RESISTANCE WIRE HEATING GROOVE-TYPE TEA DE-ENZYMING AND CARDING MACHINE: DESIGN AND TESTING
/
电阻丝加热-槽式茶叶杀青理条机的设计与试验

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DOI: https://doi.org/10.35633/inmateh-74-16

Keywords: *Tea de-enzyming and Carding Machine, Thermal Analysis, Energy Savings, Energy Consumption, Design and Experimentation.*

ABSTRACT
The force analysis of the tea leaves on the U-shaped tank of the resistance wire heating groove-type tea de-enzyming and carding machine is conducted, and then the track analysis on SolidWorks based on the force analysis. The coupled steady state thermal analysis is carried out on the heating tank of the two kinds of machinery. The comparative test and content analysis of the three prototypes and gas trough machines are conducted, and the average value of the three tests is considered. The results are presented. The output of the prototype is 3.80 kg h^{-1}, the strip rate is 88.38%, and the surface temperature of the pot groove reaches the requirement of finishing temperature.

摘要
对茶叶在电阻丝加热-槽式杀青理条机的 U 型锅槽的进行受力分析，然后基于受力分析对茶叶在 Solidworks 上进行轨迹分析。对两种样机机械加热时的锅槽,分别进行耦合稳态热分析。进行三组样机与燃气式槽式杀青机的对比试验以及内含物分析, 皆取3次试验结果的平均值; 结果表明; 样机台时产量为3.80 kg h^{-1}, 成条率为88.38%, 锅槽表面温度达到杀青温度要求。

INTRODUCTION
Green tea is the first type and currently the main tea in China, with most Chinese people consuming tea (*You et al., 2023*). Green tea differs from other tea types in that the first process of its manufacturing is tea chlorosis. In the process of tea chlorosis, the high-temperature passivation of enzyme activities stops the oxidation of polyphenols in fresh leaves, preventing the leaves of green tea from turning red. Tea chlorosis can also evaporate some of the water in the leaves, allowing them to become soft prior to kneading. Along with water evaporation, gas in fresh leaves has a low boiling point and evaporates, thus helping to improve the aroma of tea leaves. Therefore, the process of tea chlorosis plays a key role in the quality of green tea (*Wang et al., 2022*). Meanwhile, tea chlorosis and straightening play a vital role in tea processing, and knowing whether their effect is ideal is directly related to the appearance and quality of tea (*Yang et al., 2022*). Tea chlorosis is the application of external high temperature to tea leaves to transfer heat, which not only eliminates the oxidative enzyme activity of tea leaves but also contributes to evaporation by reducing the water content of tea leaves. Consequently, the tea leaves become fluffy, easy to knead and shape and can disperse easily, ensuring a fresh and fragrant green tea aroma (*Yan et al., 2022*). Straightening is the method of transforming tea leaves into strips after processing, which is conducive to the subsequent process and the formation of the quality of color, aroma, and taste of the tea leaves (*Gan et al., 2018*).

Japan has been a leading country in the research of green tea processing machinery. Since the 1970s, the development of tea processing machines in Japan has progressed rapidly, particularly for machinery involved in the steaming process of green tea and the management of tea plantations. The main equipment for processing steamed green tea is the steam fixing machine. This machine works on the principle that the condensation of steam generates a significant amount of latent heat, rapidly elevating the temperature of fresh leaves. This process effectively inactivates enzymes such as polyphenol oxidase in the tea leaves. Due to the strong penetrating power of the hot steam, the tea leaf surface temperature increases quickly, thus the fixing process is very fast. The entire steaming of fresh tea leaves can be completed in just a few seconds. After fixing, the leaves retain a good overall appearance and are less likely to develop a burnt taste. Despite the global renown of some of Japan's tea processing machinery, Japan does not produce the unique needle-shaped or flat-shaped teas that are exclusive to our country. In Japan, the focus is primarily on the production of matcha, and hence there has been extensive research conducted on matcha processing machinery, placing Japan at a leading level worldwide.

Domestic and foreign tea de-enzyming and carding machine mainly take the form of roller-type de-enzyming (gas, electricity, and coal), microwave tea de-enzyming and carding machines, electromagnetic tea de-enzyming and carding machines, heat radiation tea de-enzyming and carding machines, hot air tea de-enzyming and carding machines, and steam tea de-enzyming and carding machines (*Xu et al., 2014*). The advantages of hot air tea de-enzyming and carding machines are its de-enzyming efficiency, quality, and stability, whereas its disadvantages include high energy consumption, easy scorching of leaf edges, appearance of fish-eye bubbles, long operation of cooling time, and low thermal efficiency (*Ren et al., 2022*). Microwave tea de-enzyming and carding machines do not require preheating and result in a good appearance of green tea leaves, but the tea has a reduced aroma (i.e., no lasting phenomenon). The other disadvantages are high energy consumption, high replacement cost of the generator and other components, and low operating efficiency of the drum (*Li et al., 2019*), which have led to a gradual decrease in the number of applications of microwave de-enzyming in recent years. Electromagnetic tea de-enzyming and carding machines use high-frequency electric field heating drums, which have the advantages of faster preheating speed, easier operation, and lower energy consumption compared with traditional electric heating drums, but the cost is higher. Heat radiation tea de-enzyming and carding machines applies the infrared “direct” action mode of internal molecules to generate heat, saving more than 30% of the energy produced by the traditional tunnel-type tea de-enzyming and carding machines with a quasistatic process, and the uniformity of the material has high requirements. Hot air tea de-enzyming and carding machines use heat convection to quickly remove the surface moisture of tea leaves, making them suitable for processing the large moisture contents of fresh leaves. As described above, most tea de-enzyming and carding machines are not equipped with heat-recovery devices, so their thermal efficiencies are low; generally, natural gas or electric heating is used, which raises the machine cost (*Dai et al., 2023*). Steam green tea de-enzyming and carding machines have high-temperature steam penetration characteristics, so the rapid warming of fresh leaves does not easily scorch the leaves. This method also has high production efficiency, but the tea flavor is altered. Furthermore, the traditional processing methods differ greatly, indicating that applications can only be promoted in certain tea processing areas (*He et al., 2023*). The main equipment for green de-enzyming is shown in Figure 1.

Currently, the tea de-enzyming and carding machine commonly used for tea chlorosis are groove-type tea de-enzyming and carding machine and roller-type tea de-enzyming and carding machine and so on. The gas heating–groove tea chlorosis and barbering machine, which use tea and hot air as raw materials, are composed of multicomponent and multiphase heat systems, but they are limited by the following problems: low thermal efficiency; pot grooves are easily deformed; and pot groove have inaccurate temperature measurements.

Recently, the degree of mechanization of tea processing has gradually increased, with the manual tea de-enzyming and carding mode shifting to the mechanical tea de-enzyming and carding mode to increase market penetration. While mechanical de-enzyming has brought process efficiency and extended market sales, attention should be given to tea quality and energy saving measures. At present, most of the tea de-enzyming and carding machines are not equipped with heat recovery devices, indicating low thermal efficiency; furthermore, using natural gas costs much higher (*Jia et al., 2023*). In some applications, gas is considered inconvenient to use and requires replacement. Given the problems associated with mechanical tea de-enzyming and carding operations, the heating of groove-type tea de-enzyming and carding machines and the shift to electrical energy for heating must be studied.

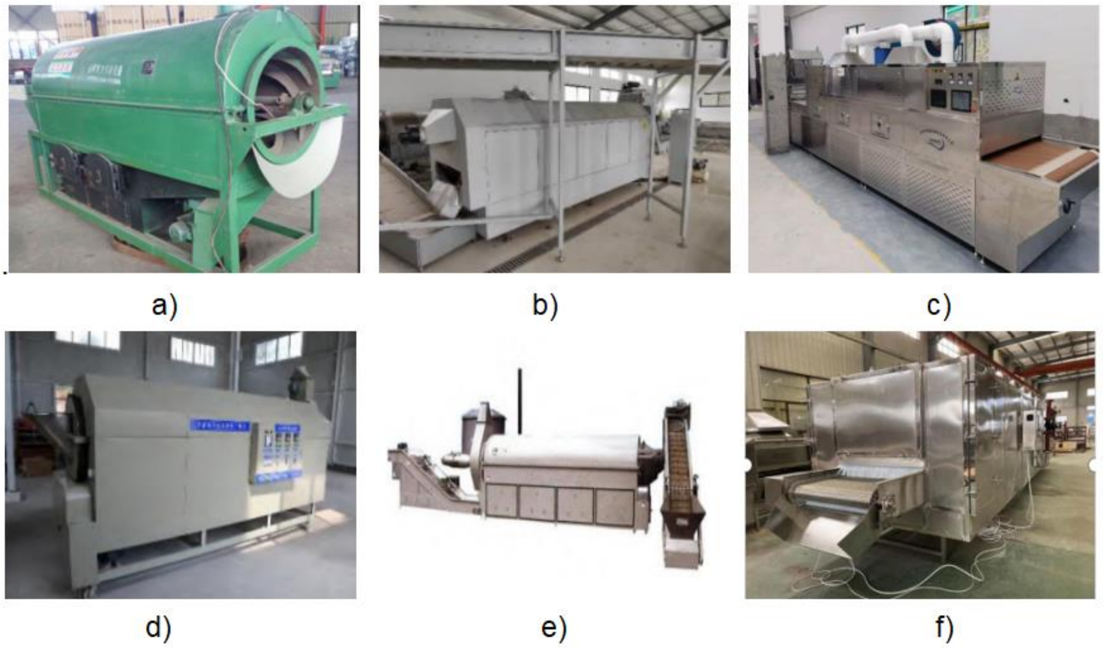

Fig. 1- Domestic and foreign tea de-enzyming and carding machine types
a) Roller-type tea de-enzyming and carding machine; b) microwave tea de-enzyming and carding machine; c) electromagnetic tea de-enzyming and carding machine; d) heat radiation tea de-enzyming and carding machine; e) hot air tea de-enzyming and carding machine; f) steam tea de-enzyming and carding machine

With white tea production in Anji, Zhejiang Province, China taken as the background, this study comprehensively considered the production, tea chlorosis effect, and energy use with respect to the design of a resistance wire heating groove-type tea de-enzyming and carding machine. By optimizing the heating method of mechanical de-enzyming, in contrast to traditional mechanical tea de-enzyming and carding machines, resistance wire heating groove tea de-enzyming and carding machine can not only meet the greening standard requirements but also solve the problem of high energy consumption of tea finishing. The machine is also simple, easy to start, and practical to operate.

SolidWorks was used to create a simplified model, which was then combined with the simulation and thermodynamic analysis of the resistance wire heating groove-type tea de-enzyming and carding machine on Workbench 2022 R1, thus laying a solid foundation for the tea chlorosis operations of such machines.

MATERIALS AND METHODS

Key components

The depth size, width size, pot groove walls, and horizontal plane between the varying angle sizes of the *U*-shaped groove directly affect the efficiency of the tea *de-enzyming*. The crank slider mechanism in the connecting rod mechanism, which handles the transmission of the key components, is connected to the *U*-shaped groove, thus achieving a *U*-shaped groove reciprocating motion.

During movement, the connecting rod exerts a forward thrust and a downward pressure on the *U*-type multi-slot pot, the servo motor drives the active wheel to rotate, and the active wheel rotation drives the driven wheel, eccentric wheel, and connecting rod to perform a reciprocating linear motion. As the connecting rod undergoes a reciprocating linear motion, it drives the fixed push plate and the strip plate to swing back and forth to achieve a uniform stripping of tea leaves. The resistive wire heating device is installed below the *U*-shaped multi-slot pot. For the thermal efficiency of the resistance wire, the heating time and the stable heat supply to the pot slot are also key factors that directly affect tea chlorosis (*Zhang et al., 2022*). A resistance wire heating device is installed at the bottom of the *U*-shaped multi-slot pot. For the thermal efficiency of the resistance wire, the heating time and the stable heat supply to the pot trough are also key factors directly affecting tea de-enzyming (*Ju et al., 2002*).

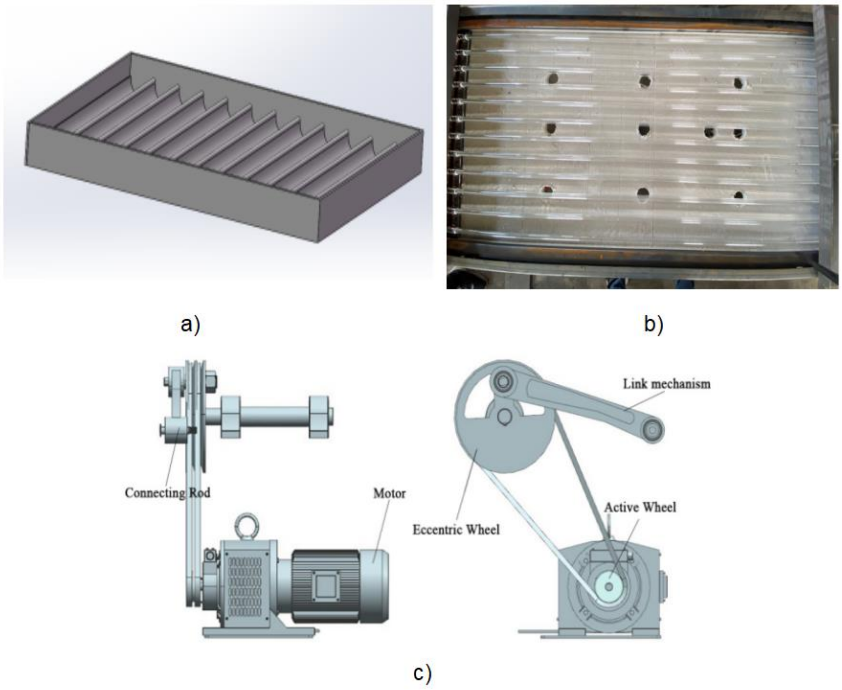

Fig. 2 - Schematic diagram of the structure of key components

a) U-shaped multi-tank pot structure; b) resistance wire heating device structure; c) crank slider mechanism

Motion analysis and simulation of tea particles in the groove

The movement of tea particles in the potting machine is mainly divided into three stages. First, the tea leaves in the potting machine perform a throwing movement. Second, the tea leaves extrude through the inner wall of the potting machine in a state of throwing movement. Finally, the tea leaves fall back into the potting machine and collide after the throwing movement (*Wu et al., 2019*).

Acceleration analysis of tea particles before and after performing a lift-and-throw

Let us take a single tea leaf as a mass point while ignoring the effect of collision between tea particles and other elements in the *U*-shaped groove under the action of the power mechanism. The tea particles are thrown upward along the inner wall of the pot groove and toward the airspace above, subjecting the tea particles to acceleration and gravity.

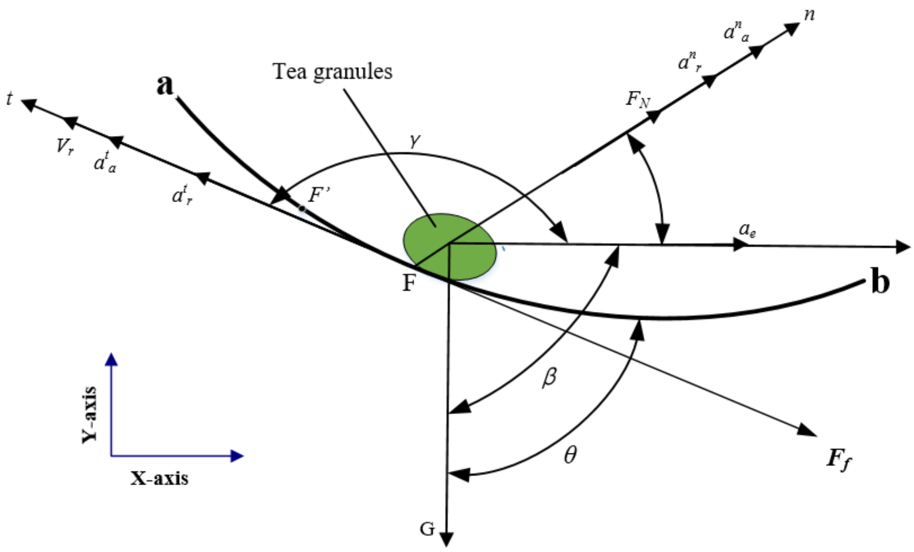

Fig. 3 - Tea-strip force subdiagram

A coordinate system is established with the *XY* axis. In the diagram, curve *ab* represents the *U*-shaped pot groove curve; *G* is the gravity force of tea particles ($G = mg$, where *m* is the mass of tea particles); F_N is the support force of the inner wall of the pot; F_f is the friction force between tea leaves and the inner wall of the pot; *μ* is the friction coefficient of the pot on the tea particles; V_r is the relative velocity of the tea particles along the surface of the pot; *n* and *t* are the normal vector of the surface of the pot and the tangential vector of the surface of the pot, respectively (the directions are in the same direction as that of V_r); a_a^n is the absolute acceleration of the tea particles during movement; (a_a) is the normal component of the absolute acceleration of the tea particles along the surface of the pot; a_a^t - a_a represents the tangential component along the surface of the pot; a_r^n is the normal component of the acceleration of the tea leaves relative to the surface of the pot; a_r^t is the tangential component of the acceleration of the tea leaves relative to the surface of the pot; *α* is the angle between the acceleration of the pot's motion at a_e and the normal vector at *n*; *β* is the angle between the gravitational force at *G* and the normal vector at *n; γ* is the angle between the acceleration of the pot's motion at a_e and the tangential vector at *t* ; and *θ* is the angle between the tangential vector at *t* and the gravitational force at *G* . The variables can be expressed as:

$$V_{rx}n_x + V_{ry} + n_y = 0 \tag{1}$$

where V_{rx} and V_{ry} are the two components of V_r on the *XY*-axis, and n_x and n_y are the components of the normal vector *n* of the *U*-shaped pot groove curve *ab* on the *XY*-axis. On this basis, it is obtained:

$$n_x = \frac{-\left|\frac{V_{rx}}{V_{rx}}\right|}{\sqrt{V_{rx}^2+V_{ry}^2}}V_{ry} \quad (V_{rx} \neq 0) \tag{2}$$

$$n_y = \frac{|V_{rx}|}{\sqrt{V_{rx}^2 + V_{ry}^2}} \quad (V_{rx} \neq 0) \tag{3}$$

The angle between two vectors can be obtained from the product of two vector quantities as follows:

$$\cos\alpha = \frac{a_e n_x}{|a_e|\sqrt{n_x^2 + n_y^2}} \tag{4}$$

$$\cos\beta = \frac{-Gn_y}{|G|\sqrt{n_x^2 + n_y^2}} \tag{5}$$

$$\cos\gamma = \frac{a_e V_{rx}}{|a_e|\sqrt{V_{rx}^2 + V_{ry}^2}} \tag{6}$$

$$\cos\theta = \frac{-GV_{rx}}{|G|\sqrt{V_{rx}^2 + V_{ry}^2}} \tag{7}$$

The point acceleration summation formula is given by:

$$a_a^n = a_e^n + a_r^n \tag{8}$$

$$a_a^t = a_e^t + a_r^t \tag{9}$$

which further obtains $a_r^n = \frac{V_r \times V_r}{\rho}$, where *ρ* is the radius of curvature of the *U*-shaped pot groove. Eqs. (10) represents the situation when the tea particles are thrown upward along the pot groove under the action of the driving force $F_N < 0$. The friction force and relative average speed of the tea particles along the wall of the pot groove are in the opposite direction.

$$a_e^n = a_e \cos\alpha \tag{10}$$

The supporting reaction force on the tea particles on the inner wall of the *U*-shaped pot groove is given by:

$$F_N = -G\cos\alpha + ma_a^n \tag{11}$$

The friction applied to the tea particles on the inner wall of the *U*-shaped pot groove is expressed as:

$$\begin{cases} F_f = G\,cos\,\theta - ma_a^t \\ F_f = \mu F_N \end{cases} \tag{12}$$

Eqs. (1) – (10) are combined to obtain the normal component of the absolute acceleration (a_a) of the tea particles along the surface of the pot during motion a_a^n.
Then, Eqs. (11) and (12) are combined to obtain:

$$a_a^t = \mathrm{g}(\mathrm{m}\cos b + \cos q) - \mathrm{m}a_a^n \tag{13}$$

$$a_a^t = a_e \cos g \tag{14}$$

The tangential component of the accelerated motion of the tea leaves relative to the surface of the pot can be derived, i.e., a_a^n , by combining Eqs. (13) and (14) to further obtain a_r^t.

Analysis of the acceleration of the motion of the tea leaves after being thrown away from the inner wall of the pot trough

The summation of acceleration is given by the following known formulas:

$$a_{ay} = a_{rx} + a_{ex} \tag{15}$$

$$a_{ay} = a_{ry} + a_{ey} \tag{16}$$

The tea particles leave the inner wall of the pot trough and are in the air with only gravity acting on the tea. This action can be expressed as follows:

$$a_{ax} = 0 \tag{17}$$

$$a_{ay} = g \tag{19}$$

$$a_{ex} = a_e \tag{19}$$

$$a_{ey} = 0 \tag{20}$$

The components of vector a_a on the *XY*-axis are given by a_{ax} and a_{ay}, while those of vector a_e on the *XY*-axis are given by a_{ex} and a_{ey}.
Combining Eqs. (15) – (20) it is obtained:

$$a_{rx} = -a_e \tag{21}$$

$$a_{ry} = g \tag{22}$$

The velocity component of the tea particles in the *U*-shaped pot groove is taken as a moving coordinate system as follows:

$$\begin{cases} V_{rxF'} = V_{rxF} + a_{rx} \cdot \Delta t \\ V_{ryF'} = V_{ryF} + a_{ry} \cdot \Delta t \end{cases} \tag{23}$$

The tea particles moving in a *U*-shaped pot groove is taken as a moving coordinate system as follows:

$$\begin{cases} x_{F'} = x_F + V_{rxF'} \cdot \Delta t + a_e \cdot \Delta t^2 \\ y_{F'} = y_F + V_{ryF'} \cdot \Delta t - g \cdot \Delta t^2 \end{cases} \tag{24}$$

where V_{rxF}, V_{ryF}, $V_{rxF'}$, $V_{ryF'}$ is the relative velocity of motion V_r of the tea particles moving along the inner wall of the pot to points F and F', which denote the velocity component of motion on the *X* and *Y* axes, respectively, and x_F, $x_{F'}$, y_F, $y_{F'}$ is the position of the tea particles at points F and *B'*.

SolidWorks-based simulation analysis of the trajectory of tea particles on the pot groove

The trajectory of tea particles in a pot groove represents a complex system. Tea particles are subject to sliding, rolling, and throwing movements during tumbling. Then, the tea particles fall into the pot groove by gravity and influence the pot groove to undergo sliding and rolling movements. In this study, for the simulation analysis, the problem is simplified, and two assumptions are made.

As the tea particles are light and soft, the normal vector velocity in the inner wall of the pot is almost equal to zero when they are thrown up and back to the pot.

When the tea particles roll along the surface of the pot, the rolling speed of the tea particles is zero.

During calculation, the initial motion of tea particles is located at the lowest part of the *U*-shaped pot groove. At this time, the initial velocity of the tea particles is zero.

On the basis of Eq. (26), motion simulation analysis is performed on SolidWorks, and the trajectory diagram of the de-enzyming process of tea particles in the *U*-shaped pot trough (*Deng et al., 1995*) is derived (Fig. 4).

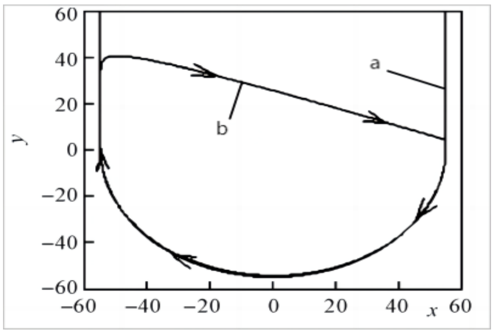

Fig. 4 - Simulation curves of tea leaf trajectory in the *U*-shaped pot groove

a) *Pot trough curve and; b) simulation movement trajectory of tea leaves*

From the trajectory diagram, the tea in the *U*-shaped pot trough undergoes periodic movement, and the change rule is essentially the same. With the heating of the tea chlorosis machine from the bottom of the pot trough, the tea particles in the *U*-shaped pot trough move in a cycle. Then, as a result of the heating effect, the tea particles at the bottom of the pot trough move with a relatively long trajectory because of rolling, friction, and heating. Thus, the heating of the tea pot trough mainly affects tea chlorosis. When the tea particles move at the bottom of the trough, the temperature at this part initially reaches the temperature of tea chlorosis. The temperature change at the bottom of the trough is small to allow the tea to be further heated and achieve the purpose of greening. The cloud motion trajectory analysis after the force analysis provides theoretical support for the subsequent simulation and experimental design.

Now the trough finishing machine is the gas type electric heating plate mechanical finishing way. In this study, the design of mechanical heating for the de-enzyming method involved replacing the gas type electric heating plate mechanical finishing with resistance wire heating. The other aspects were maintained, that is, the bottom of the *U*-shaped pot trough heating achieves the purpose of de-enzyming green.

Comparison of thermal analysis of Workbench-based simulation

SolidWorks coupled with ANSYS Fluent steady-state thermal simulation software was used to simulate the heating process of the pot trough of the resistance wire heating groove-type tea de-enzyming and carding machine and the gas heating-groove-type tea de-enzyming and carding machine. In the simulation thermal analysis, the basic parameters for setting the material of the de-enzyming and slitting machine were set according to the setting method proposed in the literature (*Qin et al., 2022*). The results are shown in Table 1.

Table 1

Basic parameter setting

Name (of a thing)	Parametric	Value
pot groove	Poisson's ratio	0.3
	Density (kg/m^{-3})	7800
	Shear modulus (Pa)	7×10^7

Simulation modeling of a U-shaped pot hole

This design was implemented in SolidWorks. The overall model of the groove-type tea de-enzyming and carding machine and the overall mechanism were both established to perform simplification, particularly by ignoring the frame, motor, and other parts that are not in direct contact with the pot trough (*Luo et al., 2022*). Then, the simulation models simulated by SolidWorks were saved in *.spt format and imported into Workbench 2022 R1.

Fluid Domain Geometry Model Extraction and Meshing

The pot groove model imported into Workbench 2022 R1 was extracted to determine the fluid domain of the simulation operation geometry model. The extracted fluid domain model was further inputted into Workbench 2022 R1, and the mesh was exported (Fig. 5).

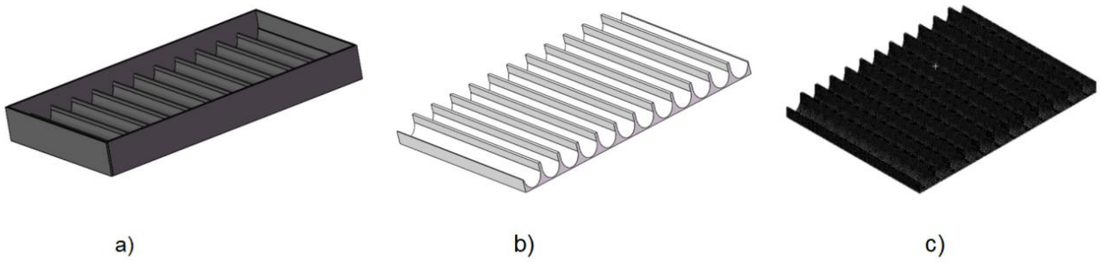

Fig. 5 - Simplified extracted fluid domain and meshing mode

a) Simplified pot model; b) extraction of the fluid domain model; c) meshing of the fluid domain

Thermodynamic simulation analyses of the operation process of the two machines were performed. The *U*-shaped pot groove can reach 300 °C and an ambient temperature of 22 °C, and other environmental impacts can be ignored. Other specific simulation parameters are shown in Table 2. The solution can be obtained after completing the various parameter settings.

Table 2

Main working parameters of the tea finishing machine

parametric	Value
Specific heat (K)	1006.43
Thermal conductivity (K)	0.0242
Resistance wire resistivity	2.277e^{-5}

Coupling simulation process

As shown in Figure 6, after processing the thermal analysis work in ANSYS Fluent, a static structure workgroup in the analysis system of the toolbox of Workbench 2022 R1 was created. The results of the model after the thermal analysis were combined with those of the static structure workgroup. The engineering data settings were selected, and the relevant parameters were confirmed for correctness.

The solutions in the steady-state thermal analysis module were linked with the settings in the static structure workgroup, resulting in the thermal deformation analysis of the pot groove under the heating condition of the resistance wire. After confirming that the parameters were correct, the solution in the steady-state thermal analysis module was associated with the settings in the static structure working group.

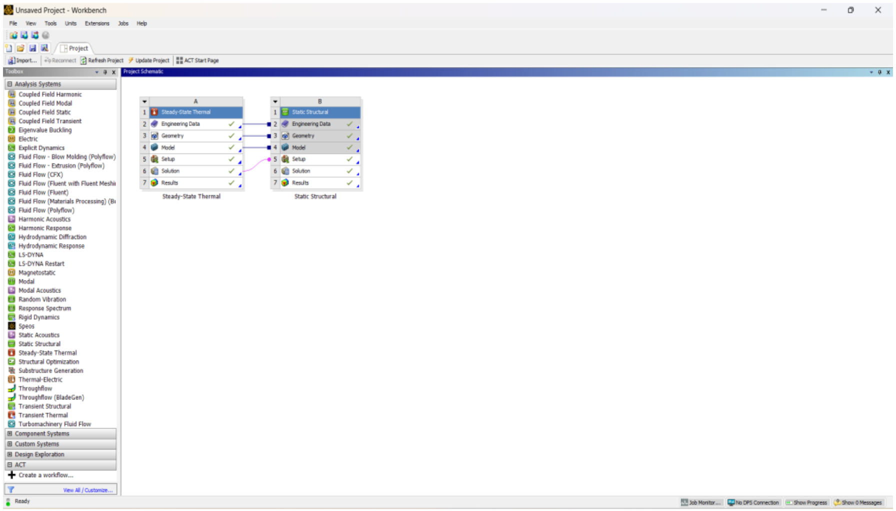

Fig. 6 - Coupled simulation with Workbench 2022 R1 static structure

The performance test

The reasonableness of the heating of the resistance wire heating–groove-type tea de-enzyming and carding machine to meet the quality standards of tea processing was verified by exploring the energy-saving effect and the quality of the tea after de-enzyming. A test was conducted in August 2023 at Yuanfeng Tea Machinery Co. Ltd. (Huzhou City, Zhejiang Province, Anji County, China). The control test was performed with a gas-type electric heating tea de-enzyming and carding machine, and the sample tea used in the test was Anji White Leaf No. 1. The test instruments were a stopwatch, infrared temperature gun, electronic scale, electronic balance, resistance wire-type tea chlorosis machine, and others. The test instruments and prototype machine are shown in Figure 7.

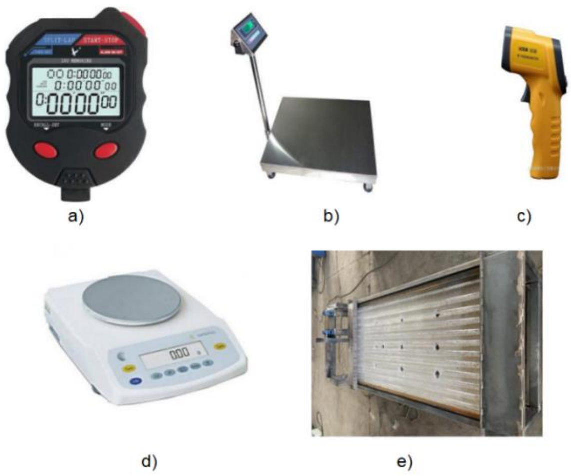

Fig. 7 - Test apparatus and de-enzyming equipment

a) Chronograph; b) electronic scale; c) infrared thermometer; d) electronic balance;
e) resistance wire-type and groove-type tea de-enzyming and carding machine

Experimental design

The local white tea leaves in Anji were selected as the test material, and the motor speed was set to 240 r/min for both the resistance wire heating–groove-type tea de-enzyming and carding machine and the gas heating–groove-type tea de-enzyming and carding machine. The motor speed was approximately 180 r/min for both machines during the striping stage, and the time of tea chlorosis and striping was 10 min.

The tea leaves were divided into two portions, and each portion was further divided into three portions and put into two kinds of greening pots and troughs after withering in two batches. After withering, the tea leaves were put into the two kinds of greening pots. Finally, the mean value of the two kinds of de-enzyming results was taken as the experimental result. After the test tea samples were processed by greening by the two different machines, the finished tea was processed according to the same method of processing, and the inclusions were measured and analyzed. The test result was issued by the Science and Technology Building of Anhui Agricultural University.

After processing the finished three tea samples, a total of nine tea samples were taken and sent to the Anhui Agricultural University Science and Technology Building for testing, which issued a test report. The results of the inclusions are shown in Tables 5 and 6. The sensory review is shown in Fig. 5, in which the same kind of mechanically processed tea sample results take the average value.

Table time output: A stopwatch was used to record each de-enzyming time (bar end), and the total mass of tea leaves was weighed after the end of the de-enzyming according to the following formula:

$$P_0 = \frac{M_0}{t} \tag{25}$$

where: P_0 is the output in kg h^{-1}; M_0 is the total mass of tea leaves after greening (kg); and t is the time needed for each greening (*h*).

Strip rate: The dried tea samples were collected after greening for picking. The broken tea, tea stems, and yellow leaves, and other excess impurities were selected, and the tea specimens, including their unstripped parts, were weighed and calculated according to the following formula:

$$Y_0 = \frac{Q_0}{T_0} \times 100\% \tag{26}$$

where: Y_0 is the rate of tea leaf formation; Q_0 is the mass of the formed portion after de-enzyming (kg); and T_0 is the sum of the formed and unformed portions of tea leaves (kg).

Surface temperature of the pot groove: Four corners of the pot groove position were checked, and an infrared thermometer was placed 15 cm from the tank surface. The temperature of the surface of the pot groove was measured. Each point was measured two to three times, and the average was taken as the pot groove's effective working temperature.

Energy consumption tests

The energy consumption of the resistance wire heating–groove-type tea de-enzyming and carding machine and the traditional electrically heated drum was also determined. A microwave de-enzyming and carding machine was used for the control experiment. The local white tea from Anji was used as the test material, and the total weight of the tea leaves was 50 kg. The drum de-enzyming and carding machine model was 6CS-100(D), whereas the microwave de-enzyming and carding machine model was CSW-30.

Key component design and analysis

The main parts of resistance wire heating–groove-type tea de-enzyming and carding machine are the *U*-shaped multi-trough pot, crank slider mechanism and resistance wire heating device, connecting rod, and motor (*Haijun et al., 2022*). During operation, the machine delivers power to the *U*-shaped multi-slot pot through the belt drive and crank slider mechanism and achieves different rotational speeds with the changing frequency of the motor. This approach can meet the demands of tea processing technology. The heating parts of the resistance wire are distributed under the *U*-shaped multi-slot pot, which is driven by the crank slider mechanism to produce a reciprocating linear motion. The withered and adjusted tea leaf specimens are put into the *U*-shaped multi-slot pot of the machine, which is under a reciprocating driving force. Similarly, a reciprocating force drives the resistance wire heating device. With tea leaves processed in the reciprocating driving force, along with the effects of the pot groove walls and the friction between the tea particles and heat, both heating and water are uniformly lost via pot track friction extrusion, and the tea leaves are gradually sorted out for stripping (*Sheng et al., 1976*).

RESULTS AND DISCUSSION

Static thermal analysis results

Coupled simulation was performed using SolidWorks and ANSYS Fluent. Simulation modeling and joint steady-state thermal analysis were conducted. The lowest temperature of the *U*-shaped pot groove heated by resistance wires is slightly higher than that of the gas-type mechanical heating. And the resistance wire groove heating steady state heat is more stable, conducive to uniform heating tea.

After completing the thermal analysis solution, ANSYS Fluent was used to postprocess it, and diagrams of thermal analysis for the two types of pot grooves (i.e., the resistance wire heating groove-type tea de-enzyming machine and the gas heating-groove-type tea de-enzyming and carding machine) were obtained (Fig. 8). When the maximum temperature is 300°C, the resistance wire heating pot and the gas-fired electric heating pot both generate heat at the bottom and achieve a temperature rise. Both pots reached the required temperature for tea de-enzyming at the bottom of the tank.

The solution in the static structure was selected for implementing the thermal analysis coupled with the static structure. Finally, the thermal deformation analysis of the pot groove heated by the resistance wire was obtained (Fig. 9).

The steady-state thermal and static structure of Workbench 2022 R1 was also used for joint simulation analysis. The thermal deformation of the *U*-shaped potting tank was analyzed under the heating of the resistance wire, with the temperature set to 300°C. The total deformation, equivalent stress, and equivalent elastic strain were also determined (Fig. 9). The total deformation of the potting tank itself is extremely small in the heating of the resistance wire. Furthermore, the total deformation value is small and can reach the standard requirement of tea de-enzyming machinery.

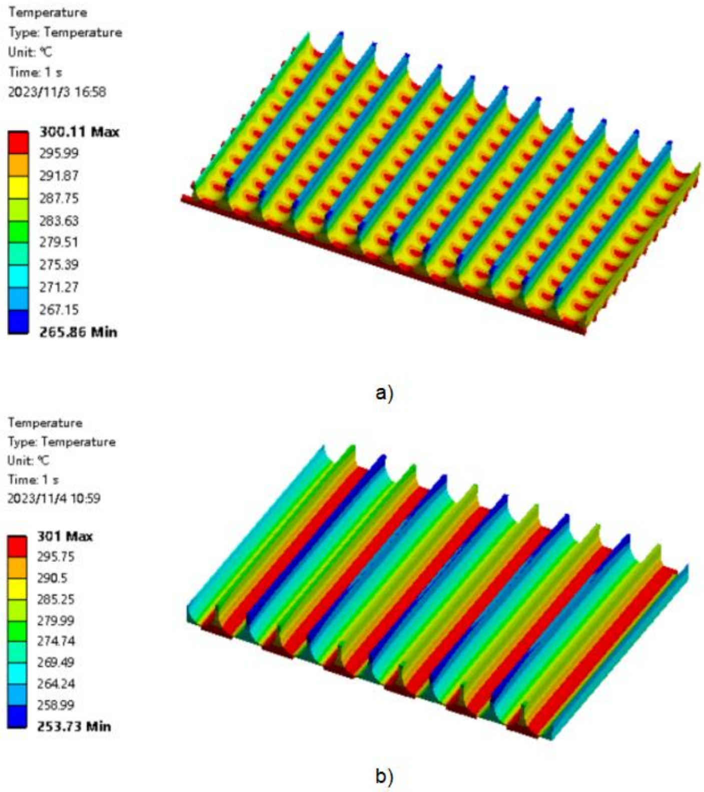

Fig. 8 - Thermal analysis of two mechanically heated pots and tanks

a) Resistor wire heating; b) Gas heating

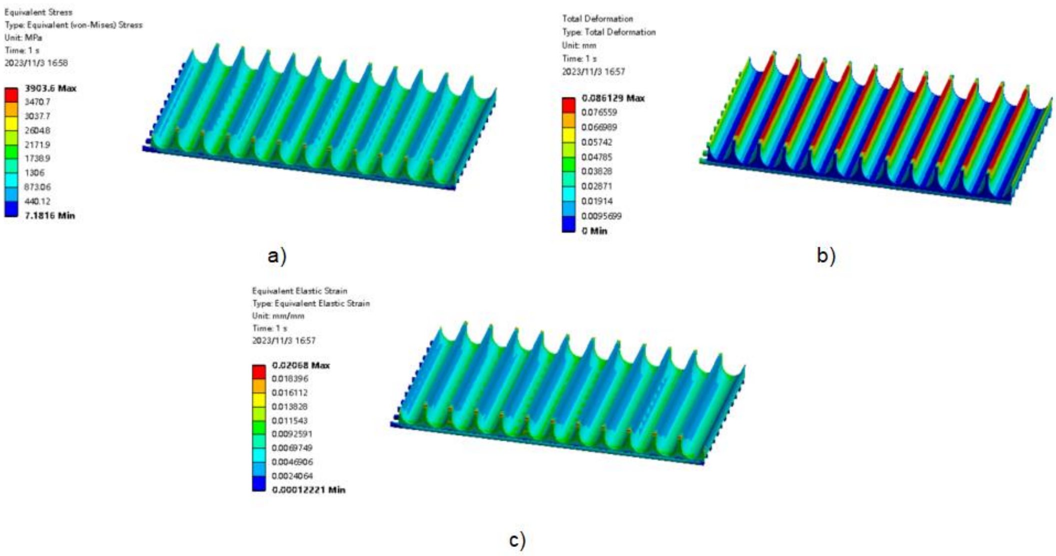

Fig. 9 - Analysis of thermal deformation of the pot groove under the condition of coupled resistance wire heating

a) Equivalent effective stress; b) total deflection; c) equivalent elastic strain

Mechanical property test results

Tables 3 and 4 show the test data of the pot groove-type of gas-fired tea de-enzyming and carding machine and the resistance wire heating–the pot groove-type of gas-fired tea de-enzyming and carding machine, respectively. The average value of the three tests with output per hour was obtained, and the gas heating–groove tea de-enzyming was 3.88 kg h^{-1}, the rate of strips was 89.0%, and the surface temperature of the pot groove was 180 °C. The output per hour of the resistance wire heating–groove tea de-enzyming was 3.80 kg h^{-1}, the rate of strips was 88.38%, and the surface temperature of the pot groove was 142.6%. The comparative data of the two different mechanical heating methods indicate that the hourly output of the resistance wire heating–trough-type tea de-enzyming and slitting machine and strip rate did not decline, the efficiency of tea chlorosis did not decrease, and the surface temperature of the pot trough achieved the temperature requirements of tea de-enzyming.

Table 3

Experimental results of the pot groove-type of gas-fired tea de-enzyming and carding machine

Test parameters	First test	Second test	Third test	average value
Output per hour (kg h^{-1})	3.79	3.98	3.88	3.88
Strip rate (%)	89.65	88.35	89.12	89.0
Potting surface temperature（°C）	184	177	180.5	180

Table 4

Test results of the resistance wire heating groove-type tea de-enzyming and carding machine

Test parameters	First test	Second test	Third test	average value
Output per hour (kg h^{-1})	3.68	3.85	3.86	3.80
Strip rate/per cent	87.45	88.7	89.10	88.38
Potting surface temperature（°C）	140	145	142.5	142.6

Table 5 shows the results of the inclusion test after the pot groove-type of gas-fired tea de-enzyming and carding. Table 6 shows the inclusion test results after the resistance wire heating groove-type tea de-enzyming. The inclusion test report indicates that the amino acid and polyphenol content of the tea samples in gas heating and resistance wire heating remains unchanged, but the water contents of the tea processed by the two mechanical heating methods are different. One of the resistance wire heating approach for tea de-enzyming has a water content of 5.9%, and the water content of gas heating after tea de-enzyming is 6.72%. The water content from the resistance wire heating is lower than that of the gas heating, with a reduction of 0.82%.

Table 5

Detection of compounds in tea leaves after the pot groove-type of gas-fired tea de-enzyming and carding machine

serial number	First test GB/8304-2002	Second test GB/T8313-2008	Third test GB/T8314-2002	Average value
Moisture (%)	7.11	6.60	6.46	6.72
Polyphenol (%)	16.6	16.8	16.3	16.57
Amino acid (%)	5	5	4	4.67

Table 6

Detection of compounds in tea leaves after the resistance wire heating groove-type tea de-enzyming machine

serial number	First test GB/8304-2002	Second test GB/T8313-2008	Third test GB/T8314-2002	Average value
Moisture (%)	5.66	5.40	6.65	5.90
Polyphenol (%)	16.5	16.3	16.1	16.30
Amino acid (%)	5	5	5	5

Table 7 presents the energy consumption test results. Mechanical energy test data for tea dehydration were carried out at the initial stage Under the condition of the same amount of tea. For the CSW-30 microwave tea de-enzyming and carding machine, the energy consumption was 45.4 kW, the preheating was 4.5 min, and the de-enzyming time was 94 min.

For the 6CS-100(D) drum tea de-enzyming and carding machine, the energy consumption was 196.1 kW, the preheating was 30 min, and the de-enzyming time was 70 min. The energy consumption of the resistance wire heating groove-type tea de-enzyming and carding machine was 34.6 kW, with a preheating time of 3 min and a de-enzyming time of 130 min. Compared with the 6CS-100(D) drum tea de-enzyming and carding machine, the energy consumption of the resistance wire heating groove-type tea de-enzyming and carding machine is saved by 10.8kW,and Compared with the energy consumption of the CSW-30 microwave tea de-enzyming and carding machine, the energy consumption of the resistance wire heating groove-type tea de-enzyming and carding machine is saved by 161.5kW. The energy consumption of the resistance wire heating groove-type tea de-enzyming and carding machine was lower than that of the 6CS-100(D) drum tea de-enzyming and carding machine and CSW-30 microwave tea de-enzyming and carding machine, it is proved that the resistance wire heating groove-type tea de-enzyming and carding machine has more energy-saving advantages. The energy consumption of the resistance wire heating groove-type tea de-enzyming and carding machine was 23.80% and 82.30% less than those of the 6CS-100(D) drum tea de-enzyming and carding machine and the CSW-30 microwave tea de-enzyming and carding machine, respectively.

Table 7

Energy consumption test record sheet

Processing	tea plant variety	Power (kW)	de-enzyming weight (kg)	Preheating / de-enzyming time (min)	Energy consumption (kg h^{-1})
Microwave	Anji white tea	30	50	4.5/94	45.4
Resistor Wire-type		16	50	3/130	34.6
Roller		130	50	30/70	196.1

Review results

After the test prototype processing of the resulting dry tea samples, under the appraisal of tea sensory evaluation experts, all the evaluation indexes could meet the requirements. The sensory review results of the three tests are shown in Table 8 and Figure 10.

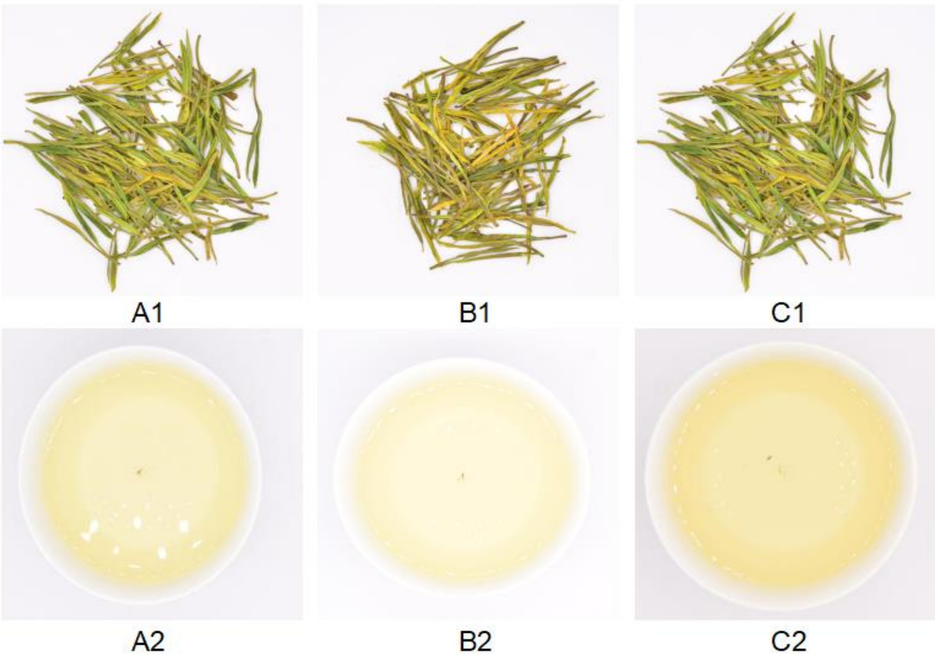

Fig. 10 - Results of tea review

A1) Experimental Sample Tea 1; A2) Soup color one; B1) Experimental Sample Tea 2; B2) Soup color two; C1) Experimental Sample Tea 3; C2) Soup color three

Table 8

Results of tea sensory evaluation

test group	color	a bar	color of soup	assessment result
1	fresh and moist (air)	lit. flat and vertical	yellowish	eligible (voter etc.)
2	emerald green	slightly curved	yellowish	eligible (voter etc.)
3	dark green	lit. flat and vertical	yellowish	eligible (voter etc.)

CONCLUSIONS

(1) The mechanical analysis of the force process of the tea specimens was processed by SolidWorks. In particular, a three-dimensional model of the resistance wire heating–groove-type tea de-enzyming and carding machine was built, and the *U*-shaped pot trough was simplified and analyzed. SolidWorks simulation was used to analyze the tea particles in the tea de-enzyming machinery via a movement trajectory process to obtain the trajectory of the tea. Coupled simulation was performed using SolidWorks and ANSYS Fluent. Simulation modeling and joint steady-state thermal analysis and thermal deformation analysis were conducted. The lowest temperature of the *U*-shaped pot groove heated by resistance wires is slightly higher than that of the gas-type mechanical heating.

(2) Under the same conditions, comparative results showed that the tea leaves heated by resistance wire tea de-enzyming had a lower water content than those heated by the gas heating–groove tea de-enzyming and carding machine.

(3) An energy consumption test was conducted on the resistance wire heating–trough-type tea de-enzyming and carding machine and the general tea de-enzyming and carding machine, followed by a comparative analysis. The energy consumption of the resistance wire–groove-type tea de-enzyming and carding machine was 82.36% and 23.80% less than those of the 6CS-100(D) drum greening machine and CSW-30 microwave tea de-enzyming and carding machine, respectively.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (52205509), Key Natural Science Research Project of Anhui Province Universities (2024AH050444), Anhui Provincial Natural Science Foundation Youth Fund Program (2208085QE155), Open Fund Program of State Key Laboratory of Tea Plant Biology and Utilization (SKLTOF20220118), and the Yuanfeng Tea Processing Technology Research and Quality Service Enhancement Enterprise Commissioning Project (KJ2022436).

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