SIN-CHN SCIENTIFIC PRESS PTE.LTD.

Molecular & Cellular Biomechanics 2025, 22(4), 1285.
https://doi.org/10.62617/mcb1285

Article

Tea polysaccharides as multifunctional bioactive compounds: Biomechanical effects of the antioxidant, anti-inflammatory and immunomodulatory effects on life and health

Haiyan Liu[1,*], Jianwei Zhang[2]

[1] College of Huangjiu, Zhejiang Industry Polytechnic College, Shaoxing 312000, China
[2] College of Health, Zhejiang Industry Polytechnic College, Shaoxing 312000, China
*** Corresponding author:** Haiyan Liu, freeair772000@163.com

CITATION

Liu H, Zhang J. Tea polysaccharides as multifunctional bioactive compounds: Biomechanical effects of the antioxidant, anti-inflammatory and immunomodulatory effects on life and health. Molecular & Cellular Biomechanics. 2025; 22(4): 1285. https://doi.org/10.62617/mcb1285

ARTICLE INFO

Received: 31 December 2024
Accepted: 14 February 2025
Available online: 4 March 2025

Abstract: The extraction method and bioactivity of tea polysaccharides from waste tea leaves and stems were investigated, with a particular focus on their biomechanical influence. Firstly, the extraction of tea polysaccharides was carried out using subcritical water, and the impact of various extraction conditions on the physicochemical properties of the polysaccharides was examined. Subsequently, this study evaluated the antioxidant activity of extracted tea polysaccharides using hydroxyl radical scavenging methods, and analyzed their effects on cell growth through cell viability experiments. In addition, the effects of tumor necrosis factor alpha (TNF-α) and interleukin-6 (IL-6) levels on anti-inflammatory effects were measured. The immunomodulatory effects of tea polysaccharides were further explored through immune function assays. Moreover, the biomechanical properties of cells, such as their elasticity, membrane stiffness, and tissue flexibility, were assessed to understand the impact of tea polysaccharides on cellular and tissue mechanics. All data were subjected to statistical analysis to ensure the reliability of the experimental results. The findings indicate that tea polysaccharides possess significant antioxidant, anti-inflammatory, immunoregulatory, and biomechanical properties, providing a reference for the resource utilization of waste tea leaves and stems, as well as potential application value for the development of new health products with integrated biomechanical benefits.

Keywords: tea polysaccharides; antioxidant; anti-inflammatory; immunoregulation; biomechanics

1. Introduction

The main bioactive compounds in tea include tea polysaccharides [1]. Tea polysaccharides are primarily derived from tea leaves, tea flowers, and tea seeds [2]. Compared to tea polyphenols, tea polysaccharides are more stable, and research on their properties, bioactivity, and structure is still in the early stages. At present, researchers commonly use techniques like enzymatic processing and ultrasound-assisted extraction to isolate tea polysaccharides. These studies have shown that tea polysaccharides have various bioactivities, including antioxidant, anti-tumor, immunomodulatory, and anti-diabetic effects, making them promising candidates for applications in functional foods and pharmaceutical formulations [3].

Tea polysaccharide has antioxidant, anti-cancer, anti-diabetes, anti-inflammatory and other biological activities. Currently, there are over 120 reported types of tea polysaccharides [4,5]. Research has shown that polysaccharides in tea leaves such as Qingzhuancha [6], Fuzhuan tea [7], and Huangcha [8] all have antioxidant activity [9–

12]. Most researchers have validated antioxidant properties of tea polysaccharides through chemical reactions including activities like the scavenging of 1,1-diphenyl-2-picrylhydrazyl (DPPH) radicals, superoxide anion radicals, and hydroxyl radicals.

Recently, scholars have gradually used in vitro cell models or mouse models to verify the antioxidant effects of tea polysaccharides. For example, Fan et al. [13] validated the antioxidant activity of tea polysaccharides by constructing a human umbilical vein endothelial cell model. In addition, researchers verified that tea polysaccharides can affect the activity of cancer such as gastric cancer, liver cancer, colon cancer, etc. through cell models and animal models [4]. The study of Liu et al. [14] showed that tea polysaccharides can exert anti-cancer potential by inhibiting the proliferation of mouse colon cancer cells. Wang et al. [15] demonstrated that selenium-enriched tea polysaccharides from Ziyang green tea can suppress the proliferation of human osteosarcoma U-2 OS cells both in vitro and in vivo, showing anti-cancer properties.

Tea drinks made from mature tea have been used to treat diabetes in China and Japan, Wang et al. [16]. Research shows that tea polysaccharide is the key ingredient in Wufeng green tea to play a role in treating diabetes. It is reported that tea polysaccharides with anti-diabetes activity mainly come from green tea. The anti-diabetes activity of tea polysaccharides may be achieved by regulating cAMP-PKA or PI3K/Akt signaling pathway [16,17]. The study of Chung et al. [18] showed that tea polysaccharides possess a hypoglycemic effect, and their mechanism of action may be by preventing the breakdown of starch into glucose, delaying the absorption and transport of glucose, and thus reducing blood sugar. In addition, researchers have found that tea polysaccharides have anti-inflammatory and immunomodulatory activities. For example, the study of Zhao et al. [19] showed that selenium rich tea polysaccharides improved ulcerative colitis in mice by improving the intestinal barrier function and modulating the gut microbiota. Kim et al. [20] extracted catechins, flavonols and crude polysaccharides from tea and found that the combination therapy of the three could weaken the expression of inflammatory genes induced by dust particles in airway epithelial cells. Tea polysaccharides can lower pro-inflammatory cytokine levels and enhance the activity of anti-inflammatory cells.

Improving colitis in mice through factor level approaches [21]. Cheng et al. [22] used the S-180 cancer xenograft model in Kunming mice. The immune regulatory activity of selenium rich tea polysaccharides was verified by typing. Meanwhile, the structure of tea polysaccharides is closely linked to their biological activity.

The biomechanical properties of cells, such as elasticity, membrane stiffness, and tissue flexibility, were evaluated to understand the effect of tea polysaccharides on cellular and tissue mechanics. Tea polysaccharides, known for their bioactive effects, were specifically studied for their potential to modify cellular biomechanics [23]. The elasticity of the cell membrane was measured using atomic force microscopy (AFM) to observe how these polysaccharides impact the deformation and rigidity of cells under stress, potentially enhancing cellular resilience. Membrane stiffness was assessed through micropipette aspiration, which provided insights into how tea polysaccharides interact with membrane components, possibly altering cell motility and mechanotransduction pathways. Tissue flexibility, crucial for cellular movement and response to mechanical forces, was analyzed using stress-strain tests on cell clusters and tissue samples. These evaluations aimed to clarify how the biomechanical properties of tea polysaccharides modulate cellular mechanical behavior, influencing processes such as cell migration, adhesion, and cellular responses to external mechanical stimuli, which could have implications for tissue regeneration and wound healing.

The relationship between components [24], Chen et al. [7] found that the primary and spatial structures of tea polysaccharides were altered after ultra-high pressure treatment, and their uronic acid content and biological activity were increased. Some researchers also claim that the cellular structure of active polysaccharides directly influences biological activity [25]; Yang et al. [24] provided a comprehensive overview of polysaccharides with hypoglycemic effects, noting that their hypoglycemic activity is influenced by factors such as molecular weight, monosaccharide composition, glycosidic linkages, higher-order structures, and polysaccharide groups. Although current research has found that tea polysaccharides have multiple biological activities, there is still a lack of analysis on their structure-activity relationships. Although the physicochemical properties and biological activity of tea polysaccharides were studied, their interaction relationships have not been studied. Therefore, researchers should also focus on the structure-activity relationship when analyzing the physicochemical properties and biological activity of tea polysaccharides [25,26].

This study aims to develop the resource utilization of discarded tea leaves and tea branches, extract tea polysaccharides through subcritical water extraction process, and evaluate their biological activities. Firstly, tea polysaccharides from discarded tea leaves and tea branches were extracted by subcritical water extraction method. The extraction process conditions were optimized, including temperature, time, and pH value of water. The effects of various extraction methods on the yield, purity, and physicochemical properties of tea polysaccharides were investigated. Next, extracted tea polysaccharides' activity was obtained through the hydroxyl radical scavenging assay, and their ability to eliminate free radicals and potential antioxidant mechanisms were explored. In the cell viability experiment, different concentrations of tea polysaccharides were used to treat cells, evaluate their effects on cell proliferation and survival rate, and further understand the cellular biological effects of tea polysaccharides. At the same time, the impact of tea polysaccharides on the levels of tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) was assessed using ELISA, and their anti-inflammatory potential was evaluated. In addition, in order to explore the immune regulatory function of tea polysaccharides, this study studied the impact of tea polysaccharides on the body's immune system through immune function experiments, and analyzed whether they can regulate immune cell activity and enhance immune response. All experimental data were analyzed using statistical methods to ensure the scientific validity of the results. The research results in this study indicate that tea polysaccharides extracted from subcritical water have strong antioxidant activity, which can effectively eliminate hydroxyl radicals and slow down oxidative damage; Meanwhile, tea polysaccharides demonstrate notable anti-inflammatory properties by mitigating inflammatory responses; In addition, tea polysaccharides have a significant regulatory effect on the immune system, which can enhance the capability of immune cells and immune response. In summary, tea polysaccharides in discarded tea leaves and tea branches not only have high biological activity, but also have broad application prospects, providing scientific basis for their development in functional foods, health products, and other related fields, and opening up new paths for the resource utilization of tea waste.

2. Materials and methods

2.1. Tea polysaccharide extraction

This study selected waste tea leaves, which were trimmed after the spring tea harvest in Shaoxing, as raw materials. The study explored the efficiency of two extraction methods: Traditional water extraction and subcritical water extraction, and conducted multiple parallel comparative experiments. Tea leaves, as common waste materials in the tea industry, are rich in tea polysaccharides, phenolic compounds, and other bioactive components, showing great potential for development. By employing effective extraction processes, these beneficial components can be recovered, not only achieving waste utilization but also providing new ideas for adding value to the tea industry chain.

Traditional water extraction is a commonly used method, where tea leaves or tea stems are crushed and mixed with water, then heated to a certain temperature and maintained for a specific period. The solubility and thermodynamic properties of water are utilized to extract tea polysaccharides from the plant.

Subcritical water extraction is an extraction technique [27] in which water, acting as a solvent in a subcritical state (temperature and pressure between liquid and gas phases), is used. This method has high solubility and low solvent consumption. This study employed the subcritical water extraction method to obtain tea polysaccharides by modifying parameters such as the water temperature (130 ℃).

2.2. Experimental study on the hydroxyl radical scavenging activity of tea polysaccharides

The scavenging activity of different tea polysaccharides was measured using the D-deoxyribose-iron system method. The main reagents used include deoxyribose (DR), AR grade, Sigma-Aldrich Co., USA; thiobarbituric acid (TBA), AR grade and other reagents. The experiment was conducted in phosphate-buffered saline (PBS) at a pH of 7.4 to simulate physiological conditions. It was performed at 37 ℃ to mimic the internal environment of the human body.

2.3. Cell viability

RAW 264.7 cells were obtained from a biotechnology company and maintained in DMEM medium containing 10% (v/v) fetal bovine serum (FBS). The cells were incubated at 36 ℃ in a 5% CO_2 atmosphere within a constant-temperature incubator. To evaluate the impact of different polysaccharides on cell viability, an MTT assay was conducted. The cells were seeded in 96-well plates at a density of 1×10^4 cells per well, and after incubation, polysaccharides were added at concentrations of 2, 4, 6, 8, and 10 mg/mL.

2.4. Measurement of TNF-α and IL-6 levels

The ELISA kits were used to measure TNF-α and IL-6 levels and the inhibitory effects of each polysaccharide on these markers in LPS-induced RAW 264.7 cells were evaluated.

2.5. Effect on immune function test

The test animals were healthy adult mice provided by the Animal Science Department. The experimental group of mice was administered tea polysaccharides orally, and their weight was recorded. The spleen and thymus were then weighed (wet weight), and the spleen index and thymus index (organ wet weight) were compared with the control group.

2.6. Statistical analysis

Data were analyzed using Excel 2016 and SPSS 20.0 software. The differences between groups were evaluated by One-way ANOVA, with pairwise comparisons conducted using Duncan's test. For data presented as percentages, a square root arc sine transformation was applied prior to variance analysis.

3. Results and discussion

3.1. Tea polysaccharide yield

As shown in **Table 1**, the subcritical water extraction method has a significant advantage over traditional water extraction in terms of tea polysaccharide yield. The average yield of tea polysaccharides is 1.72 times higher with subcritical water extraction compared to the traditional water extraction method. This result suggests that subcritical water extraction is more efficient at extracting tea polysaccharides from tea leaves, likely due to the stronger dissolving power of subcritical water under higher temperature and pressure conditions. This allows it to better break down the cell wall structure of the tea leaves, releasing more active components. Additionally, subcritical water has lower surface tension and stronger polarity, which enhances its interaction with tea polysaccharide molecules, thus improving the extraction efficiency. During the experiment, the subcritical water extraction method not only increased the yield of tea polysaccharides but also demonstrated clear advantages in extraction time, typically requiring a shorter duration and lower energy consumption. Compared to traditional water extraction, subcritical water extraction is more environmentally friendly and energy-efficient, effectively reducing energy consumption and solvent use, in line with the development trend of modern green extraction technologies. Therefore, subcritical water extraction shows great potential in the extraction of tea polysaccharides, not only enhancing the yield of tea polysaccharides but also providing a new approach for the efficient use of tea leaves, with broad application prospects.

Table 1. Comparison of tea polysaccharide yields from subcritical water extraction and traditional water extraction.

	First experiment yield rate (%)	Second experiment yield rate (%)	Third experiment yield rate (%)	Fourth experiment yield rate (%)	Fifth experiment yield rate (%)	Average value (%)	Standard Deviation
Traditional water extraction method	12.79	13.24	14.16	12.09	11.44	12.74	1.05
Subcritical water extraction method	20.85	23.01	24.22	22.45	19.17	21.94	1.96

3.2. Antioxidant effects of tea polysaccharides

Oxidative stress is progressively acknowledged as a key factor in the onset of various chronic diseases, such as neurodegenerative conditions, diabetes, and certain types of cancer. Additionally, oxidative stress plays a significant role in the aging process, as the accumulation of oxidative damage to cellular structures—such as lipids, proteins, and DNA—leads to the deterioration of cell function and tissue integrity over time. This damage, caused by an excess of reactive oxygen species (ROS) like hydroxyl radicals (·OH), can overwhelm the body's antioxidant defense mechanisms, promoting the onset of various health issues. Therefore, the ability to mitigate oxidative damage by neutralizing free radicals is of immense therapeutic value.

Among natural antioxidants, tea polysaccharides have shown promising potential in reducing oxidative stress and its associated harm. Tea polysaccharides are complex carbohydrates extracted from tea leaves, which have been demonstrated to possess remarkable free radical scavenging properties. These polysaccharides are abundant in bioactive compounds, including sugars, flavonoids, and polyphenols, which contribute to their ability to interact with and neutralize harmful free radicals. In vitro studies have shown that tea polysaccharides can significantly reduce oxidative damage by scavenging free radicals, thus helping to protect cells from oxidative stress-induced injury. The free radical scavenging activity of tea polysaccharides is closely related to their concentration. The relationship between the concentration of tea polysaccharides and their ability to scavenge hydroxyl radicals (·OH) was shown in **Figure 1**. Each data point represents the average of three independent experiments, with error bars added to reflect the variability of the data. From the figure, it is apparent that as the concentration of tea polysaccharides increases, the scavenging ability also strengthens. This trend occurs because, with higher concentrations, there are more molecules of tea polysaccharides available to interact with free radicals, effectively neutralizing them. The polysaccharide molecules contain functional groups capable of binding to reactive radicals, such as ·OH, and converting them into stable, non-reactive products. The greater the number of polysaccharide molecules in solution, the greater the opportunity for these molecules to engage with and neutralize free radicals, resulting in a stronger scavenging effect.

This concentration-dependent relationship ($y = 8.8 + 6.1x$, $R^2 = 0.96$, where x is the polysaccharide concentration and y is the clearance rate) suggests that the effectiveness of tea polysaccharides in reducing oxidative stress can be enhanced by increasing their concentration. At elevated concentrations, the capacity to neutralize reactive oxygen species (ROS) is notably enhanced, helping to mitigate or prevent cellular damage induced by oxidative stress. Furthermore, the interactions between tea polysaccharides and free radicals lead to the formation of stable, harmless products, thus preventing the further generation of reactive radicals that could cause additional cellular harm.

The antioxidant potential of tea polysaccharides also provides broader implications for their role in health promotion. Chronic oxidative stress is affected by several age-related conditions, including heart disease and type 2 diabetes. The antioxidant properties of tea polysaccharides may play a significant role in slowing the development of these diseases. Furthermore, since oxidative stress is a major contributor to aging, incorporating tea polysaccharides into the diet or as a supplement could help slow the aging process by reducing cellular oxidative damage.

In summary, the capacity of tea polysaccharides to neutralize hydroxyl radicals and other ROS highlights their significant potential as natural antioxidants. The concentration-dependent increase in scavenging activity demonstrates that higher concentrations of tea polysaccharides can provide more effective protection against oxidative damage. This underscores the importance of understanding the optimal dosage and concentration for their use in both preventative and therapeutic contexts. With continued research into their bioactivity and clinical efficacy, tea polysaccharides could become a valuable tool in the fight against oxidative stress and its related health consequences.

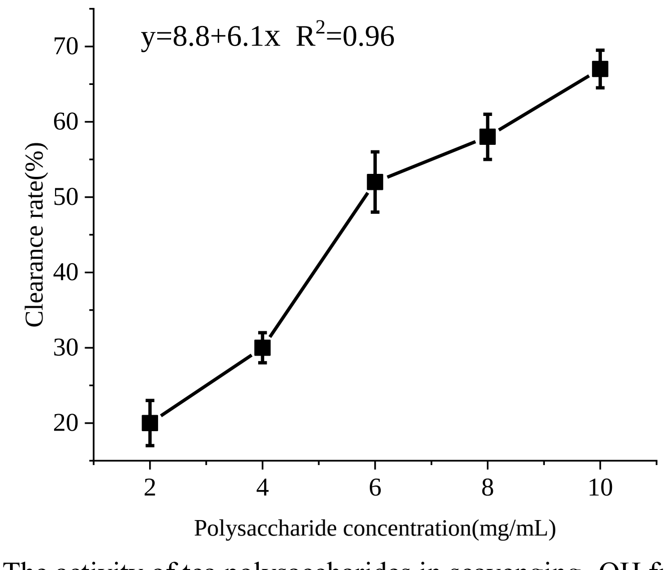

Figure 1. The activity of tea polysaccharides in scavenging ·OH free radicals.

3.3. Anti-inflammatory effects of tea polysaccharides

Chronic inflammation is a pathogenic factor in various diseases including cardiovascular diseases, diabetes, and cancer. Prolonged inflammatory responses can lead to tissue damage and exacerbate disease progression. As a natural bioactive compound, tea polysaccharides possess significant anti-inflammatory properties and can regulate the immune system through multiple mechanisms to inhibit inflammatory responses. Research indicates that tea polysaccharides exert their anti-inflammatory effects by regulating the function of immune cells.

As shown in **Figure 2**, the effect of tea polysaccharides on cell viability is concentration- and cell-type-dependent. At low concentrations, they help maintain cell health and promote cell proliferation, while at high concentrations, they may induce cell apoptosis or inhibit cell growth. This suggests that tea polysaccharides have potential applications in immune regulation, anti-inflammation, and anti-tumor activities.

Figures 3 and **4** demonstrate that tea polysaccharides can decrease the levels of inflammation-related factors such as TNF-α and IL-6, thereby alleviating the intensity of the inflammatory response. In experiments involving RAW 264.7 cells, tea polysaccharides were found to decrease the expression of TNF-α and IL-6, indicating their positive role in inhibiting the release of inflammatory factors. By modulating the secretion of these cytokines, tea polysaccharides help suppress excessive immune responses, thereby reducing the risk of chronic inflammation.

Additionally, tea polysaccharides can regulate the function of immune cells, influencing their proliferation, differentiation, and migration, further maintaining immune system balance and mitigating the negative impacts of inflammation. In conclusion, tea polysaccharides, as a natural anti-inflammatory agent, have significant potential for a wide range of applications, particularly in the prevention and treatment of inflammation-related diseases, offering a promising future.

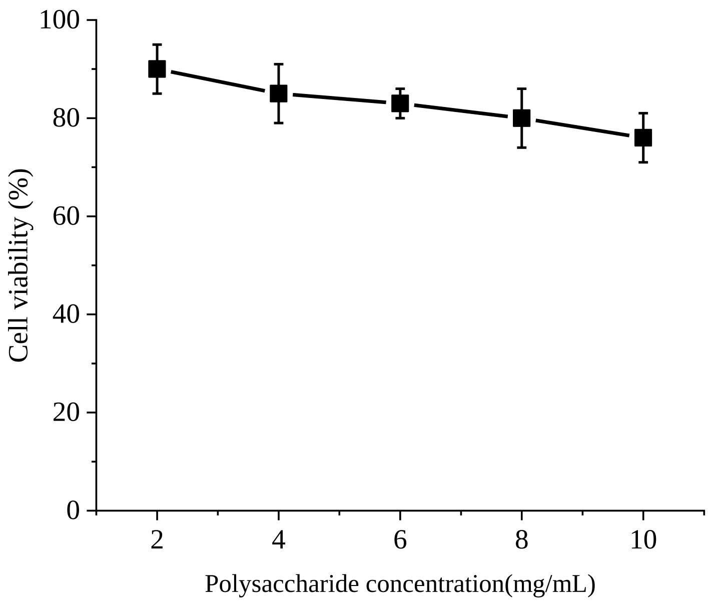

Figure 2. Effects of tea polysaccharides on cellular activity.

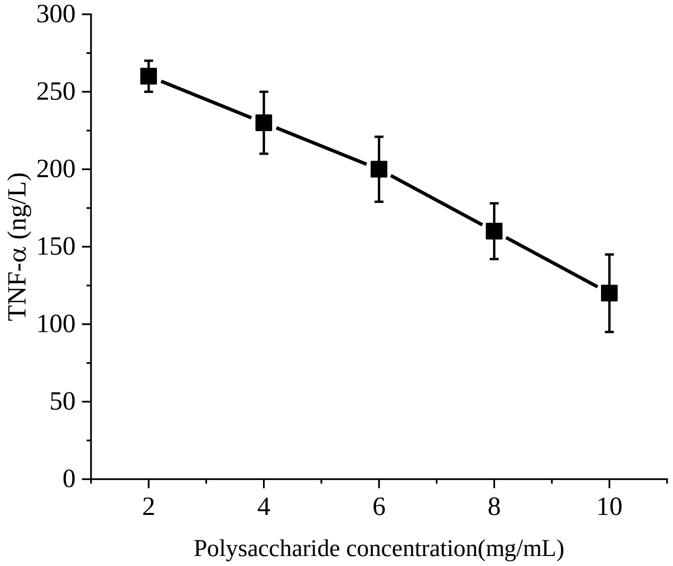

Figure 3. Effects of tea polysaccharides on TNF-α.

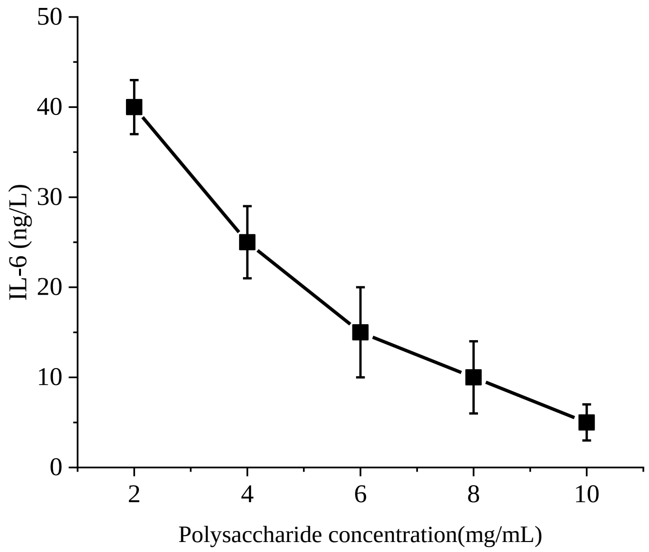

Figure 4. Effects of tea polysaccharides on IL-6.

To verify whether tea polysaccharides reduce TNF-α levels by inhibiting the NF-κB pathway, this study incorporated Western blot analysis. **Figure 5** demonstrates the effects of varying tea polysaccharide concentrations on the relative expression levels of NF-κB. The results showed that increasing tea polysaccharide intake significantly reduced TNF-α expression levels, as NF-κB is a central regulatory pathway in inflammatory responses, and its activation promotes the transcriptional activation of pro-inflammatory cytokines such as TNF-α.

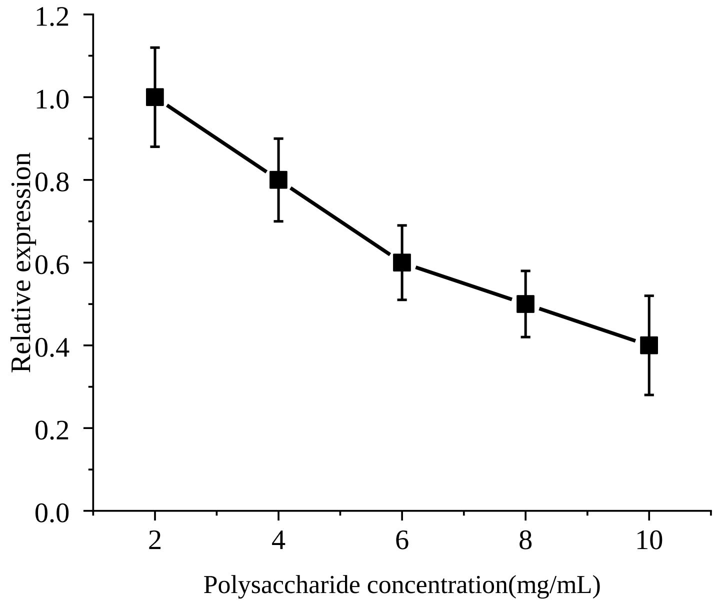

Figure 5. Effects of tea polysaccharides on relative expression.

Table 2 discusses the impact of tea polysaccharides on hemorheological parameters, which include the red blood cell aggregation index (RCA), red blood cell rigidity index (VR), and red blood cell deformability index (TK). It can be observed that the hemorheological parameters in the tea polysaccharide group were significantly reduced. Tea polysaccharide intervention can protect skeletal muscle, myocardium, and liver from damage, improve the metabolic state and blood rheology, and promote and accelerate the recovery of body functions.

Table 2. Changes in rheological indicators of blood cells.

	RCA	**VR**	**TK**
Control	4.35	6.78	20.42
TPS	4.03	4.51	26.19

Since the experimental design did not consider the distinctions between other anti-inflammatory drugs and tea polysaccharides, only the practical application potential of tea polysaccharides is discussed in this study. As a natural product, the efficacy of tea polysaccharides may exhibit dose-dependent responses. At low doses, they demonstrate beneficial effects such as anti-inflammatory and immunomodulatory activities. However, higher doses may induce toxic effects. Studies indicate that certain natural polysaccharides at elevated doses could lead to liver/kidney damage or immunosuppression [28]. Thus, determining the safe dosage range for tea polysaccharides is critical.

3.4. Immunomodulatory effects of tea polysaccharides

Tea polysaccharides exhibit significant immunomodulatory effects. Research indicates that tea polysaccharides would enhance the immune function by boosting the activity of immune organs, thereby improving overall immune status. As shown in **Table 3**, after 14 days of continuous oral administration of tea polysaccharides in the treated mice increased by 8.0% and 11.0%, respectively. The thymus are major immune organs, with the spleen playing an important role in filtering blood and removing antigens, while the thymus is the key site for T cell maturation and differentiation. Tea polysaccharides, through their action on these immune organs, significantly enhanced the immune response ability of the mice.

Specifically, tea polysaccharides exert immunomodulatory effects through various mechanisms. First, they can promote the activity and phagocytic function of macrophages, enhancing their ability to recognize and clear pathogenic microorganisms. Second, tea polysaccharides can affect the function of B cells, promoting antibody production and strengthening cellular immune responses. Furthermore, tea polysaccharides can activate various components of the immune system by modulating the IL-2 and TNF-α, thus enhancing the body's defense against pathogens. Studies have also shown that tea polysaccharides can motivate the proliferation of immune cells, particularly increasing the number of immune cells, thereby improving the function of these immune organs.

In conclusion, tea polysaccharides demonstrate potential as immunomodulators by enhancing the function of immune organs, promoting immune responses. The results from the 14-day oral administration experiment confirm that tea polysaccharides have a notable stimulating impact. on the immune system of mice, further supporting their value in enhancing immune function and improving the body's resistance.

Table 3. Effect of oral tea polysaccharides on the spleen and thymus of normal mice.

	Num. of animals	Body weight (g)	Spleen weight (mg)	Thymus weight(mg)
Control TPS	15	26.2	102	52.3
Treatment	15	25.9	110	58.2

3.5. Effect of tea polysaccharides on the biomechanical properties of cells

Cell migration plays a crucial role in injury repair, especially the migration of endothelial cells, which is a key process in angiogenesis. The scratch assay is a commonly used method to assess cell migration, reflecting the impact of substances on endothelial cell migration capacity. In vivo studies have shown that tea polysaccharides (TPS) can effectively control wound inflammation and promote wound healing. In vitro scratch assay results revealed that compared to the control group, after incubating with 0.5 mg/mL TPS for 12 and 24 h, the migration distance of human umbilical vein endothelial cells (HUVECs) increased by 70.1% and 61.3%, respectively (**Figure 6**). When treated with 1 mg/mL TPS, the migration distances increased by 123.1% and 105.9%, respectively. These results suggest that TPS significantly promotes the migration of HUVECs, thereby aiding in wound repair.

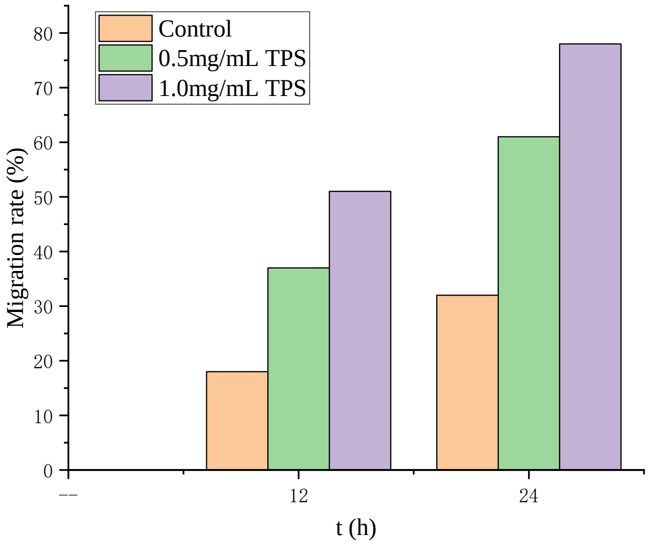

Figure 6. Migration rate of HUVECs in culture media.

4. Conclusion

This study successfully extracted tea polysaccharides from discarded tea leaves and tea stems using subcritical water extraction and explored the effects of various extraction conditions on the yield of tea polysaccharides. The results show that subcritical water extraction is an advanced method for obtaining tea polysaccharides, which can maximize the extraction of active components from tea leaves and stems under relatively mild conditions, with a favorable yield of the extract. Analysis of the physicochemical properties of the extracts reveals that the tea polysaccharides have high solubility and stability in water, providing a solid foundation for their further applications.

In terms of biological activity, the extracted tea polysaccharides exhibited significant antioxidant effects and were effective in scavenging hydroxyl radicals. The hydroxyl radical scavenging experiment demonstrated strong antioxidant capacity, which can reduce cellular damage caused by free radicals. This suggests that tea polysaccharides have promising anti-aging potential and may offer protective effects against oxidative stress-related diseases. Further cell viability experiments showed that tea polysaccharides promoted cell proliferation and growth, demonstrating good biocompatibility and making them suitable for health product development.

Additionally, tea polysaccharides also exhibited notable anti-inflammatory properties. In experiments, tea polysaccharides significantly reduced the levels of TNF-α and IL-6, indicating that they can effectively suppress inflammatory responses. This characteristic suggests that tea polysaccharides have potential applications in the prevention of inflammation-related diseases.

Immunomodulatory tests further demonstrated the effect of tea polysaccharides on immune system regulation. Tea polysaccharides notably boosted the immune response in mice, as reflected by increased spleen and thymus indices and heightened immune cell activity. These findings suggest that tea polysaccharides may not only influence the proliferation of immune cells but also stimulate the immune system, thereby improving overall immune resistance.

The biomechanical characteristics of cells, including elasticity, membrane stiffness, and tissue flexibility, were evaluated to explore how tea polysaccharides influence cellular and tissue mechanics.

In conclusion, tea polysaccharides exhibit excellent biological activities in terms of antioxidant, anti-inflammatory, and immune modulation. Moreover, they provide a new solution for the resource use of discarded tea leaves and stems. These findings offer theoretical support for the development of functional foods or health supplements based on tea polysaccharides and provide broad prospects for their applications in the health product.

Author contributions: Conceptualization, HL and JZ; methodology, HL; formal analysis, HL; investigation, JZ; data curation, HL; writing—original draft preparation, HL; writing—review and editing, JZ; funding acquisition, JZ. All authors have read and agreed to the published version of the manuscript.

Ethical approval: Not applicable.

Funding: This work was supported by 2024 Shaoxing science and technology agriculture special project(2024A12001).

Conflict of interest: The authors declare no conflict of interest.

References

1. Ouyang J, Zhou F, Lu DM, et al. Research progress of tea polysaccharides in regulating obesity (Chinese). Journal of Tea Science. 2020; 40(5): 565–575.
2. Chen G, Yuan Q, Saeeduddin M, et al. Recent advances in tea polysaccharides: Extraction, purification, physicochemical characterization and bioactivities. Carbohydrate Polymers. 2016; 153: 663–678.
3. Weng W, Li S, Zhang Q, et al. Research progress of composition and health function of tea polysaccharide (Chinese). China Journal of Traditional Chinese Medicine and Pharmacy. 2021; 36(12): 7261–7264.
4. Hu T, Wu P, Zhan J, et al. Structure variety and its potential effects on biological activity of tea polysaccharides. Food Science and Human Wellness. 2022; 11(3): 587–597.
5. Chen H, Wang Z, Qu Z, et al. Physicochemical characterization and antioxidant activity of a polysaccharide isolated from oolong tea. European Food Research and Technology. 2009; 229(4): 629–635.
6. Yang X, Huang M, Qin C, et al. Structural characterization and evaluation of the antioxidant activities of polysaccharides extracted from Qingzhuan brick tea. International Journal of Biological Macromolecules. 2017; 101: 768–775.
7. Chen G, Wang M, Xie M, et al. Evaluation of chemical property, cytotoxicity and antioxidant activity in vitro and in vivo of polysaccharides from Fuzhuan brick teas. International Journal of Biological Macromolecules. 2018; 116: 120–127.
8. Wang H, Chen J, Ren P, et al. Ultrasound irradiation alters the spatial structure and improves the antioxidant activity of the yellow tea polysaccharide. Ultrasonics Sonochemistry. 2021; 70: 105355.
9. Zheng Q, Li W, Zhang H, et al. Optimizing synchronous extraction and antioxidant activity evaluation of polyphenols and polysaccharides from Ya'an Tibetan tea (Camellia sinensis). Food Science & Nutrition. 2019; 8(1): 489–499.
10. Xu P, Chen H, Wang Y, et al. Oral administration of puerh tea polysaccharides lowers blood glucose levels and enhances antioxidant status in alloxan-induced diabetic mice. Journal of Food Science. 2012; 77(11): 246–252.
11. Guo R, Zhang J, Liu X, et al. Pectic polysaccharides from Biluochun tea: A comparative study in macromolecular characteristics, fine structures and radical scavenging activities in vitro. International Journal of Biological Macromolecules. 2022; 195: 598–608.
12. Tang Y, Sheng J, He X, et al. Novel antioxidant and hypoglycemic water-soluble polysaccharides from jasmine tea. Foods. 2021; 10(10): 2375.
13. Fan M, Zhu J, Qian Y, et al. Effect of purity of tea polysaccharides on its antioxidant and hypoglycemic activities. Journal of Food Biochemistry. 2020; 44(8): e13277.

14. Liu LQ, Li HS, Nie SP, et al. Tea polysaccharide prevents colitis-associated carcinogenesis in mice by inhibiting the proliferation and invasion of tumor cells. International Journal of Molecular Sciences. 2018; 19(2): 506.
15. Wang Y, Chen J, Zhang D, et al. Tumoricidal effects of a selenium (Se)-polysaccharide from Ziyang green tea on human osteosarcoma U-2 OS cells. Carbohydrate Polymers. 2013; 98(1): 1186–1190.
16. Wang H, Shi S, Bao B, et al. Structure characterization of an arabinogalactan from green tea and its anti-diabetic effect. Carbohydrate Polymers. 2015; 124: 98–108.
17. Li S, Chen H, Wang J, et al. Involvement of thePI3K/Akt signal pathway in the hypoglycemic effects of tea polysaccharides on diabetic mice. International Journal of Biological Macromolecules. 2015; 81: 967–974.
18. Chung JO, Yoo SH, Lee YE, et al. Hypoglycemic potential of whole green tea: Water-soluble green tea polysaccharides combined with green tea extract delays digestibility and intestinal glucose transport of rice starch. Food & Function. 2019; 10(2): 746–753.
19. Zhao Y, Chen H, Li W, et al. Selenium-containing tea polysaccharides ameliorate DSS-induced ulcerative colitis via enhancing the intestinal barrier and regulating the gut microbiota. International Journal of Biological Macromolecules. 2022; 209: 356–366.
20. Kim J, Choi H, Choi DH, et al. Application of green tea catechins, polysaccharides, and flavonol prevent fine dust induced bronchial damage by modulating inflammation and airway cilia. Scientific Reports. 2021; 11(1): 2232.
21. Liu LQ, Nie SP, Shen MY, et al. Tea polysaccharides inhibit colitis-associated colorectal cancer via interleukin-6/STAT3 pathway. Journal of Agricultural and Food Chemistry. 2018; 66(17): 4384–4393.
22. Cheng L, Chen L, Yang Q, et al. Antitumor activity of Se-containing tea polysaccharides against sarcoma 180 and comparison with regular tea polysaccharides and Se-yeast. International Journal of Biological Macromolecules. 2018; 120: 853–858.
23. Wang ZM, Li L, Guo SY, et al. Review on structure-activity relationship of active polysaccharides (Chinese). Modern Chemical Industry. 2002; 8: 18–21, 23.
24. Yang Y, Liu J, Tan Y, et al. Progress inunderstanding the structure-activity relationship and hypaglycemic mechanism of polysaccharides. Food Science. 2021; 42(23): 355–363.
25. Zhang W, Jiang H, Rhim JW, et al. Tea polyphenols (TP): A promising natural additive for the manufacture of multifunctional active food packaging films. Critical Reviews in Food Science and Nutrition. 2022; 63(2): 288–301.
26. Yao J, Liu H, Ma C, et al. A review on the extraction, bioactivity, and application of tea polysaccharides. Molecules. 2022; 27(15): 4679.
27. Cheng Y, Xue F, Yu S, et al. Subcritical water extraction of natural products. Molecules. 2021; 26(13): 4004.
28. Hou C, Chen L, Yang L, et al. An insight into anti-inflammatory effects of natural polysaccharides. International Journal of Biological Macromolecules. 2020; 153: 248–255.