Food Chemistry: X 19 (2023) 100844

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x

Effects of electromagnetic roller-hot-air–steam triple-coupled fixation on reducing the bitterness and astringency and improving the flavor quality of green tea

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A R T I C L E I N F O

Keywords:
Green tea
Roller-hot-air–steam triple-coupled fixation
Catechins
Free amino acids
Chlorophyll
Bitterness
Astringency

A B S T R A C T

Despite the importance of fixation in determining green tea quality, its role in reducing the bitter and astringent taste of this beverage remains largely unknown. Herein, an electromagnetic roller-hot-air–steam triple-coupled fixation (ERHSF) device was developed, and its operating parameters were optimized (steam volume: 20 kg/h; hot-air temperature: 90 °C; hot-air blower speed: 1200 r/min). Compared with conventional fixation treated samples, the ratio of tea polyphenols to free amino acids and ester-catechins to simple-catechins in ERHSF-treated samples was reduced by 11.0% and 3.2%, reducing bitterness and astringency of green tea; amino acids, soluble sugars, and chlorophyll contents were significantly increased, enhancing the freshness, sweetness, and greenness; the color indexes, such as *L*/*L** value of brightness and -*a*/-*a** value of greenness, were also improved, and ERHSF-treated samples had the highest sensory scores. These results provided theoretical support and technical guidance for precise quality improvement of summer-autumn green tea.

1. Introduction

Green tea is the most widely produced and consumed tea in China. In 2021, its production and sales reached 1.8494 and 1.31 million tons, respectively, accounting for 60.37% and 56.87% of the total in China (Mei & Liang, 2021). Green tea characteristically has a green appearance, a green liquor color, and a green infused leaf, in addition to a fresh brisk taste and a highly clean-pure aroma. Owing its unique sensory quality and potential health-promoting effects (e.g., anti-cancer, anti-oxidant, anti-inflammatory, and anti-bacterial properties, in addition to blood lipid metabolism regulation), green tea has become increasingly popular among consumers (Fang et al., 2019; Makiuchi et al., 2016; Yang, Wang, & Sheridan, 2018). Although the yield of summer-autumn green tea is significantly higher than that of spring tea ($P < 0.05$), the former contains significantly higher levels of bitter taste substances, such as tea polyphenols (TPs) and caffeine, and lower levels of fresh and sweet taste substances, such as free amino acids and soluble sugars, thereby having a bitter and poor umami taste and an overall low economic benefit (Shi et al., 1984; Xu et al., 2012). It is, therefore, essential to improve the flavor quality and economic value of summer-autumn green tea.

Fixation is the key process responsible for flavor formation in green tea. During fixation, the activity of the polyphenol oxidase enzyme is rapidly reduced at elevated temperatures, thereby preventing the oxidation of TPs and maintaining the green color of the tea and liquor (Li et al., 2022). In addition, high temperatures promote the loss of moisture and grassy volatiles from the leaves, while generating and accumulating new aroma compounds and promoting the degradation of proteins and polysaccharides; this process is conducive to the accumulation of fresh-sweet taste substances, such as free amino acids and soluble sugars

Abbreviations: ERHSF, Electromagnetic roller-hot-air–steam triple-coupled fixation; TCF, three coupled fixation; ERF, Electromagnetic roller fixation; ERHF, Electromagnetic roller-hot-air coupled fixation; ERSF, Electromagnetic roller-steam coupled fixation; QMWVs, Quality material weighted values; EGCG, Epi-gallocatechin-3-gallate; ECG, Epicatechin gallate; EGC, Epigallocatechin; EC, Epicatechin; GCG, Gallocatechin gallate; CG, Catechin gallate; GC, Gallocatechin; C, Catechin; TSC4, Total 4-types of simple-catechins; TETC4, Total 4-types of ester-catechins; TAC8, Total amount of catechins; TETC4/TSC4, Ratio of total ester-catechins to simple-catechins; TPs, Tea polyphenols; AAs, Amino acids; TPs/AAs, Ratio of tea polyphenols to total free amino acids.

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https://doi.org/10.1016/j.fochx.2023.100844
Received 24 November 2022; Received in revised form 11 August 2023; Accepted 16 August 2023
Available online 19 August 2023

(Wang et al., 2021). Currently, the main fixation methods employed during the production of green tea include rolling fixation, pan-frying fixation, hot-air fixation, steam fixation, and microwave fixation. The use of different methods and parameters is beneficial in terms of varying the contents and ratios of the tea quality components while determining the characteristic flavors of the final products (Ma, Shi, & Qian, 2012). For example, microwave and steam fixation involve rapid heat transfer and strong penetration that are conducive to the formation of the green appearance, liquor color, and infused leaves; however, they tend to result in a poor aroma and an undesirable taste (Ye et al., 2019). Hot-air fixation involves a short heating time and is conducive to the formation of a pleasant aroma and a mellow taste; however, it tends to generate rapid water loss from the leaf edges, resulting in charred edges and a yellow leaf color (Zhu, Yue, & Yuan, 2009). Roller fixation and pan-frying fixation are conducive to the formation of a pleasant aroma and a mellow-brisk taste (Wang et al., 2020b). Roller fixation is widely adopted during processing because of its high production efficiency and its ability to allow continuous processing and achieve high-quality fixated leaves. In this context, the use of electromagnetic roller fixation to impart high-precision temperature control and efficiently utilize the heat energy has received growing interest (Hua et al., 2015). Pan-frying fixation is also a key technique in the processing of famous green teas, such as West Lake Longjing, owing to its low investment costs and high flexibility; however, it has a low production efficiency (Shi et al., 2022).

To date, most studies into green tea fixation have focused on spring tea, and no systematic study has been carried out into the technology involved in the processing of summer-autumn green tea and its role in improving the quality of this beverage. Although pan-frying fixation and roller fixation are conducive to the formation of an obvious chestnut aroma, they promote a bitter taste (Flaig, Qi, Wei, Yang, & Schieberle, 2020; Qi et al., 2016). In addition, steam-hot-air fixation can reduce the contents of bitter substances generated, such as anthocyanins and flavonoid glycosides; however, this technique tends to lead to a poor tea color attributes (Ao, Tang, Zhang, Gong, & Gu, 2011). Overall, the limits of existing studies on conventional fixation methods have prevented improvement in the total aroma, taste, and color quality characteristics of summer-autumn green tea.

Based on the widely adopted roller fixation, this study aimed to develop a novel heating technology that combined three fixation methods (electromagnetic roller, steam, and hot-air), namely the electromagnetic roller-hot-air–steam triple-coupled fixation (ERHSF) device (Chinese patent No. ZL 201820841750.5). Considering the hot-air temperature, hot-air blower speed, and steam volume as key control parameters, orthogonal design and range analysis were adopted to investigate the importance of the various technical parameters of the ERHSF process, and the optimal parameters for summer-autumn tea processing were determined according to the contents of characteristic biochemical components and sensory evaluation scores. Subsequently, the optimized ERHSF procedure was compared with three conventional methods that are widely adopted during green tea production. Through a comprehensive analysis of the characteristic biochemical components, objective quantitative indicators of the tea appearance and tea liquor, and overall sensory quality, we determined the optimal fixation method for summer-autumn green tea using the ERHSF device. This study proposed a novel fixation technology to comprehensively improve the flavor, appearance, and liquor of summer-autumn tea. Our findings provide theoretical basis and guidance for future studies on green tea processing.

2. Structural composition and technical characteristics of the ERHSF device

The ERHSF device (Fig. 1) consisted of rollers, an electromagnetic heating system, a hot-air generation system, a steam generation system, and a dehumidification device. This equipment was based on the hot-air-roller coupled fixation machine (Chinese patent No. ZL201410473680.9), and the electromagnetic heating technology was adopted to heat the cylinder, thereby integrating roller, steam, and hot-air fixation methods. In this device, an electromagnetic heat source with a thermal efficiency of >45% was employed (Hua et al., 2015), and the three-stage electromagnetic heating system satisfied the "high first and then low" technical requirements of the fixation temperature while achieving precise temperature control (fluctuation degree ±2 ℃). In addition, the solid, liquid, and gas phases involved in the process were integrated to maximize the advantages of the three heating sources during fixation. Furthermore, the design based on implantation of the steam conveying pipe at the front, positioning of the hot-air conveying pipe at the back, and the presence of a large-to-small steam aperture guarantees both enzyme inactivation and a quality improvement for the finished green tea. Moreover, the placement of a dehumidification device at the leaf outlet end ensured that the ambient humidity in the roller does not become excessive during the latter stages of fixation, ultimately preventing the product from turning yellow and undergoing deterioration.

3. Materials and methods

3.1. Experimental materials and reagents

Fresh tea leaves (a bud with two or three leaves, moisture content ~75%) of Zhongcha 108 (*Camellia sinensis L.*) obtained on July 16, 2020, from Yuyao city (Zhejiang, China) were selected for this study. All chromatographic grade standards were purchased from the Shanghai

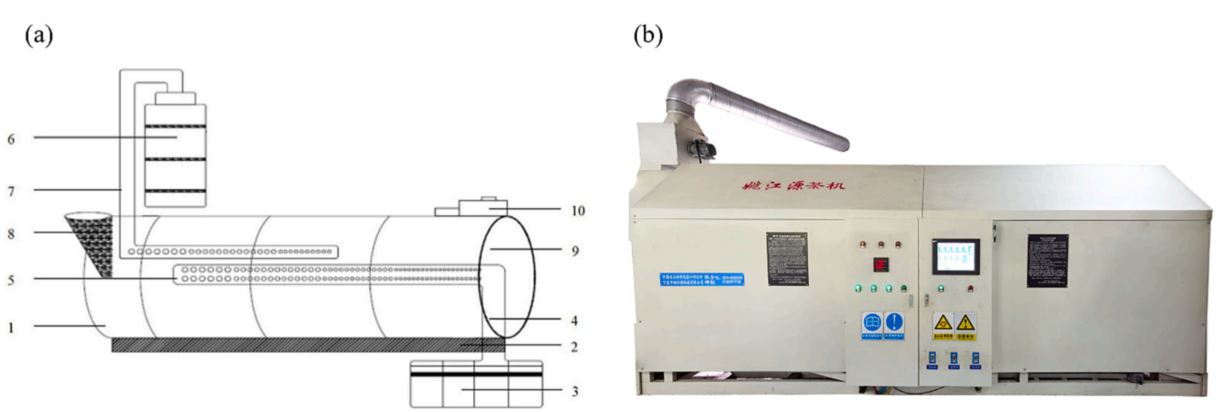

Fig. 1. Design and physical images of the electromagnetic roller-hot-air–steam triple-coupled fixation. (a) design image and (b) physical image. In (a), the numbered components are as follows: 1 = drum; 2 = electromagnetic heating system; 3 = hot-air generator; 4 = hot-air duct; 5 = circular hole; 6 = steam generator; 7 = steam duct; 8 = inlet device; 9 = outlet end; and 10 = dehumidification device.

Yuanye Biological Technology Company (Shanghai, China), and the purities of these chemical standards were ≥98% in all cases.

3.2. Experimental methods

3.2.1. Experimental design

Three factors were investigated, namely the steam volume (code A), hot-air temperature (code B), and hot-air blower speed (i.e., hot-air volume, code C). Three levels were set for each factor to carry out an L9 (3^3) orthogonal test and range analysis. Optimization of the ERHSF parameters was conducted using the factor design parameters outlined in Table 1. Through sensory evaluation and analysis of the characteristic biochemical contents of the green tea samples, the optimal parameters were determined. Subsequently, the ERHSF technique was compared with three conventional fixation methods, namely electromagnetic roller fixation (ERF), electromagnetic roller-hot-air coupled fixation (ERHF), and electromagnetic roller-steam coupled fixation (ERSF), in terms of the key functional and quality components of the final tea products, including the contents of free amino acids (AAs, Zhang et al., 2022), tea polyphenols (TPs, Liu et al., 2014), chlorophyll (Prawira-Atmaja et al., 2018), soluble sugars (Huang et al., 2022), catechins (Hung et al., 2018), and caffeine (Tfouni, Camara, Kamikata, Gomes, & Furlani, 2018). In addition, objective quantitative indicators, such as tea appearance and liquor color, and sensory quality were considered as evaluation indicators for comprehensive analysis to investigate the effect of ERHSF on reducing the bitterness and astringency and improving the overall green tea quality.

3.2.2. Green tea processing

With the fresh tea leaves of Zhongcha 108 as the raw material, the manufacturing process consisted of the following steps:

1) Spreading: The fresh tea leaves were spread using a continuous tea-spreading machine (YJY-20 M, Yuyao Yaojiangyuan Tea Machine Co., Ltd., Zhejiang, China) for 12 h at 23 °C and 60% relative humidity until the leaf moisture content reaches ~ 70%.
2) Fixation: The spread tea leaves were fixated using an electromagnetic roller-hot-air–steam triple-coupled tea fixation machine (YJY-GH4550-80B, Yuyao Yaojiangyuan Tea Machine Co., Ltd., Zhejiang, China) under a three-stage temperature program of 260 + 240 + 220 °C, hot-air blower speed of 1400 r/min, fixation time of 2.0 min, and leaf delivery rate of 110 kg/h.
3) Rolling: After allowing the spread leaves to cool for 1 h, the fixated tea leaves were rolled using a continuous tea rolling machine (YJY-55, Yuyao Yaojiangyuan Tea Machine Co., Ltd., Zhejiang, China) for 35 min according to a pressure combination of no pressure (gland down to 5 cm) for 10 min, light pressure (gland down to 10 cm) for 10 min, moderate pressure (gland down to 15 cm) for 10 min, and light pressure (gland down to 10 cm) for 5 min, with a rolling frequency of 45 r/min.
4) First drying: The rolled tea leaves were dried using a fuel-type hot-air tea dryer (YJY-RY-25, Yuyao Yaojiangyuan Tea Machine Co., Ltd., Zhejiang, China) for 9.0 min at 110 °C with a chain plate transmission speed of 900 r/min and a hot-air blower speed of 1200 r/min.
5) Second drying: After allowing the leaves to cool for 30 min, they were subjected to a second drying process for 11.5 min at 110 °C, with a chain plate transmission speed of 750 r/min and a hot-air blower speed of 1200 r/min.

3.2.3. Control parameters for the fixation tests

Referring to the literature (Hua et al., 2015; Yuan et al., 2013), a single or two-phase coupled fixation method was set up for comparative tests according to the following fixation parameters:

Control 1 (ERF): Roller temperature = 260 + 240 + 220 °C, roller speed = 1400 r/min, fixation time = 2.0 min;

Control 2 (ERHF): Hot-air temperature = 110 °C, hot-air blower speed = 1050 r/min, roller temperature = 260 + 240 + 220 °C, roller speed = 1400 r/min, fixation time = 2.0 min;

Control 3 (ERSF): Steam volume = 25 kg/h, roller temperature = 260 + 240 + 220 °C, roller speed = 1400 r/min, fixation time = 2.0 min.

3.3. Analysis of main biochemical components, objective indicators, and sensory quality

3.3.1. Determination of main biochemical components

The tea polyphenol content was determined according to the Folin-Ciocalteu colorimetric method, while the free amino acid content was determined using the ninhydrin colorimetry method (Hua et al, 2021). The total soluble sugar content was determined using the anthrone-sulfuric acid colorimetric method (Wang et al, 2022).

The chlorophyll content was determined using a Shimadzu spectrophotometer (UV-3600, Suzhou, China) (Wang et al., 2022). Briefly, 0.1 g of finely ground tea sample was mixed with 1 mL of absolute ethyl

Table 1
Orthogonal design of parameter optimization of ERHSF and results of quality components and total score of sensory quality.

No.	Test factor levels			Indicators evaluated							
	Steam quantity (A) /kg·h^{-1}	Hot-air temperature (B) /°C	Hot-air blower speed (C) /r·min^{-1}	Amino acids/%	Polyphenols/ %	Chlorophyll/ mg. g^{-1}	Soluble sugars/%	Catechins/ %	Caffeine/ %	Quality material weighted values/%	Score of sensory quality
1	30	130	900	3.65 ± 0.01	17.12 ± 0.02	2.03 ± 0.01	5.19 ± 0.07	12.4 ± 1.06	0.83 ± 0.03	8.12 ± 0.18	86.65 ± 0.26
2	20	110	1200	5.38 ± 0.01	17.63 ± 0.04	2.13 ± 0.01	6.52 ± 0.07	17.18 ± 0.38	1.49 ± 0.00	9.67 ± 0.08	87.90 ± 0.53
3	30	90	1200	4.82 ± 0.01	16.81 ± 0.03	1.86 ± 0.00	6.93 ± 0.01	16.97 ± 0.24	1.40 ± 0.02	9.32 ± 0.05	87.50 ± 0.38
4	20	130	1050	3.54 ± 0.00	17.43 ± 0.02	1.76 ± 0.00	4.47 ± 0.00	9.60 ± 0.12	0.91 ± 0.02	7.62 ± 0.03	85.90 ± 0.21
5	25	130	1200	4.40 ± 0.01	18.43 ± 0.01	1.74 ± 0.04	4.28 ± 0.10	10.61 ± 0.71	1.09 ± 0.05	8.22 ± 0.13	85.25 ± 0.31
6	30	110	1050	4.13 ± 0.02	18.10 ± 0.07	1.71 ± 0.01	4.11 ± 0.09	10.45 ± 0.41	0.96 ± 0.00	8.01 ± 0.10	85.30 ± 0.33
7	25	110	900	4.30 ± 0.01	18.40 ± 0.05	1.88 ± 0.02	4.36 ± 0.08	13.67 ± 1.24	1.05 ± 0.04	8.67 ± 0.22	85.70 ± 0.14
8	25	90	1050	4.84 ± 0.03	18.05 ± 0.07	1.72 ± 0.00	7.48 ± 0.07	19.98 ± 0.28	1.40 ± 0.01	10.15 ± 0.08	87.20 ± 0.27
9	20	90	900	4.32 ± 0.01	16.64 ± 0.01	2.21 ± 0.00	7.24 ± 0.02	17.88 ± 0.4	1.26 ± 0.04	9.36 ± 0.07	85.60 ± 0.31

alcohol, and 1 mL of distilled water and 50 mg reagent of a chlorophyll kit from Nanjing Jiancheng Bioengineering Institute (Nanjing, China) were added to the sample. The mixture was thoroughly ground in dark conditions, and the absorbance of chlorophyll *a* and chlorophyll *b* was determined using a Shimadzu (Suzhou, China) UV-3600 spectrophotometer at 663 nm and 645 nm after extraction for 3 h.

The contents of the caffeine and catechin components were determined using high-performance liquid chromatography (HPLC, Agilent 1100VL, Agilent Technologies Inc., CA, USA) (Hua et al., 2015). The tea infusions were filtered through a 0.22-μm Millipore filter before injection. The HPLC conditions with VWD detector for caffein and catechin composition were as follows: chromatographic column, WAT054275-C18 column, 5 μm and 4.6 mm × 250 mm; injection volume, 10 μL; column temperature 40 ℃; mobile phase A, 2% acetic acid and mobile phase B, acetonitrile with flow velocity, 1.0 mL/min; test wavelength, 280 nm; and gradient elution, mobile phase B subjected to the linear variation from 6.5 to 15% within 16 min, 15–25% at 16–25 min, 25–6.5% at 25–25.5 min, and maintained at 6.5% between 25.5 min and 30 min.

$$\text{Total 4} - \text{types of simple} - \text{catechin (TSC4)} = \text{C} + \text{EC} + \text{GC} + \text{EGC} \quad (1)$$

$$\text{Total 4} - \text{types of ester} - \text{catechin (TETC4)} = \text{CG} + \text{ECG} + \text{GCG} + \text{EGCG} \quad (2)$$

$$\text{Total amount of catechin (TAC8)} = \text{C} + \text{EC} + \text{GC} + \text{EGC} + \text{CG} + \text{ECG} + \text{GCG} + \text{EGCG} \quad (3)$$

Based on previous studies on bitter and astringent substances in tea (Ma et al., 2023; Liu et al., 2014; Xu et al., 2018; Yu et al., 2020; Zhang, Cao, Granato, Xu, & Ho, 2020), the quality material weighted values (QMWVs) of green tea quality components were calculated as below:

$$\text{QMWVs} = \text{tea polyphenol content} \times 20\% + \text{free amino acid content} \times 25\% + \text{soluble sugar content} \times 20\% + \text{total catechin content} \times 10\% + \text{caffeine content} \times 10\% + \text{chlorophyll content} \times 15\%. \quad (4)$$

3.3.2. Analysis of objective indicators

3.3.2.1. Appearance color. A Konica Minolta portable spectrophotometer (CM-600d, Shanghai, China) was used to measure the *L*, *a*, and *b* values of the appearance color of the tea samples. "*L*" represents brightness, "*a*" represents the red-green degree, and "*b*" represents the yellow-blue degree (Wang et al., 2020a).

3.3.2.2. Liquor color. A Konica Minolta tabletop spectrophotometer (CM-5 type, Shanghai, China) was used to measure the L^*, a^*, and b^* values of the tea liquor. "L^*" represents the translucent degree, "a^*" represents the red-green degree, and "b^*" represents the yellow-blue degree (Wang et al., 2020a).

3.3.3. Sensory evaluation

The sensory quality of each green tea sample was assessed by five professional tea tasters according to the National Standard of China (GB/T 23776–2018). The panelists were familiar with sensory experiments, all of whom have achieved a certificate for tea-quality evaluation of the Tea Scientific Society of China. Tea samples (50 g) were placed on standard white plates for dry-tea appearance evaluation, and 3 g of which were collected using the uniform heap-sampling method for liquor color, taste, and aroma evaluation. Boiling water (150 mL) was added to each corresponding teacup soaking for 5 min, and then the liquor and the leaves were separated immediately. The properties of the tea samples were examined in this order: aroma (hot scent), liquor color, aroma (warm scent), taste, aroma (cold-down scent), and leaf bottom (Yuan et al., 2018). The 100-score green tea quality grading system was adopted.

$$\text{Total sensory score} = \text{aroma score} \times 30\% + \text{taste score} \times 30\% + \text{dry tea appearance score} \times 20\% + \text{liquor color score} \times 20\% \quad (5)$$

3.4. Statistical analysis

All measurements were performed in triplicate and data were expressed as the mean ± standard deviation. SPSS 22.0 (SPSS, Chicago, IL, USA) was used for the orthogonal design and range analysis to determine the significant differences among the different treatment methods.

4. Results and discussion

4.1. Optimization of ERHSF process parameters

Biochemical substances and their contents determine green tea quality. Tea polyphenols, mainly catechins, are the most essential taste substances in tea liquor, which are responsible for bitterness and astringency, with a strong positive correlation between concentration and intensity (Xu et al., 2018; Zhang et al., 2020). Amino acids and soluble sugars impart a fresh and sweet taste to tea liquor, which in turn relieve its bitterness and astringency (Liu et al., 2014; Zhang et al., 2020). Caffeine has a bitter taste and interacts with theanine to enhance the umami taste of tea liquor (Yin et al., 2014). Meanwhile, chlorophyll is the component responsible for the greenness of the green tea.

As shown in Table 1 and Fig. 2, different fixation parameters had a distinct impact on various quality substances of the finished tea. The contents of free amino acids, caffeine, catechins, and soluble sugars were influenced to the greatest extent by hot-air temperature (B); the content of TPs was most affected by steam quantity (A), followed by hot-air temperature (B) and hot-air blower speed (C); and the chlorophyll content was most affected by hot-air blower speed (C). Moreover, the optimal fixation parameters for different quality biochemical components varied, such as A2B1C3 for higher content of free amino acids, A3B3C2 for lower content of catechins, A1B1C3 for higher content of soluble sugars and caffeine, and A1B1C1 for higher content of chlorophyll and lower content of TPs. Under thermal action, the dehydroxylation and decarboxylation reactions of amino acids can be enhanced (Wu et al., 2022), and the high-temperature moist condition during fixation promotes the hydrolysis of polysaccharides and the reaction between soluble sugars and amino acids (Qiu et al., 2022), as well as the degradation of chlorophyll (Donlao & Ogawa, 2019; Qiu et al., 2022). Furthermore, a lower temperature and a lower humidity were conducive to the accumulation of soluble sugars, free amino acids, and chlorophyll (Fig. 2). Overall, hot-air temperature of fixation had the highest impact on the quality components of summer-autumn green tea, with its optimal level at B1 (90 °C), and the optimal parameters varied for the different quality components.

To comprehensively analyze the influence of the three key ERHSF parameters on the quality components of green tea, the QMWVs were set

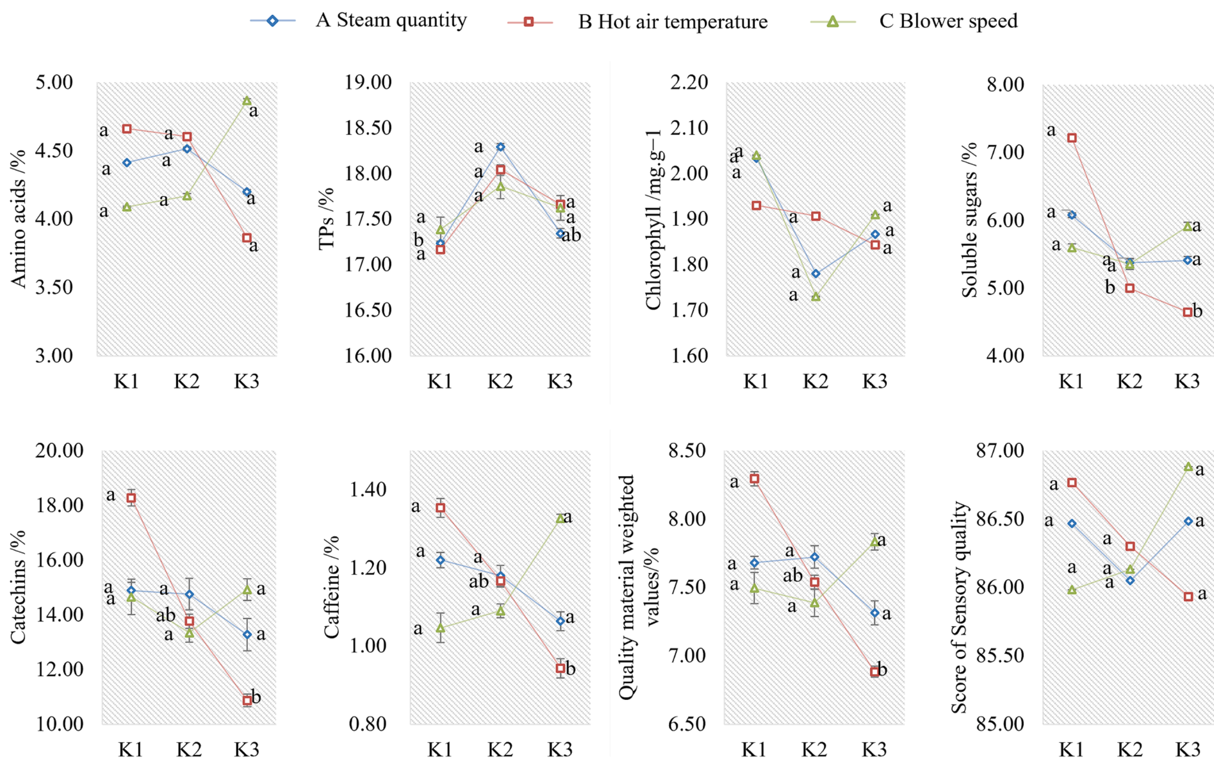

Fig. 2. Significance comparison of the impact factors and parameter optimization for the ERHSF technique based on various quality components and the total sensory quality score. Different letters indicate significant differences between the treatments, as determined based on the means of the LSD test ($P < 0.05$).

drawing on the research methods of previous studies (Hua et al., 2015; Yuan et al., 2013). Considering the total sensory scores of the finished tea samples (Fig. 2), the order factors affecting the QMWVs and total sensory scores were relatively consistent, i.e., B > A > C, indicating that the QMWVs could be used to represent the overall sensory quality of summer-autumn green tea. The optimal fixation parameters combinations were determined as A2B1C3 (steam volume, 25 kg/h; hot-air temperature, 90 °C; hot-air blower speed, 1200 r/min) and A1B1C3 (steam volume, 20 kg/h; hot-air temperature, 90 °C; hot-air blower speed, 1200 r/min). More specifically, a low air temperature and a high volume of hot-air were beneficial in improving the quality of summer-autumn green tea; and steam volume was mainly responsible for affecting the catechin content and proportion of the various catechins, which in turn influenced the QMWVs and sensory quality.

To obtain the optimal ERHSF parameters for summer-autumn green tea, the two parameter combinations of A2B1C3 and A1B1C3 were further compared (Table 2). Compared with the samples treated under A2B1C3, those treated according to A1B1C3 had significantly higher contents of chlorophyll, soluble sugars, total catechins, and caffeine ($P < 0.05$), lower content of TPs, and reduced value ($P < 0.05$) of TEC4/

Table 2
Comparison of the effects of different combinations of fixation parameters.

Column		Process combination of ERHSF			
		$A_2B_1C_3$ (steamquantity25 kg.h^{-1},hotairtemperature90 ℃,andhot air blower speed 1200r/min)		$A_1B_1C_3$ (steam quantity 20 kg.h^{-1}, hot air temperature 20 ℃, and hot air blower speed 1200 r/min)	
Chemical composition	Amino acid/%	4.64 ± 0.01^a		4.32 ± 0.01^a	
	Tea polyphenols/%	17.61 ± 0.02^a		16.79 ± 0.08^b	
	Chlorophyll/mg.g^{-1}	1.56 ± 0.02^b		2.21 ± 0.08^a	
	Soluble sugar/%	5.57 ± 0.02^b		6.44 ± 0.08^a	
	Catechin/%	12.07 ± 0.56^b		13.68 ± 0.52^a	
	Non-ester-catechin/%	2.20 ± 0.02^b		2.63 ± 0.02^a	
	Ester-catechin/%	9.87 ± 0.28^b		11.05 ± 0.28^a	
	TETC4/TSC4	4.48 ± 0.10^a		4.20 ± 0.10^b	
	Caffeine/%	1.04 ± 0.03^b		1.13 ± 0.03^a	
	QMWV/%	7.34 ± 0.07^a		7.54 ± 0.09^a	
		Description	Score	Description	Score
Sensory description	Appearance	Curly and tippy; yellowish green	87.00 ± 0.82^b	Curly and tippy; yellowish green and glossy	88.50 ± 0.41^a
	Liquor color	Yellowish green; barely bright	86.00 ± 0.41^b	Green; highly bright	89.00 ± 0.41^a
	Aroma	With the character of chestnut aroma	87.00 ± 0.82^b	Obviously with the character of chestnut aroma	89.00 ± 0.00^a
	Taste	Mellow and barely umami	86.00 ± 0.41^b	Umami, mellow and brisk	88.00 ± 0.82^a
	Total score of sensory quality	86.50 ± 0.32^b	88.60 ± 0.22^a		

Note: Different letters in the same row indicate significant differences between the treatments, as determined based on the means of the LSD test ($P < 0.05$).

TSC4. In addition, tea samples prepared according to A1B1C3 had a glossy yellowish greenness of tea appearance, bright greenness of tea liquor, obvious chestnut aroma, and umami taste, with a significantly higher sensory quality score than another ($P < 0.05$).

Indeed, previous studies have reported similar results. For example, compared with that treated with single-steam fixation, green tea treated with the combined steam-hot-air fixation had superior liquor, taste, and aroma qualities (Zhu et al., 2009). Meanwhile, underwent roller-hot-air–steam combination fixation was more favorable for the formation of desirable liquor color and chestnut aroma compared to the roller-steam combination fixation (Wang et al., 2020b). Therefore, we speculated that during roller fixation, the mutual effect of lower steam volume and air temperature promoted the degradation and conversion of TPs (Hua et al., 2015; Qiu et al., 2022), thereby affecting the catechin content and proportion of the various catechins. This promoted the degradation of proteins and polysaccharides to enrich the amino acid and soluble sugar contents under heating (all three conditions), thereby improving the flavor of green tea, and slowed the degradation of chlorophyll, preventing the appearance color change to yellow. Overall, these factors improved the quality of green tea, resulting in a fresh and mellow taste, glossy green appearance, and bright green liquor color.

4.2. Comparison of different fixation methods in determining green tea quality

Taking ERF, ERHF, and ERSF as the controls and adopting the

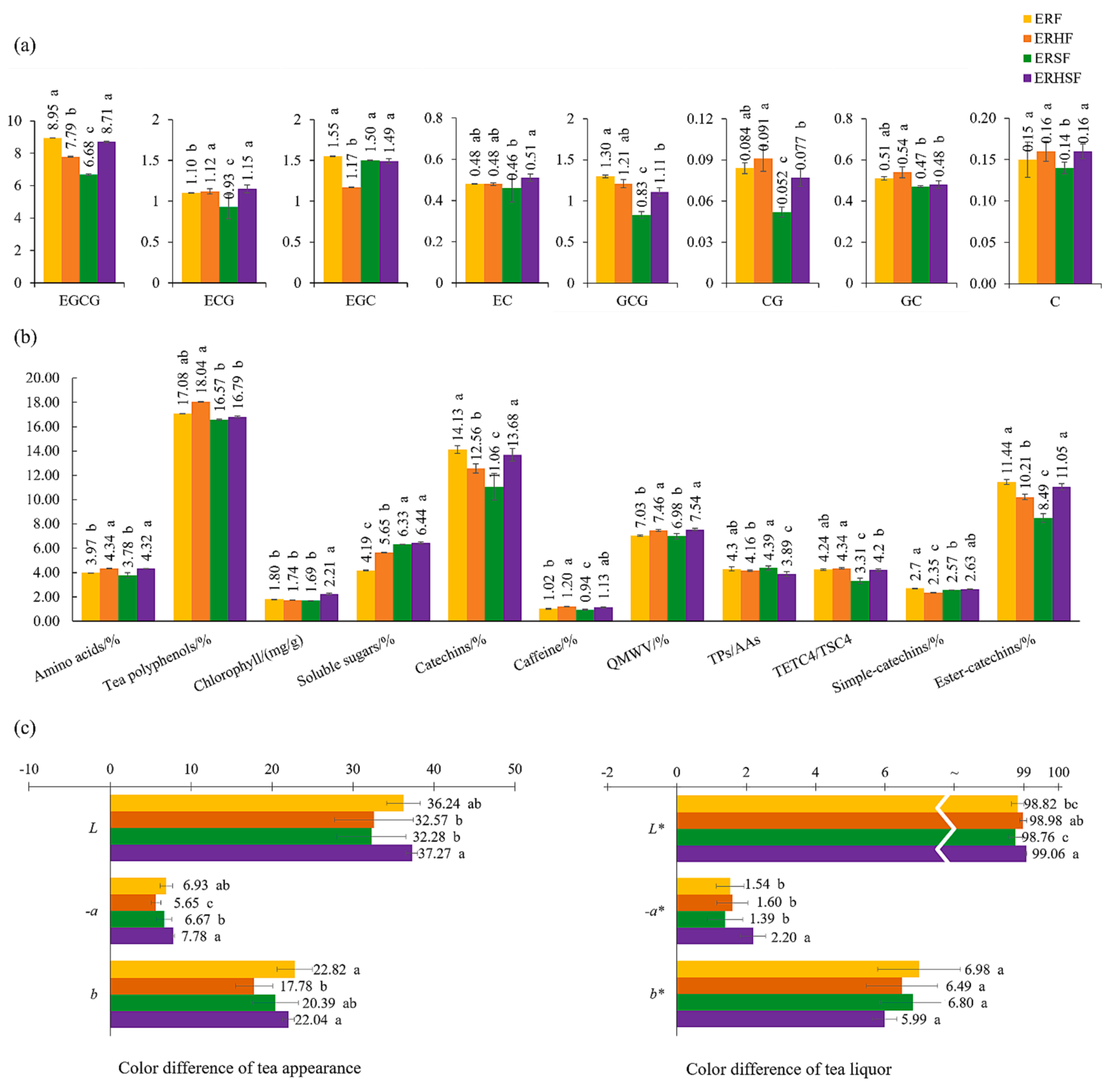

Fig. 3. Comparison of the green tea specimens prepared using different fixation methods. (a) Contents of eight catechins. (b) Quality component contents. (c) Appearance and liquor color quality indicators. ERF = electromagnetic roller fixation; ERHF = electromagnetic roller-hot-air coupled fixation; ERSF = electromagnetic roller-steam coupled fixation; ERHSF = electromagnetic roller-hot-air–steam triple-coupled fixation; L = translucent degree of appearance; a = red-green degree of appearance; b = yellow-blue degree of appearance; L^* = translucent degree of liquor; a^* = red-green degree of liquor; and b^* = yellow-blue degree of liquor. Different letters indicate significant differences between the treatments, as determined based on the means of the LSD test ($P < 0.05$).

optimal ERHSF parameters described above, the effects of the various fixation methods on the finished tea samples were evaluated in terms of the biochemical quality components, quantitative indicators, and sensory quality.

4.2.1. Effect of fixation methods on biochemical quality components

As shown in Fig. 3a and 3b, the contents of the various biochemical quality components in tea samples differed depending on the fixation method employed. Ester-catechins, such as EGCG, are the main bitter and astringent taste substances in tea liquor (Xu et al., 2018), while simple-catechins, such as EC, contribute to the sweetness of the tea liquor (Zhang et al., 2016). The tea samples treated with ERHSF exhibited lower TPs, GCG, GC, and CG contents and a lower TETC4/TSC4 value (ratio of total ester-catechins to simple-catechins) than those treated under conventional ERF ($P < 0.05$), indicating that a certain humidity during fixation was conducive to hydrolysis of the ester-catechins. In addition, the highest free amino acid and soluble sugar contents were obtained for the ERHSF-treated samples ($P < 0.05$), suggesting that a certain humidity during fixation was conducive to promoting polysaccharide hydrolysis and the accumulation of soluble sugars. Under these conditions, the fresh and sweet tastes of the tea liquor were enhanced, and these results were consistent with those of previous studies (Hua et al., 2015; Zhu et al., 2014).

Furthermore, it has been reported that the TPs/AAs value (ratio of tea polyphenols to total free amino acids) of green tea correlates positively with the bitterness of tea liquor and significantly negatively with freshness of tea liquor (Dong, Huang, Su, & Li, 2022; Liu et al., 2014; Shen et al., 2020). Tea samples treated with ERHSF had lower TPs/AAs ratios than those treated with conventional fixation approaches, and the novel ERHSF technique was beneficial in improving the sweet and fresh taste of green tea liquor.

The destruction and degradation of chlorophyll during fixation has previously been reported leading to a darkening of the green tea appearance (Wang et al., 2021). As shown in Fig. 3b, ERHSF was more conducive to the retention of chlorophyll than single or dual treatment fixation. Overall, these findings confirmed that the proposed ERHSF approach was superior to conventional fixation techniques in terms of quality improvement of summer-autumn green tea.

4.2.2. Effect of fixation methods on quantitative indicators

The quantitative indicators of color are widely used to judge tea appearance and tea liquor, as they can objectively and accurately reflect the color quality. As shown in Fig. 3c, the various fixation methods examined herein exhibited significantly different effects on the quantitative color indicators of the green tea appearance and liquor ($P < 0.05$). More specifically, the green tea treated with ERHSF exhibited the highest L, $-a$, L^*, and $-a^*$ values ($P < 0.05$); therefore, the combination of roller, steam, and hot-air treatment contributed to an improved brightness and greenness. This finding was consistent with the difference in chlorophyll contents in tea samples, further confirming that the chlorophyll content is positively correlated with the greenness of green tea appearance and liquor (Lai & Guo, 2012; Shu, Wang, Ouyang, Meng, & Tong, 2021). Overall, these results suggest that ERHSF treatment can maximize the quality of the summer-autumn green tea appearance and liquor.

4.2.3. Effect of fixation methods on sensory quality

As summarized in Table 3, the sensory quality was significantly affected by the fixation methods employed for green tea samples. In terms of tea appearance and liquor color, the samples subjected to ERHSF and ERF treatments showed a superior color quality, which was related to the high chlorophyll retention; in contrast, the green tea obtained following ERHF treatment exhibited the least desirable appearance and liquor color, as confirmed by the comparison of the quantitative color indicators.

In terms of the taste and aroma, tea samples obtained by ERHSF treatment exhibited a chestnut-like aroma and had the highest umami score, which corresponded to high amino acid and soluble sugar contents and low TPs/AAs and TETC4/TSC4 ratios. However, it should be noted that the tea samples obtained by ERSF treatment had a more watery smell owing to high humidity conditions at high temperatures (Wang et al., 2018), thereby hindering expression of the aroma, which was not resolved by subsequent dehydration (Zhao, Shi, Li, Chen, & Zhu, 2013). Overall, owing to its uniform and complete fixation effect with careful temperature and humidity control, the ERHSF approach addressed the shortcomings of single and double fixation technologies, thus promoting a reduction in the content of TPs and catechins and an increase in that of free amino acids, soluble sugars, and chlorophyll and improving the liquor color, taste, and aroma of the green tea samples to achieve the highest total sensory scores ($P < 0.05$).

4. Conclusions

The proposed fixation method showed remarkable effects on the contents of biochemical quality substances, appearance, liquor color, and sensory quality of summer-autumn green tea. Orthogonal design and comparative analysis showed that hot-air temperature was the key factor in electromagnetic roller-hot-air–steam triple-coupled fixation (ERHSF) technology, and the following optimal fixation parameters were identified: steam volume of 20 kg/h, hot-air temperature of 90 °C, and hot-air blower speed of 1200 r/min. Compared with conventional fixation technologies, the ERHSF technology could significantly reduce the bitterness and astringency of summer-autumn green tea and promote the degradation of tea polyphenols and ester-catechins, the thermal hydrolysis of proteins and polysaccharides to accumulate amino acids and soluble sugars, as well as the retention of chlorophyll. The

Table 3
Comparison of sensory quality of green tea treated with different fixation methods.

Fixation methods	Appearance		Liquor color		Taste		Aroma		Total score
	Description	Score	Description	Score	Description	Score	Description	Score	
ERF	Curly and tippy; yellowish green and barely glossy	88.00 ± 0.22[a]	Yellowish green; bright	88.00 ± 0.22[a]	Mellow and barely umami	86.00 ± 0.22[b]	Chestnut aroma	86.00 ± 0.41[b]	86.80 ± 0.41[b]
ERHF	Curly and tippy; yellowish green with slightly grey	83.00 ± 0.41[c]	Yellowish green; barely bright	82.00 ± 0.00[c]	Mellow; slightly stuffy	86.00 ± 0.41[b]	Chestnut aroma	86.00 ± 0.82[b]	84.60 ± 0.41[c]
ERSF	Curly and tippy; yellowish green	86.00 ± 0.22[b]	Yellowish green; barely bright	84.00 ± 0.22[b]	Mellow	84.00 ± 0.82[c]	Chestnut aroma; comparatively stuffy	85.00 ± 0.22[b]	84.70 ± 0.82[c]
ERHSF	Curly and tippy; yellowish green and glossy	88.50 ± 0.41[a]	Green; highly bright	86.50 ± 0.41[a]	Umami, mellow and brisk	87.00 ± 0.82[a]	Obviously with the character of chestnut aroma	86.00 ± 0.00[a]	88.60 ± 0.22[a]

Note: Different letters in the same column indicate significant differences between the treatments, as determined based on the means of the LSD test ($P < 0.05$).

ERHSF treatment samples had the lowest TPs/AAs and TETC4/TSC4 ratios and the highest quality material weighted value (QMWV). Moreover, the appearance brightness "*L**", greenness "*-a*", liquor brightness "*L**", and greenness "*-a**" values were the highest in ERHSF treatment samples, along with an obviously lasting chestnut-like aroma and best umami taste, which indicated an obvious improvement in taste, appearance, and liquor of summer-autumn green.

Our results provide theoretical support and technical guidance for the precise quality improvement of summer-autumn green tea. Follow-up work should focus on the application of metabolomics to comprehensively analyze the effect of the ERHSF technology on the levels of non-volatile and volatile metabolites in summer-autumn tea.

Author Contributions

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the Science and Technology Innovation Project of Chinese Academy of Agricultural Sciences (CAAS-ASTIP-TRICAAS), Zhejiang Provincial Natural Science Foundation of China (LGC22C160005), and National Science Foundation of China, China (31972465).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2023.100844.

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