlled assay, a cosmetic vehicle containing white tea extracts demonstrated a 22% reduction in $CD1a^+$ (epidermal Langerhans cells) staining, indicating a protective effect on the skin's immune system. Additionally, both white and green teas showed a considerable reduction in oxidative DNA damage caused by UV radiation, reinforcing their role as effective photo-protective agents[86]. The lighter color of white tea makes it particularly suitable for topical preparations, especially for regular use around the face. As a result, skincare products containing white tea extracts have gained popularity in the market. These products offer a range of benefits, including white tea body cream which softens and hydrates the skin, white tea shower gel which refreshes and softens the skin, leaving a fragrant scent, white tea toilet water which provides fragrant and revitalized skin and white tea hand cream which alleviates rough patches and calluses, leaving hands soft and smooth. All these products are originated from USA[85]. Tea extracts, including white tea, are not limited to skincare formulations as it contains caffeine. They are also increasingly being incorporated into haircare products, offering a holistic approach to personal care. The antioxidant-rich nature of tea extracts contributes to the overall health and vitality of hair, promoting shine and strength[87]. As consumer interest continues to grow, manufacturers are likely to explore innovative ways to harness the potential of white tea in beauty products, providing consumers with effective and naturally derived options for their skincare and haircare routines. Fig. 2 illustrates the applications of white tea in product development.

5. Exploring future directions for white tea: innovations in health, nutrition, and product development

White tea's unique flavor profile and health-promoting qualities open exciting possibilities for innovative applications and product development. One promising avenue is the expansion of ready-to-drink white tea infusions, combining white tea's delicate flavor with fruits, herbs, or botanicals. These beverages could provide convenient, health-enhancing options with potent antioxidant benefits, leveraging the polyphenolic compounds that neutralize ROS[69]. Similarly, white tea's potential extends to functional foods such as yogurt, where it maintains beneficial bacteria like *Lactobacillus* spp., enhancing gut health without significantly affecting post-acidification[70]. Further research into white tea's prebiotic properties could foster a synergistic relationship between probiotics and polyphenols, improving intestinal health and enhancing colon bioavailability during fermentation[72-73].

Due to its rich polyphenolic content, particularly catechins like EGCG, white tea holds promise as a dietary supplement. Studies indicate its potential role in weight management and metabolic health, where catechins enhance fat oxidation and reduce obesity-related markers[74]. This multifaceted approach to weight loss includes inhibiting micelle formation and promoting sympathetic nerve-induced thermogenesis, reducing serum lipid and sugar absorption[75]. Incorporating white tea into confectionery products, such as pectin jellies and popsicles, offers healthier alternatives with antioxidant benefits. Optimizing storage stability and bioactive compound retention, particularly in vegan formulations using hydrocolloids like agar or pectin, remains an area for future development[76-78].

Fig. 2 Applications of white tea in product development.

The cosmetics industry also presents significant opportunities for white tea applications. Its antioxidant and photoprotective properties make it ideal for skincare formulations that protect against UV-induced damage and oxidative stress[85-86]. White tea extracts demonstrate a reduction in oxidative DNA damage and support skin immune responses, suggesting potential in topical products like creams and serums. Additionally, these properties extend to haircare, promoting overall health and vitality[87]. Innovations such as white tea-infused meal replacement shakes or endurance capsules highlight their metabolic enhancement, stress-relieving properties, and improved physical performance. These products cater to markets focused on health and fitness, integrating white tea's calming *L*-theanine and energy-boosting methylxanthines[41,82]. By exploring these avenues, future research and product development can utilize white tea's full potential, meeting the growing demand for natural, multifunctional health products.

6. Conclusion

In conclusion, this extensive exploration underscores white tea's diverse applications, from traditional consumption to innovative product development. Rich in polyphenols, amino acids, and alkaloids, white tea exhibits notable health benefits, including antioxidant and anti-inflammatory properties. Its potential in renoprotection, anti-irradiation, and neuroprotection, as well as its adaptability in various industries, positions it as a versatile resource. The review highlights white tea's pivotal role in bridging traditional wisdom with modern applications, offering insights into its chemical composition, health benefits, and processing technologies. As the tea industry evolves, white tea stands as a promising ingredient for functional foods, beverages, and beyond. This comprehensive examination contributes nuanced perspectives, paving the way for continued research, innovation, and integration of white tea into diverse consumer preferences. Overall, white tea emerges as a multifaceted beverage with far-reaching implications for health, wellness, and the future landscape of the tea industry.

Conflict of interest

Baojun Xu is an associate editor for *Food Science and Human Wellness* and was not involved in the editorial review or the decision to publish this article. The authors declare no conflict of interest.

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