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Original Article

Health benefits and mechanisms of Tianmuhu White Tea in modulating glycolipid metabolism and oxidative stress

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Abstract: Objectives: To investigate the potential of Tianmuhu White Tea (TMH Tea) in modulating metabolic dysfunctions associated with high-fat diet (HFD)-induced obesity and mitigating oxidative stress in an aging mouse model. Methods: Institue for Cancer Research (ICR) mice were assigned to HFD and normal diet groups, and each group received either water, TMH White Tea, or Green Tea X for 30 days. Body weight (BW) was monitored, and blood samples were collected for biochemical analysis. An aging model was induced using D-galactose (D-gal) intraperitoneal injection. Oxidative stress was assessed by measuring malondialdehyde (MDA) levels and the activities of antioxidant enzymes (glutathione peroxidase (GSH-Px) and superoxide dismutase (SOD)). Trace elements and total polyphenols (TP) were measured by inductively coupled plasma mass spectrometry and Folin-Ciocalteu assay, respectively. Results: TMH White Tea significantly reduced BW gain in HFD-fed mice compared to Green Tea X (**P = 0.004) and water (**P = 0.000). TMH Tea also normalized blood glucose levels (**P < 0.01). Although Green Tea X also slightly reversed serum glucose levels (*P < 0.05), its effect was less pronounced than with TMH Tea (*P < 0.05). TMH Tea reduced serum triglyceride and cholesterol levels compared to water (**P < 0.01 for triglycerides and *P < 0.05 for cholesterol) and Green Tea X (*P < 0.05 for both). In the aging model, both teas reversed D-gal-induced alterations in MDA (*P < 0.05) and liver index (*P < 0.05), with no significant difference between them. D-gal-induced reductions in SOD and GSH-Px activities were significantly enhanced by TMH White Tea (*P < 0.05), but not by Green Tea X. Additionally, TMH Tea contained more selenium (4.3 mg/kg vs. 0.9 mg/kg) and similar TP content (29.3% vs. 28.2%) compared to Green Tea X, which may contribute to its beneficial effects. Conclusions: TMH White Tea may help mitigate obesity-related metabolic disorders and oxidative stress, providing notable metabolic and antioxidant benefits.

Keywords: Tianmuhu White Tea, glycolipid metabolism, oxidative stress, aging, health benefit

Introduction

Tea, consumed for nearly 5,000 years, is one of the most popular non-alcoholic beverages worldwide [1-3]. Due to its desirable psychologic effects, potential health benefits, and sociocultural significance, over two billion cups of tea are consumed daily across the globe [4-6]. As a functional beverage, the processing technology of green tea preserves the natural substances in fresh leaves, resulting in high levels of active compounds such as tea polyphenols (TPs), catechins, chlorophyll, caffeine, amino acids, and vitamins [7, 8]. Research has shown that tea consumption has preventive and therapeutic effects on obesity, diabetes, and oxidative stress-related diseases, with these health benefits primarily attributed to the aforementioned active compounds [9-14].

With modern lifestyle changes and the increasing pace of work-life balance, the rising prevalence of metabolic diseases like obesity and diabetes has prompted the development of natural prevention and intervention strategies, especially those involving food and beverages.

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These strategies have led to a focus on healthier, functional diets [15, 16]. As one of the most widely consumed beverages, tea offers an affordable, effective, and easily accessible solution. Current research highlights the bioactive compounds in tea, emphasizing their pharmacologic mechanisms and applications in medicine, food, and cosmetics. Studies have shown that tea-derived antioxidants effectively inhibit lipid oxidation in meat products, thereby extending shelf life [17]. Furthermore, tea contains essential trace elements (Se, Mn, Zn, I, and Fe), with selenium acting as a cofactor for Se-dependent enzymes, protecting cells from oxidative damage [18-20]. Compared to conventional beverages, tea offers superior bioavailability of these micronutrients [21, 22]. However, systematic studies on the effects of tea on glucose and lipid metabolism, as well as oxidative stress in experimental animals, remain limited.

Tianmuhu (TMH) White Tea, an albino variety of green tea from Liyang in Jiangsu Province, thrives in hilly regions with a warm climate, ample rainfall, and sufficient sunlight, creating an ideal environment for tea cultivation [23]. Slightly acidic, mineral-rich soils, particularly those high in selenium, contribute to the high concentration of active ingredients and trace elements in the tea, which are beneficial to human health [24-26]. Despite its unique growing conditions and possible health benefits, scientific research on this particular variety of tea is still limited.

To assess the health effects of TMH White Tea, we conducted in vivo studies in experimental mice, focusing on its impact on glycolipid metabolism and oxidative stress. Our results demonstrate for the first time that long-term consumption of TMH White Tea may help regulate blood glucose and lipid levels while reducing oxidative stress in aging mouse models.

Materials and methods

Tea

TMH White Tea used in this study was obtained from the TMH Tea Research Institute (Liyang, Jiangsu, China), harvested in April 2024 from a single cultivation batch. The control green tea (denoted as Green Tea X hereafter) was purchased from a supermarket, with a production date of April 2024. The tea was stored in airtight, lightproof containers at 4°C to preserve its flavor, freshness, and bioactive properties. For preparation, the tea was brewed according to the standard sensory evaluation methodology for tea (GB/T 23776-2009), with a brewing ratio of 3 g of tea to 150 mL of distilled water at 85°C for 5 minutes, followed by natural cooling to room temperature before administration. This standard preparation ensured consistency and reproducibility across the experiments.

Animals

In vivo experiments were conducted in accordance with the guidelines of the Council of Shanghai University on Animal Care. All experiments involving live mice were approved by the Ethics Committee of Shanghai University (2024-298). Four-week-old ICR mice were purchased from Jingweiyu Biotechnology Co., Ltd. (Suzhou, China), housed in specific pathogen-free conditions, and maintained under a 12-hour light/12-hour dark cycle with free access to food and water/tea. Fresh tea infusion was prepared daily to ensure consistency in bioactive compound content.

The mice were randomly divided into high-fat diet (HFD) and normal diet (ND) groups, receiving high-fat feed (40% fat, Shuyu Biotechnology Co. Ltd., Shanghai, China) and normal feed (Beijing Keao Xieli Feed Co. Ltd., Beijing, China), respectively. Each group was further divided into three subgroups of six mice, receiving either pure water (water), normal green tea (Green Tea X), or TMH White Tea.

In the tea-drinking groups, regular drinking water was replaced entirely with tea infusion, with no additional purified water provided throughout the experiment.

Both tea-treated and control groups received the same volume of liquid daily, and the tea infusion and control water were replaced at the same time each day to prevent degradation or microbial growth.

Evaluation of glycolipid metabolism and oxidative stress

After 30 days, all mice were euthanized by CO_2 inhalation followed by cervical dislocation, and blood samples were collected for biochem-

ical analysis. The following assessments were made:

Glycolipid metabolism: The effects of different treatments on body weight (BW) gain and blood biochemical markers were evaluated.

Oxidative stress: To induce aging, mice were intraperitoneally injected with D-galactose (D-gal) at a dose of 400 mg/kg/day. After 30 days of treatment, blood samples were collected to evaluate oxidative stress markers, including malondialdehyde (MDA), Glutathione peroxidase (GSH-Px), and superoxide dismutase (SOD) levels.

Measurement of GSH-Px and SOD activity

Blood samples were collected from the jugular vein of the experimental mice and kept at 4°C until analysis. GSH-Px activity was measured by the reaction rate at which GSH is catalyzed, with absorbance measured at 412 nm [27]. SOD activity was determined by the reaction between WST-1 and superoxide anions, with absorbance changes measured in the reaction system. GSH-Px and SOD levels were assayed using commercially available kits (GSH-Px A005, SOD A001-1, Nanjing Jiangcheng Biotechnology Institute, Nanjing, China) following the manufacturer's instructions.

Determination of MDA release

MDA, a biomarker for lipid peroxidation, was quantified by its reaction with thiobarbituric acid (TBA), forming a red compound that absorbs at 532 nm. MDA levels in serum were determined using a specific MDA detection kit (A003-1, Nanjing Jiangcheng Biotechnology Institute, Nanjing, China), according to the manufacturer's protocol.

Measurement of trace elements and total phenolic content in the teas

The trace element contents in TMH White Tea and Green Tea X were determined using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500a) [28]. For preparation, 1 g of tea was weighed, placed into a high-pressure digestion vessel, and treated with 5 mL of nitric acid and 2 mL of hydrogen peroxide. The sample underwent a temperature ramp (250°C for 6 minutes, 400°C for 5 minutes, and 450°C for 5 minutes). After cooling, the digestate was diluted to 50 mL with deionized water and analyzed using ICP-MS. Total polyphenol (TP) content was measured using the Folin-Ciocalteu method [29]. Tea samples were ground and extracted with 70% ethanol at 70°C for 1 hour. The resulting extract was filtered, and 0.5 mL of the diluted extract was mixed with 2.5 mL of 0.2 mol/L Folin-Ciocalteu reagent, followed by reaction at room temperature for 4 minutes. Sodium carbonate solution (75 g/L) was added, and the mixture was incubated for 2 hours in the dark. Absorbance was measured at 760 nm, with gallic acid used as the standard.

Statistical analysis

Data were expressed as means ± standard deviations (SDs). BW differences were compared using repeated-measures ANOVA, while other data were analyzed by one-way ANOVA. Post hoc pairwise comparisons following ANOVA were performed using the least significant difference (LSD) method. Significant differences were considered at $P < 0.05$.

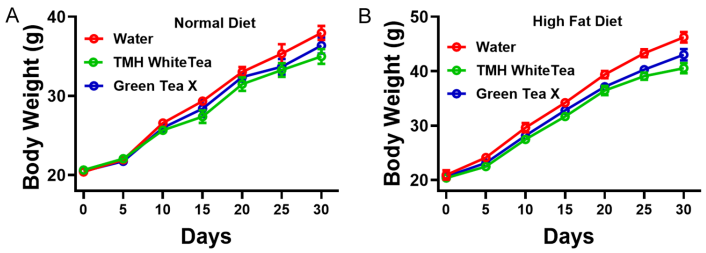
Results

TMH White Tea significantly reduces HFD-induced weight gain

As shown in **Figure 1**, the BWs of ICR mice gradually increased over the 30-day experimental period. The HFD significantly elevated the BW of the mice, particularly in the latter half of the experiment (after 15 days), reflecting the obesogenic effects of the diet. Regular consumption of either Green Tea X or TMH white tea significantly reduced BW gain in both the ND (**Figure 1A**) and HFD (**Figure 1B**) groups, as confirmed by repeated-measures ANOVA. Notably, TMH White Tea significantly slowed BW gain in HFD-fed mice compared to those treated with Green Tea X (**P = 0.004, **Figure 1C**). Although TMH White Tea also reduced BW gain in ND-fed mice compared to the Green Tea X group, this difference was not statistically significant (ns, $P > 0.05$). These results suggest that TMH White Tea is more effective than Green Tea X at mitigating BW gain, particularly under HFD conditions.

TMH White Tea modulates serum glucose and lipid levels

The influence of TMH White Tea on blood glucose and lipid levels in response to an HFD is



C

Groups	Normal Diet	High Fat Diet
TMH White Tea VS Water	p=0.001 (**)	p=0.000 (**)
Green Tea X VS Water	p=0.037 (*)	p=0.001 (**)
TMH White Tea VS Green Tea X	p=0.082 (ns)	p=0.004 (**)

Figure 1. Effects of the Tianmuhu (TMH) White Tea on body weight of experimental ICR mice during the experimental period of 30 days. Mice were fed with either normal diet (ND) (A) or high fat diet (HFD) (B, C). Data are presented as mean ± SD, **P < 0.01, *P < 0.05, ns means "not significant" (P > 0.05).

shown in **Figure 2A**. After 30 days of HFD exposure, blood glucose levels significantly increased from 7.5 ± 0.69 to 13.7 ± 0.45 mmol/L, surpassing the normal range. However, regular consumption of TMH White Tea notably reversed these elevated glucose levels. Specifically, after 30 days of continuous tea intake, serum glucose levels in the HFD-fed groups returned to within the normal range (6.67 ± 0.29 mmol/L, **P < 0.01). Although Green Tea X also slightly reversed HFD-induced serum glucose elevation (*P < 0.05), this effect was less pronounced than that of TMH White Tea (*P < 0.05). In the ND group, the blood glucose levels of mice administered TMH White Tea were significantly lower than those in the water and Green Tea X groups (**P < 0.01 and *P < 0.05, respectively), though all groups remained within the normal range.

Additionally, tea-treated mice showed substantial reductions in triglyceride (TG) and total cholesterol (Chol) levels. As shown in **Figure 2B**, **2C**, HFD-fed mice exhibited significantly increased serum TG and Chol levels, which were markedly reversed by TMH White Tea (**P < 0.01 for TG and *P < 0.05 for Chol), whereas Green Tea X showed no significant effect (ns, P > 0.05). Furthermore, TMH White Tea appeared significantly more effective than Green Tea X in lowering serum TG and Chol levels (*P < 0.05).

Under a ND, long-term tea consumption did not significantly affect serum TG levels (ns, P > 0.05), but the serum Chol levels were slightly lower in the TMH White Tea-fed group compared to the water group (*P < 0.05). These results indicate that glucose and lipid metabolism disorders, such as elevated blood glucose, TG, and Chol levels, induced by HFD feeding, were significantly mitigated by tea intake (**Figure 2**).

TMH White Tea decreases oxidative stress in the aging mouse model

The effects of TMH White Tea on oxidative stress were evaluated in an aging mouse model. As shown in **Figure 3A**, D-gal significantly increased serum MDA levels compared with the sham group (PBS injection), confirming successful induction of the aging mouse model. Notably, consumption of TMH White Tea significantly reduced MDA levels in the aging mice (*P < 0.05), whereas Green Tea X showed no significant effect (ns, P > 0.05). Moreover, TMH White Tea exhibited a more pronounced reduction in MDA levels compared to Green Tea X (*P < 0.05).

Similarly, changes in the liver index, another indicator of aging, mirrored those of MDA (**Figure 3B**). The activities of antioxidants SOD and GSH-Px, crucial for reducing oxidative stress, were significantly lower (*P < 0.05 for SOD and **P < 0.01 for GSH-Px) in the D-gal-treated groups compared to the sham group. Regular feeding of TMH White Tea significantly enhanced SOD and GSH-Px activities (**Figure 3C**, **3D**, both *P < 0.05), while no such improvement was observed with Green Tea X (ns, P > 0.05). These results suggest that TMH White Tea effectively reduces oxidative stress in the mouse model by enhancing endogenous antioxidative enzyme activity.

Contents of Trace Elements and TP in TMH White Tea

To assess the bioactive components of TMH White Tea, we measured the trace element and TP. **Table 1** presents the bioactive compound data for TMH White Tea and Green Tea X. TMH White Tea contained a relatively high selenium

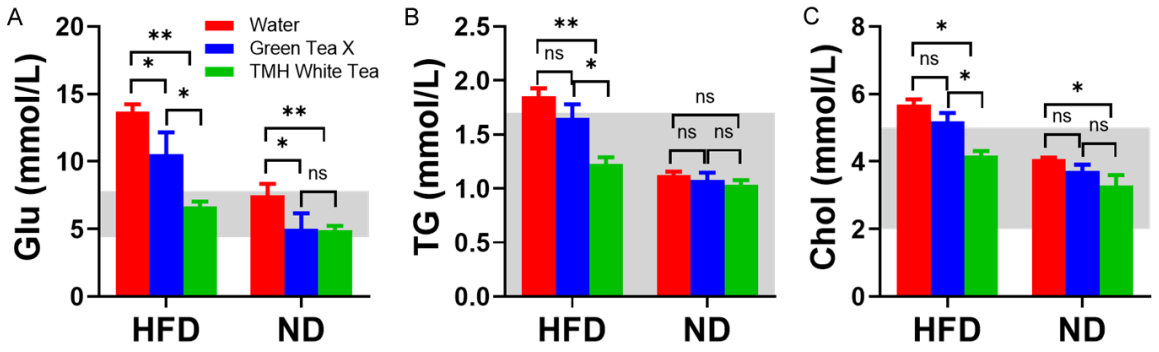


Figure 2. Effects of the Tianmuhu (TMH) White Tea and control Green Tea X on glycolipid metabolism in the high fat diet (HFD)-fed and normal diet (ND)-fed mice. At the end of 30 days, (A) fasting blood glucose, (B) triglycerides (TG) and (C) total cholesterol (Chol) were measured. The difference was shown in the glycolipid metabolism state among groups. Data are presented as mean ± SD, **P < 0.01, *P < 0.05, ns means "not significant" (P > 0.05).

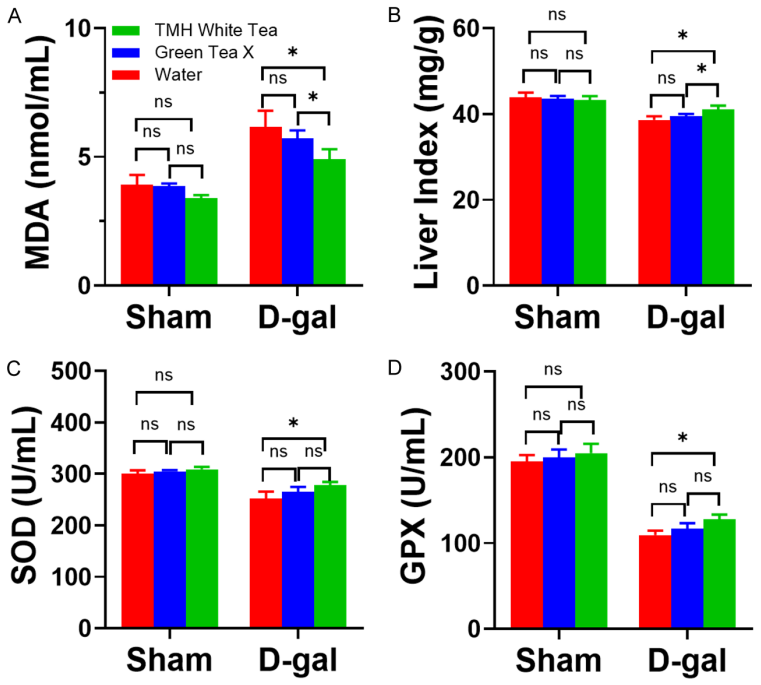


Figure 3. Serum oxidative stress data of experimental mice after 30 days' treatment. ICR mice were intraperitoneally injected with D-galactose or PBS (Sham), and randomly divided into three groups, which were fed with pure water, Green Tea X and Tianmuhu (TMH) White Tea, respectively. After 30 days, the mice were euthanized, and (A) serum malondialdehyde (MDA), (B) liver index, (C) serum superoxide dismutase (SOD); and (D) serum glutathione peroxidase (GSH-Px) were assessed. Data are presented as mean ± SD, **P < 0.01, *P < 0.05, ns means "not significant" (P > 0.05).

(Se) content of 4.3 mg/kg, compared to 0.9 mg/kg in Green Tea X. According to the Agricultural Industry Standard of the People's Republic of China (NY/T 600-2002), tea with Se content ranging from 0.25 to 4 mg/kg is classified as Se-enriched tea [30]. Additionally, TMH White Tea had a higher TP content (approximately 29.3%) and significant levels of trace elements, including iron (Fe, 66.7 mg/kg), manganese (Mn, 746 mg/kg), zinc (Zn, 45.2 mg/kg), copper (Cu, 13.1 mg/kg), fluoride (F, 75 mg/kg), and iodine (I, 0.118 mg/kg), which were comparable to the levels in Green Tea X. The abundance of TPs and trace elements is considered a key mechanism underlying the protective effects of tea against oxidative stress-related diseases and aging [31, 32].

Discussion

Tea, one of the most beloved plants worldwide, has been the subject of extensive research to uncover its biological properties and potential health benefits [6]. Epidemiological, cellular, and animal studies consistently show that tea consumption is linked to reduced risks of diabetes, obesity, chronic inflammation, and even cancer [33-36]. These findings have spurred interest in evaluating the specific health impacts of various tea types, particularly those with unique bioactive compositions.

In this study, we systematically investigated the effects of TMH White Tea, a premium tea variety cultivated in the selenium-rich region of

Table 1. Content of trace elements and polyphenols in the Tianmuhu (TMH) White Tea and Green Tea X (serving as a comparator)

Bioactive compound	Unit	Content in TMH White Tea	Content in Green Tea X	Content range in Se-enriched Tea
Fe	mg kg-1	66.7	73.5	-
Mn	mg kg-1	746	728.3	-
Zn	mg kg-1	45.2	40.4	-
Se	mg kg-1	4.3	0.9	0.25-4 [30]
Cu	mg kg-1	13.1	12.7	-
F	mg kg-1	75	67	-
I	mg kg-1	0.118	0.156	-
TPs	%	29.3	28.2	15-30 [58]

TPs: total polyphenols.

Liyang, Jiangsu Province, China [37]. Tea is traditionally classified into categories based on its fermentation levels, ranging from green tea (unfermented) to Puerh tea (fully fermented) [38]. Despite its name, "TMH White Tea" undergoes no fermentation and is processed using traditional green tea methods such as fixation and rolling, making it a type of green tea. The term "white tea" refers to the whitish appearance of the young buds harvested during the spring whitening stage. While it retains the characteristics of green tea, the unique whitened raw material gives it a "clear soup, white leaves" appearance, reinforcing its designation as "white tea". This study focused on TMH White Tea's ability to modulate glycolipid metabolism in HFD-induced obese mice and alleviate oxidative stress in a D-gal-induced aging mouse model. Our findings provide compelling evidence that TMH White Tea has significant anti-obesity, antioxidant, and antiaging effects, potentially due to its unique bioactive constituents, including TPs and Se.

Excessive energy intake, particularly from HFDs, is a major contributor to metabolic disorders such as obesity, insulin resistance, and dyslipidemia [39, 40]. In experimental models, HFD-fed mice reliably develop hyperglycemia, hyperlipidemia, and weight gain, making them an ideal model for studying metabolic syndrome [41]. This study illustrates that the regular consumption of TMH White Tea significantly attenuated BW gain induced by an HFD. This observation is consistent with previous studies indicating that tea consumption can help mitigate obesity and improve metabolic health. For example, Xu and colleagues found that tea consumption could aid in weight loss and reduce the occurrence of obesity, particularly when combined with a balanced diet and physical exercise [9]. The anti-obesity effects of tea are mediated through multiple synergistic mechanisms, including the modulation of lipid metabolism via the inhibition of pancreatic lipase activity, thereby reducing intestinal fat absorption [42-45]. Additionally, tea polyphenols promote metabolic regulation by supporting the proliferation of beneficial gut microbiota, which enhances metabolic homeostasis [46, 47]. Given that TMH White Tea is rich in polyphenols derived from young leaves, its superior metabolic benefits may stem from higher catechin concentrations compared to fermented or aged teas [48].

Aging, driven by factors such as DNA damage, mitochondrial dysfunction, and oxidative stress, is associated with a progressive decline in physiologic function [49, 50]. The accumulation of reactive oxygen species disrupts cellular homeostasis, leading to protein misfolding, DNA mutations, and impaired organ function [51]. Antioxidant strategies, both natural and exogenous, are promising for delaying aging and preventing related diseases [52]. To evaluate TMH White Tea's antiaging potential, we used a D-gal-induced aging mouse model, which accelerates aging via oxidative and endoplasmic reticulum stress [51]. Our results showed that D-gal treatment increased MDA levels while decreasing GSH-Px and SOD activities. Importantly, continuous consumption of TMH White Tea mitigated these effects, reducing MDA levels and increasing GSH-Px and SOD activities. These findings suggest that TMH White Tea's bioactive compounds effectively scavenge free radicals and enhance endogenous antioxidant defenses.

Se-enriched tea has shown superior antioxidant and anti-obesity effects compared to conventional green tea [53, 54]. Zhang et al. reported that Se-enriched green tea resulted in greater increases in antioxidant enzyme activities compared to regular green tea in HFD-fed

mice [55]. Additionally, Se-enriched green tea regulates the 5-hydroxytryptamine signaling pathway, enhancing the inhibition of liver fat synthesis and the reduction of hepatic TG and TC levels [55]. Tea plants have a strong ability to accumulate Se, particularly in Se-rich areas or under Se fertilizer application [26]. As shown in **Table 1**, TMH White Tea contains comparable levels of TPs and trace elements to Green Tea X, contributing to its protective effects against oxidative stress-related diseases and aging. The relatively high Se content (4.3 mg/kg) in TMH White Tea likely amplifies its health benefits, especially through the synergistic interaction between polyphenols and selenium [56-58].

This study offers valuable insight into the health benefits of TMH White Tea, though it acknowledges some methodological limitations. The main limitation is the modest sample size (n = 6 per group) used for *in vivo* analyses. While statistically significant differences were observed, expanding the sample size would enhance the validity and generalizability of the results. Additionally, while tea infusion was prepared under standardized conditions, the daily intake by mice was not precisely controlled due to the free-access drinking design, introducing inter-subject dose variability. Future studies could improve dosing precision by employing controlled intragastric administration, volumetric intake monitoring, or metabolic cage usage, all of which could enhance physiological relevance. Subsequent investigations should integrate quantitative measurement techniques and biologically representative exposure models to overcome these limitations.

In conclusion, our findings suggest that TMH White Tea, an albino variant of green tea cultivated in Liyang, China, offers noteworthy health benefits, including the reduction of blood glucose, TG, and Chol levels, as well as exhibiting antioxidant properties. The presence of bioactive substances such as TPs, selenium, and other trace elements may contribute to these health benefits.

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Disclosure of conflict of interest

None.

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