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REVIEW ARTICLE

Green preparation, safety control and intelligent processing of high-quality tea extract

Yang Wei[a#], Yuxuan Pang[a#], Peihua Ma[c], Siwei Miao[a], Jia Xu[a], Kang Wei[a], Yuanfeng Wang[b] and Xinlin Wei[a]

[a]Department of Food Science and Engineering, School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai, PR China; [b]College of Life Sciences, Shanghai Normal University, Shanghai, PR China; [c]Department of nutrition and Food science, College of Agriculture and Natural Resources, University of Maryland, College Park, Maryland, USA

ABSTRACT

Tea contains a variety of bioactive components, including catechins, amino acids, tea pigments, caffeine and tea polysaccharides, which exhibit multiple biological activities. These functional components in tea provide a variety of unique flavors, such as bitterness, astringency, sourness, sweetness and umami, which meet the demand of people for natural plant drinks with health benefits and pleasant flavor. Meanwhile, the traditional process of tea plantation, manufacturing and circulation are often accompanied by the safety problems of pesticide residue, heavy metal, organic solvents and other exogenous risks. High-quality tea extract refers to the special tea extract obtained by enriching the specific components of tea. Through green and efficient extraction technologies, diversed high-quality tea extracts such as high-fragrance and high-amino acid tea extracts, low-caffeine and high-catechin tea extracts, high-bioavailability and high-theaflavin tea extracts, high-antioxidant and high-tea polysaccharide tea extracts, high-umami-taste and low-bitter and astringent taste tea extracts are produced. Furthermore, rapid detection, green control and intelligent processing are applied to monitor the quality of tea in real-time, which guarantee the stability and safety of high-quality tea extracts with enhanced efficiency. These emerging technologies will realize the functionalization and specialization of high-quality tea extracts, and promote the sustainable development of tea industry.

KEYWORDS

High-quality tea extract; tea functional components; green preparation; safety control; intelligent processing

HIGHLIGHTS

- Main high-quality tea extracts and their preparation methods were introduced.
- Potential pollutants in the processing of tea extracts and their detection methods were proposed.
- Emerging intelligent processing technologies of tea extract were summarized.
- The applications of high-quality tea extracts in food industry were explored.
- Future trends of tea extracts and relevant suggestions were presented.

1. Introduction

As one of the most consumed beverages in the world, tea is a globally popular health drink (Liang et al. 2021). Recently, "Traditional tea processing techniques and their associated social practices in China" has been added to United Nations Educational, Scientific and Cultural Organization (UNESCO)"s Representative List of the Intangible Cultural Heritage of Humanity. Generally, the processing steps of tea could be summarized as plucking, fixing, withering, rolling, fermenting and drying (Qi et al. 2018). Based on different processing steps, tea can be divided into six types: green tea, black tea, dark tea, yellow tea, white tea and oolong tea. Tea contains a variety of functional ingredients, such as tea polyphenols, theanine, theaflavins, tea saponins, and caffeine, which exhibits multiple physiological activities such as anti-tumor, anti-bacterial, anti-oxidation, anti-virus, prevention of cardiovascular and cerebrovascular diseases, and regulation of immunity (Tanaka et al. 2013; Wang et al. 2019, 2020; Wu et al. 2018; Zhang et al. 2021). To exert the key role of functional components in tea, the high valued tea products can enrich these components through a series of processing techniques.

China is the largest country to produce and consume tea in the world (Pan et al. 2022). The main exporters of Chinese tea include 129 countries and regions on six continents. Among them, Asia and Africa have become the main tea export market, accounting for more than 80% of total export volume. While the export volume of tea in China has reached a plateau, the continuous increasing yield has caused serious overcapacity and overstock of tea, which is urgent to broaden the supply and demand market of tea extracts. Tea deep processing is an important way to solve the outlet of low grade tea (summer and autumn tea), enhance the added value of tea, and expand the application field of tea across the boundary (Raghunath et al. 2023). Deep processing of

CONTACT Xinlin Wei foodlab2010@163.com
#The authors contributed equally to this work.

tea mainly refers to the separation and preparation of active components or functional components of tea by integrating several advanced processing technologies in biochemical engineering, separation and purification engineering with fresh tea leaves, pruned leaves, tea leaves, tea seeds, as well as semi-finished products, finished products or by-products derived from tea production, which are applied to human health, animal health, plant protection, household chemicals and other fields (Liu 2019). Up to date, tea extracts, as one of the terminal products in tea deep processing industry, have been widely used in foods, cosmetics and other industries. Nevertheless, the traditional processing techniques for preparing tea extracts involve hot water extraction or organic solvent extraction, which suffer from low extraction efficiency, residual organic solvents, high loss rate of functional components, and inability to perform directional extraction. Meanwhile, there are also safety risks in the process of tea manufacturing. The potential pollutants in tea mainly include pesticide residues, colorants, plasticizers, environmental pollutants, microorganisms, and toxic heavy metals (Abd El-Aty et al. 2014). Thereinto, excessive pesticide residues are often the most important issue in tea export, and the traditional extraction process fails to completely dissolve and desorb the pesticide residues in tea, which may cause safety problems (Chen et al. 2021).

High-quality tea extract refers to the tea extract obtained by directional enriching the specific active ingredients of tea through key extraction technologies. The preparation of high-quality tea extracts through emerging key technologies of green extraction and intelligent processing can improve extraction efficiency, enrich functional components and decrease safety risk. Meanwhile, as end products derived from high-quality tea extracts, tea products (such as instant tea and tea concentrate juice) are produced through cooling, filtration, concentration, drying, and packaging, are expected to become highly functionalized, which promotes the transformation of tea industry from quantity growth to quality improvement. The development of high-quality tea extracts will take the road of high-quality, personalized, and functionalized to improve the utilization rate and elevate the value of summer and autumn tea resources (low-end tea). This review summarized the recent progress of tea extracts and put forward future prospects, focusing on the applications of green and efficient preparation, safety detection and intelligent processing technologies of main high-quality tea extracts (high aroma and high amino acid tea extract, low caffeine and high catechin tea extract, high bioavailability and high theaflavin tea extract, high antioxidant and high polysaccharides tea extract, and high umami and low bitterness tea extract) (Figure 1) in the tea industry. Moreover, a brief introduction is proposed for the application of tea extracts in food industry. Furthermore, we put forward some future trends of high-quality tea extracts and relevant suggestions. This review will provide comprehensive reference for the innovation of key technologies and the high-quality development of the tea industry.

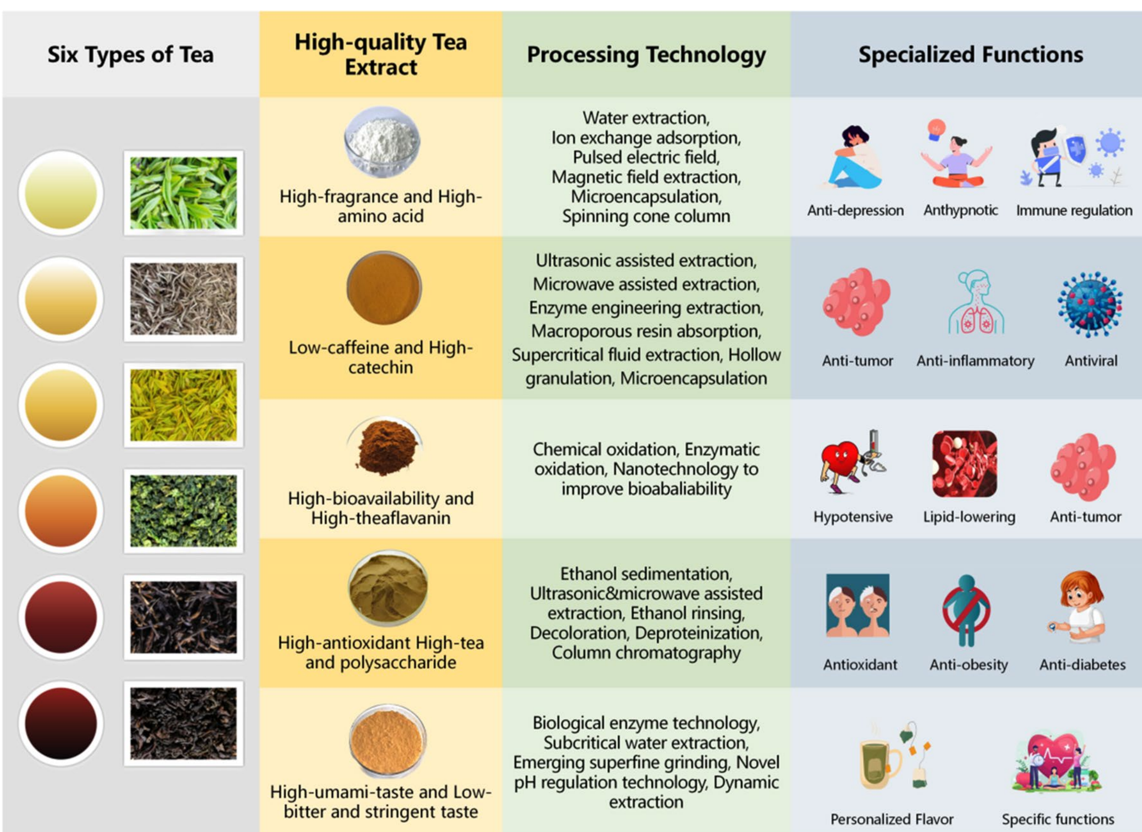

Figure 1. Main types, preparation technology and specialized functions of high-quality tea extracts.

2. Green preparation of high aroma and high amino acid tea extract with flavor preservation

Amino acids are the primary substance to make up proteins, accounts for 2%–5% of the dry weight of tea. As a unique amino acid in tea, theanine accounts for more than 50% of the free amino acids in tea and shows the main source of umami. In addition, theanine has shown various functions such as anti-depression, anthypnotic, anti-oxidation, anti-inflammation, and immune regulation (Chen et al. 2023; Huang et al. 2022; Shao, Wei, and Wei 2022; Wei, Wang, et al. 2022). Aroma is the sensation produced by volatile substances stimulating the olfactory nerves, and the aroma of tea is a comprehensive expression of dozens or even hundreds of aromatic substances, which involves in alcohols, aldehydes, ketones, acids and esters (Xu, Wang, and Gu 2019). High aroma and high amino acid tea extract means tea extracts with high content of aroma components and amino acids by extraction techniques. During the preparation of high amino acid tea extract, changes in different conditions often lead to the gradual loss of aroma substances. Therefore, optimization of the key technology of tea processing and application of high-fidelity flavor improvement technology can obtain high-aroma, high-amino acid and high-flavor fidelity tea extracts, which can further broaden the social supply of functional tea products and develop application prospects (Figure 2).

2.1. Effects of different processings on the change of flavor substances

2.1.1. Extraction

In the field of tea deep processing, the primary extraction process of tea functional components and flavor substances is still mainly concentrated in the water-ethanol solvent system. The principle of leaching is to dissolve the functional components in the tea tissue cells under the action of the solvent to further dissolve in the solvent system. Different extraction conditions will affect the flavor and extraction rate of tea extract. Specifically, the particle size of raw materials, extraction temperature, extraction time and solid-liquid ratio are the key factors affecting the extraction process (Yang et al. 2015). The smaller particle size of tea raw material causes the larger contact area with the solvent, which elevates the extraction efficiency of tea functional components. Extraction temperature usually show a positive correlation with extraction rate, but the high temperature will lead to the oxidation of functional components in tea and the occurrence of Maillard reaction, which has adverse effects on tea flavor. Prolonged extraction time may cause partial oxidation of tea polyphenols and complexation reactions between substances in tea soup, which deteriorates the quality of tea soup (Ramalho et al. 2013). The increase of solvent can promote the dissolution of tea functional components. While the increase of solid-liquid ratio will accelerate the extraction of tea extract, the excessive solvent used will damp the subsequent concentration steps.

2.1.2. Concentration

The concentration process has a significant impact on the preparation of high-quality tea extracts. Inappropriate concentration will cause the loss of flavor substances in tea extracts and reduce the quality of the product. Common concentration techniques mainly include vacuum evaporation concentration and membrane concentration. Vacuum evaporation and concentration is to heat the material under vacuum conditions, and evaporate the water in a relatively low temperature environment, which is widely used in the industrial processing of tea. The low-temperature vacuum concentration has been utilized to evaluate the sensory quality of different types of instant tea. It was reported that

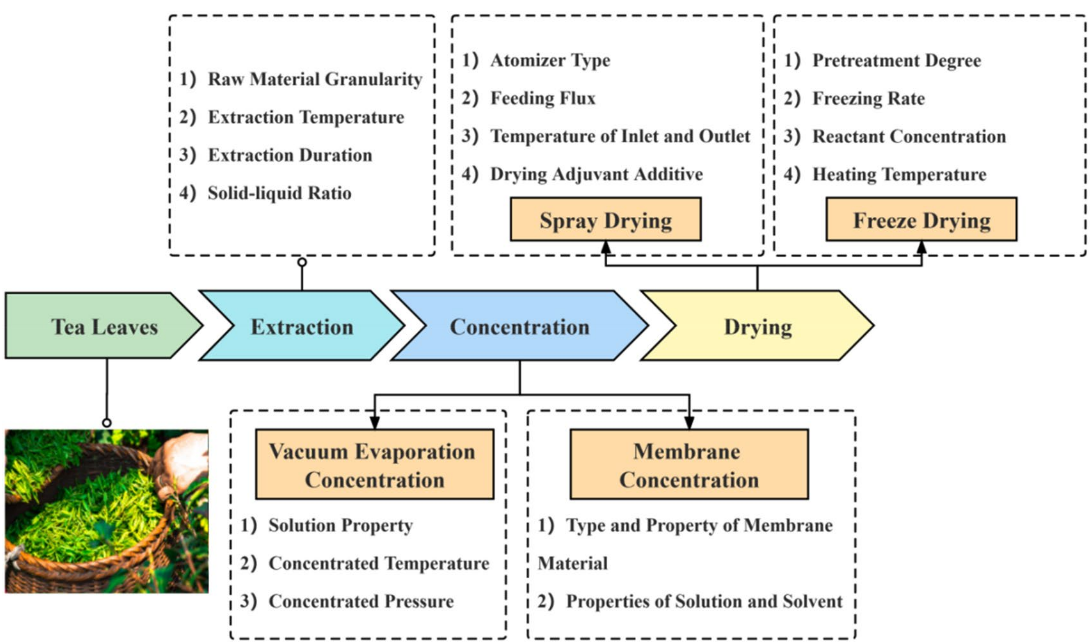

Figure 2. The factors of different process conditions affecting the content of flavor substances.

vacuum evaporation and concentration could better maintain the sensory characteristics of instant tea and improve the content of tea polyphenols and other physicochemical indicators. Nevertheless, it is easy to cause heat-sensitive components to volatilize during vacuum treatment in the production of low-quality tea extracts.

Membrane concentration can be divided into reverse osmosis (RO) concentration and nanofiltration (NF) concentration. The RO concentration is to apply pressure on one side of the membrane to overcome the natural osmotic pressure of the solution, thereby making the solvent reverse the direction of natural osmosis, which can produce high-quality tea extracts with higher retention of aroma and flavor compounds. Nevertheless, high pressure, irreversible membrane fouling, and limited concentration factor have constrained RO concentration from the industrial application (Rastogi 2016). Comparably, NF concentration can be operated at lower pressure and delivers high permeate flux with a low operating cost, which reduces the investment and operational cost of the equipment (Vincze and Vatai 2004). In a recent study, Bardhan, Subbiah, and Mohanty (2020) used an aquaporin embedded hollow fiber membrane module to prove that the tea extract can be concentrated without losing its aroma to draw solution. The developed model may be used for design and optimization of the large scale forward osmosis (FO) process for aqueous food and beverage industries.

2.1.3. Drying

Drying is a key part of the preparation of high-quality tea extracts. The optimization of the parameters of drying process can improve the extraction efficiency, flavor characteristics, and quality of tea extracts. Spray drying and freeze drying are the two most widely used drying techniques in the preparation of high-quality tea extracts. Spray drying has the advantages of low energy consumption, short drying time, low economic cost, and considerable retention of flavor substances and functional components (Shishir and Chen 2017). The parameters affecting spray drying mainly include atomizer type, feed flow rate, inlet and outlet temperature, and the use of drying aids (Zhang et al. 2022). Thi Anh Dao et al. (2021) used the spray-drying process to obtain the maximal polyphenol content of the green tea powder, suggesting that optimal spray-drying temperature, input flow rate were evaluated at 136 °C, 6.8 rpm, respectively. The total polyphenol content (TPC), EGCG, and caffeine content of 322.06 mg GAE/g, 11.4%, and 2.8% of dry basis, respectively. Moreover, the selection of drying aids is also an important factor affecting spray drying to improve drying efficiency and product quality.

The principle of freeze-drying is to quickly freeze the material at low temperature and heat it under vacuum conditions. The moisture in the material is directly sublimated from solid to gaseous state to achieve the purpose of drying. The process parameters affecting freeze-drying mainly include the degree of pretreatment, freezing rate, material concentration and heating temperature (Zhang et al. 2017). Vardanega et al. (2019) compared the effects of spray drying and freeze drying on the quality of tea powder, suggesting that spray drying and freeze drying showed no significant effect on the stability of functional compounds in tea powder. Notably, the moisture content of the material obtained by freeze drying was lower, and the freeze-dried particles showed a porous structure with a higher rehydration rate.

2.2. Theanine enrichment and extraction

2.2.1. Ion exchange adsorption

The ion exchange method is a more commonly used technology for theanine extraction, which is to use theanine itself as an ampholyte and achieve the separation of theanine under appropriate pH conditions (Lin et al. 2016). Wang, Gong, et al. (2012) used three continuous adsorption columns of polyamide, macroporous resin and cation exchange resin to adsorb and separate tea polyphenols, caffeine and theanine, respectively, which obtained theanine crystals with a purity of 98% and the recovery rate of 78.8%. Yang, Dong, et al. (2022) reported that adsorption of L-theanine onto the cation resins was influenced by the acidity, contact time and temperature. The adsorption behavior could be described by the pseudo-second-order rate equation and fitted to Langmuir and Freundlich models. Different adsorption rate and selectivity between different resins might be attributed to the distinctive structure of resins and different ionization of adsorbates. This method has the advantages of facile operation, environmental protection, and high extraction efficiency (Zhang et al. 2020).

2.2.2. Pulsed electric field

High voltage pulsed electric field (PEF) is a new extraction technology with short processing time, low processing temperature and high extraction rate (Table 1). PEF can place a complex biological sample between two electrodes exposed to a high-intensity electric field, and apply a voltage in the form of repeated pulses with a duration of about a few nanoseconds to a few milliseconds to break the cell wall, thereby elevating the extraction rate of theanine (Liu, Liu, et al. 2022). Ye et al. (2014) used PEF-assisted extraction combined with vacuum freeze-drying to prepare high-aroma instant tea powder, and demonstrated that the optimum PEF extraction conditions of the main chemical components were 1:16 of tea-water ratio, 20 kV·cm^{-1} of electric field strength, and 125 Hz of pulse frequency, which can better preserve the original flavor of tea.

2.2.3. Magnetic field extraction

Magnetic field is divided into stable magnetic field and alternating magnetic field, which can produce certain biological effects on organisms with the advantages of nontoxic, pollution-free, and high safety (Table 1). Tarapatskyy et al. (2018) effectively improved amino acid content in tea infusion through magnetic field extraction technology. During the brewing process of green tea and black tea infusion samples, the free amino acids in the tea soup changed significantly after the application of variable magnetic fields at the

Table 1. Advantages and disadvantages of common extraction techniques in tea extracts

Type	Techniques	Advantages	Disadvantages
Extraction	Microwave-assisted extraction (MAE)	Strong penetrativity, fast heating rate, high extraction efficiency, low solvent dosage, energy conservation	The sample and the extract are still in contact after the extraction, which need further separation; High temperature easily leads to the degradation of thermally labile compounds
	Ultrasonic-assisted extraction (UAE)	High extraction efficiency, short extraction time, energy-saving process, low solvent consumption	The effect of the acoustic decay
	Enzyme-assisted extraction (EAE)	High catalytic efficiency, strong specificity, mild reaction conditions, low solvent consumption, high extraction efficiency	Optimization of appropriate enzyme species and ratio of mixed enzymes
	Supercritical Fluid Extraction (SFE)	High extraction rate, nontoxic and non-flammable extraction solvent, green environmental extraction process	The balance of the solvent and solute; the residue of cosolvent; high equipment operating cost
	Subcritical Water Extraction (SWE)	Good solvent dispersion, fast processing speed, non-solvent residue	High cost. High pressure makes it difficult to add solids
	Pulsed Electric Field (PEF)	Short processing time, low processing temperature, high extraction rate, high selectivity	The effect of the dielectric composition conductivity. high price of the equipment
	Macroporous Resin Absorption	Large specific surface area, large adsorption capacity, fast adsorption speed, mild adsorption conditions, good selectivity, low cost	Residue of organic solvent, optimization of appropriate resin species
Separation	Membrane Separation (MS)	Suitable for heat-sensitive substances, no phase change, no chemical change, good selectivity, low energy consumption	Poor degradability, poor continuous production capacity due to the easily clogging membrane
	Solvent separation	Continuous operation, high speed, high purity, less damage to heat-sensitive substances	Large amount of solvent, high equipment and safety requirements
Purification	Sevage method of deproteinization	Mild reaction conditions, simple process, not easy to change the material structure	Too much elution times, low purity
	Column chromatography	Low energy consumption, high reusability, high purity	Complicated process, long time consumption, large amount of solvent, difficult to industrialize

frequency of 100 mT and 50 Hz. Amongst, the total amino acid content of green tea increased by 8.5%, and the essential amino acid content increased by 17% on average. Moreover, the content of amino acids and essential amino acids in black tea infusion increased by 4.7% and 12.6% on average. Therefore, magnetic field assisted extraction technology can be used as an effective technology to enrich amino acids in high quality tea extract.

2.3. Flavor preservation

2.3.1. Microencapsulation

Microencapsulation is a high-tech food processing technology emerging in the food and pharmaceutical industries, which has a good preservation effect on the aroma and other flavor characteristics of food (Rodrigues and Grosso 2008). In the production of tea beverages, β-cyclodextrin (β-CD) has a better effect of maintaining and strengthening flavor (Hu et al. 2021). Since β-CD has a cavity-like structure, it is suitable for embedding active ingredients such as tea polyphenols and theanine, which is widely used in tea processing. Cui et al. (2017) showed that aqueous BCD offered a better yield to recover epigallocatechin from tea leaves than that obtained using an aqueous 50% ethanol solution, which can further improve the flavor of tea.

2.3.2. Spinning Cone column

Spinning Cone Column (SCC) is a highly efficient and unique liquid-gas contact distillation technology. The principle of this technology is to reduce the boiling point of materials by increasing the vacuum, thus separating various substances with different boiling points at a relatively low temperature (Yu, Jiang, and Xiao 2013). SCC can effectively avoid the loss of volatile flavor substances based on maintaining the extraction rate of main chemical components. Presently, there are several patents using the SCC technology to retain the volatile aroma substances in Tieguanyin instant tea powder and retain its original flavor. In particular, an Australian company named Flavourtech used SCC technology to elevate the retention rate of key aroma components such as aldehydes and cis-hept-2,4-dienal with tea flavor by more than 11 times.

3. Green and efficient extraction of tea extract with low caffeine and high catechin

Catechin is the main functional component in tea, mainly including epigallocatechin gallate (EGCG), epigallocatechin (EGC), epicatechin gallate (epicatechin gallate, ECG), and epicatechin (EC) (Rains, Agarwal, and Maki 2011). Catechin has outstanding performance in anti-inflammatory, anti-cancer, anti-oxidation, antiviral and other aspects (Jiang et al. 2022). The intake of caffeine can cause some adverse effects including sleep deprivation, heart palpitations, and anxiety (Tfouni et al. 2018) among some intolerable people. Through the related separation and extraction technology, caffeine in the tea extract can be effectively removed to elevate the content of catechins. Therefore, the quality of tea extract can be improved by using green high-tech to prepare low-caffeine and high-catechin tea extract products, which can meet the requirements of the high functional demand of market (Figure 3).

3.1. Catechin enrichment and extraction and caffeine separation and extraction

3.1.1. Ultrasonic or microwave assisted extraction

Ultrasonic or microwave assisted extraction is the most common extraction technology combined with traditional solvent extraction, which shows the advantages of high

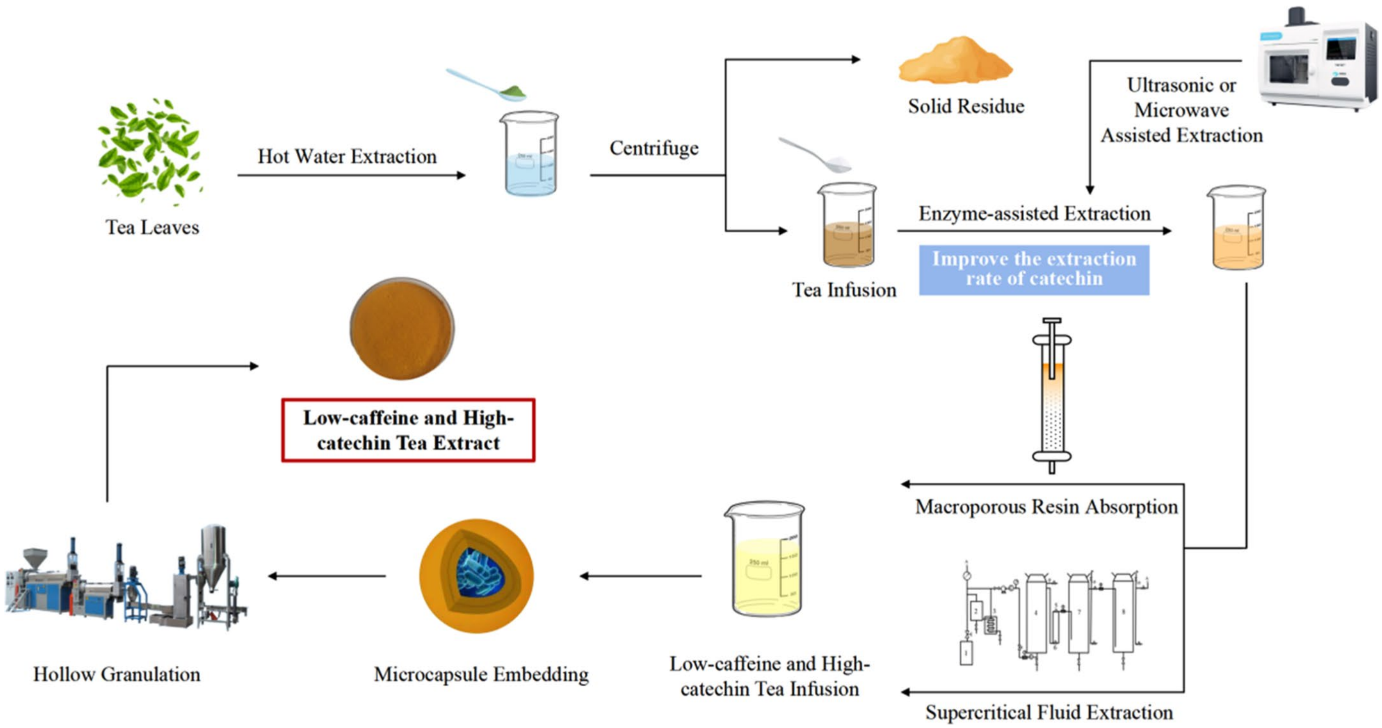

Figure 3. The flow chart of the preparation of low caffeine and high catechin tea extracts.

extraction efficiency, short extraction time, less solvent usage, and energy saving (Table 1). The optimization of extraction conditions (extraction time, temperature and power) is the core of ultrasonic or microwave-assisted extraction. Fujioka et al. (2022) combined ultrasonic- and microwave-assisted extraction of catechins from green tea, indicating that combined extraction could improve the extraction rate of EGCG, which was several times higher than that of ultrasonic or microwave extraction alone. Moreover, the combined extraction also exhibited high stability and limited oxidative degradation of catechins at high temperature. Luo et al. (2020) combined ultrasonic-assisted extraction with deep eutectic solvent to extract green tea polyphenols. The optimal parameters were solid-liquid ratio of 1:36 (g/mL), ultrasonic power of 461.5 W and ultrasonic time of 21 min, which increased the total phenol content by 31%. Therefore, suitable extraction conditions combined with ultrasonic- or microwave-assisted extraction can effectively increase the content of catechin in tea extract.

3.1.2. Enzyme engineering extraction

The enzyme engineering extraction method uses pectinase, cell separation enzyme and cellulase to decompose or soften plant cell walls and promote the outflow of intracellular components, which improves the extraction rate of bioactives (Li, Fang, et al. 2020). Compared with ultrasonic- and microwave-assisted extraction, enzymatic extraction has the advantage of low cost without the need for expensive new equipment (Table 1). Enzymatic extraction can be carried out at room temperature without organic solvent to guarantee the purity, stability and activity of the product. Furthermore, some active ingredients can be modified and transformed to make the products have stronger biological activity *via* enzymatic extraction. In the future, the introduction of enzyme engineering into industrial large-scale production is expected to reduce production costs and improve extraction efficiency. Chandini et al. (2011) compared the efficiency of pectinase- and tannase-assisted extraction of polyphenols from black tea, suggesting that pectinase treatment can increase the extraction rate of polyphenols by 11.5%, while tannase treatment can enhance the hydrolysis activity of gallic acid and improve its solubility, thereby further increasing the extraction rate of polyphenols by 14.3%. Huang et al. (2013) used tannase-assisted extraction of catechins in tea stem extracts, showing that tannase-assisted extraction elevated the content of catechins in tea stems, and the galloylated catechins were transformed into non-galloylated catechins. The enzyme engineering extraction method has shown the advantages of facile and efficient extraction, environmental protection, and high safety, which exhibits a good development prospect in the field of high-quality tea extract processing.

3.1.3. Macroporous resin adsorption

The principle of macroporous resin adsorption is determined by its physical structure including its pore size and external surface area. After the solution passes through the macroporous resin, the components to be separated are adsorbed. Due to the different pore sizes inside the resin, different components will be left after the solution enters, and then the macroporous resin will be eluted and recovered to extract, separate, and purify the desired effective components (Table 1). Wang, Chen, et al. (2021) compared the adsorption capacity and separation effect of three traditional resins and four new resins on EGCG and ECG to investigate the reusability of the resins. The purity of EGCG and ECG reached 95.87 ± 0.89% and 95.55 ± 1.30%, the total recoveries were 58.66% and 62.45%, respectively, and there was no significant difference in the perfermance after the resin was reused 6 times. Sevillano et al. (2014) compared the effects of seven different types of macroporous resins on removing caffeine from green tea, and then scored the relevant parameters, indicating that the best resin was Diaion 20HP with a score of 90.50%. However, the high demand of resin in the extraction process makes it difficult to be widely applied in industrial production.

3.1.4. Supercritical fluid extraction

Supercritical fluid extraction (SFE) is an emerging technology for extracting active ingredients from solid and liquid matrices using supercritical solvents. The critical temperature of CO_2 is close to room temperature as one of the most environmentally friendly solvents for extraction, which has the advantages of non-flammable, nontoxic, non-carcinogenic, non-corrosive, and no waste. SFE has the characteristics of high extraction rate and short time as one of the most used methods for extracting catechins and removing caffeine (Table 1). Münevver Sökmen, Demir, and Alomar (2018) used supercritical fluid to extract caffeine and catechins in green tea, and the extraction rate of catechins reached the highest at 25 MPa, 60 °C, ethanol as a modifier, and a flow rate of 0.5 mL/min for 3 h. The supercritical CO_2 extraction method showed good results in both extracting catechins and removing caffeine. Kim et al. (2008) used supercritical CO_2 and water as co-solvents to selectively extract caffeine from green tea while retaining a large amount of EGCG, showing that the removal rate of caffeine reached 66%.

3.2. High-quality tea extract with low caffeine and high catechin

3.2.1. CO_2 hollow granulation

Due to the limitations of uneven drying, small powder particle size, moisture absorption, and agglomeration in traditional spray drying or freeze drying, it is necessary to improve the quality of powder through granulation technology with enhanced stability and instant solubility. Presently, the common granulation technology mainly includes fluidized spray granulation method, crushing granulation method and boiling granulation method. CO_2 hollow granulation technology is to mix tea liquor with CO_2 before spray drying. The mixture will form a hollow structure under the action of the atomizer to improve the properties of the powder. Belščak-Cvitanović et al. (2015) used the hollow granulation method to effectively evaluate the bioactive components in tea extracts. The results showed that up to 162 mg/g of EGCG was achieved, while low-caffeine contents (<5 mg/g) indicated the potential of obtaining low caffeine functional ingredients.

3.2.2. Microencapsulation

Microencapsulation refers to the use of thin films or matrices to cover and surround liquid or solid particles with tiny droplets or particles (Choudhury, Meghwal, and Das 2021). This technology has been widely used to improve the quality of tea products, mainly including the production of high-quality instant tea, the suppression of cloudiness after cold, the extension of shelf life, the moisture-proof and shaping of instant tea (Liang et al. 2022). In a previous study, Reddy et al. (2020) used β-CD to encapsulate catechin and flavonol extracts, which effectively improved the thermal stability of the extract and enhanced its free radical scavenging ability. Due to the structure of multiple phenolic hydroxyl groups, catechin is easily oxidized and decomposed, resulting in a decrease in its bioavailability. Microencapsulation can effectively improve the stability of catechin and ensure its high bioavailability. Zhang and Zhao (2015) used ionic gelation method to prepare nano-scale microcapsules by embedding tea polyphenols in Zn and chitosan to improve their stability, and the encapsulation efficiency was as high as 97%. Moreover, the free radical scavenging ability of TP-Zn composite microcapsules is higher than that of free tea polyphenol monomers, and therefore microencapsulation retains the bioavailability of tea polyphenols and improves their antioxidant capacity.

4. Directional preparation of tea extract with high bioavailability and high theaflavins

Theaflavins are mainly a general term for a class of compounds with a benzotropenone structure formed by oxidative condensation of catechins and their derivatives under the catalysis of polyphenol oxidase and other enzymes (Xu et al. 2022; Xue et al. 2019), which exhibit various physiological activities such as lowering blood pressure, reducing blood fat, anti-oxidation, and strengthening skeletal muscle (Xu et al. 2023). In addition, theaflavins also effectively improve the sensory properties of black tea. Nevertheless, the unique chemical structure of theaflavins results in unstable chemical properties and low bioavailability.

4.1. Mechanism of oxidation of catechin to theaflavins

The oxidation process of catechin to theaflavins is complicated. The chemical structure of catechin contains multiple unstable phenolic hydroxyl groups, among which the phenolic hydroxyl groups on the B ring are easily oxidized to form o-quinones under the action of polyphenol oxidases. Furthermore, o-quinones are easy to oxidize, polymerize and condense to form theaflavins, thearubigins and theabrownins (Kusano et al. 2015). Matsuo, Tanaka, and Kouno (2009) found that pyrogallol-type catechins and catechol-type catechins were easily oxidized to form theaflavins and diflavanols under the catalysis of polyphenol oxidase. Stodt et al. (2014) proved that theaflavins could only be produced by enzymatic oxidation in the simultaneous presence of trihydroxy-B-ring flavanols and dihydroxy-B-ring flavanols. Therefore, theaflavins is mainly formed through the oxidation of catechins by enzymatic reactions, and the enzymatic oxidation of catechins is more complicated and variable. Currently, the main research is on the single pathway of catechin oxidation, that is, the formation of theaflavins through enzymatic reactions. There are few studies on the joint action of multiple production pathways, therefore, the formation mechanism of theaflavins needs to be further explored.

4.2. Preparation technology of high theaflavin tea extract

The traditional extraction method of theaflavins is mainly solvent extraction, which is facile to operate and can be applied to large-scale industrial production. However, this method has limitations such as low extraction rate of theaflavins and difficulty in separation and purification (Luo et al. 2017). Therefore, the methods for preparing theaflavins by simulated oxidation have been widely used, including chemical oxidation and enzymatic oxidation (Figure 4).

4.2.1. Chemical oxidation

Catechin is easily oxidized to produce theaflavins under the action of chemical oxidants. The common chemical oxidants mainly include $K_3Fe(CN)_6$, $NaHCO_3$, $FeCl_3$, etc (Shan et al. 2010). Compared with the preparation of theaflavins by enzymatic oxidation, chemical oxidation uses oxidant instead of enzyme for catalysis, which avoids the influence of unstable enzyme activity with the advantages of simplified preparation process and strong controllability. Li and Xiao (2004) selected an acidic oxidant to oxidize tea polyphenols *in vitro* to prepare theaflavins. Meanwhile, they established a two-liquid phase oxidation system and optimized related parameters to elevate the content of theaflavins. Zhang, Jiang, and Jiang (2008) compared three different acidic oxidants to prepare theaflavins, suggesting that the production of theaflavins was positively correlated with the concentration of oxidants, and $FeCl_3$ exhibited the best oxidation effect. Moreover, all three oxidants contain Fe^{3+}, which play a key role in the oxidation of catechins to theaflavins.

4.2.2. Enzymatic oxidation

During the processing of tea leaves, catechins will be oxidized under the catalysis of different types of enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) to generate various oxidation products, including theaflavins and thearubigins. The preparation of theaflavins by enzymatically oxidizing catechins is a widely used technology. In a recent study, Liu et al. (2023) developed a high-theaflavin instant black tea by optimizing enzymatic oxidation, using PPO to catalyze oxidation *in vitro*, and then optimized the enzyme addition amount, pH, reaction time, reaction temperature and other conditions to elevate the final average content of theaflavins to 2.11 ± 0.04%. In another study, Hua et al. (2021) explored the effects of PPO, POD and enzymes extracted from fresh tea leaves (EEFT) on the formation of theaflavins during *in vitro* liquid fermentation. The results demonstrated that EEFT showed the strongest catechin oxidation ability and could oxidize over 90% of catechin within 15 min, but the applicability of this enzyme source was still limited. In addition, PPO demonstrates the second strongest catechin oxidizing ability with a constant oxidation rate to promote the production of theaflavins.

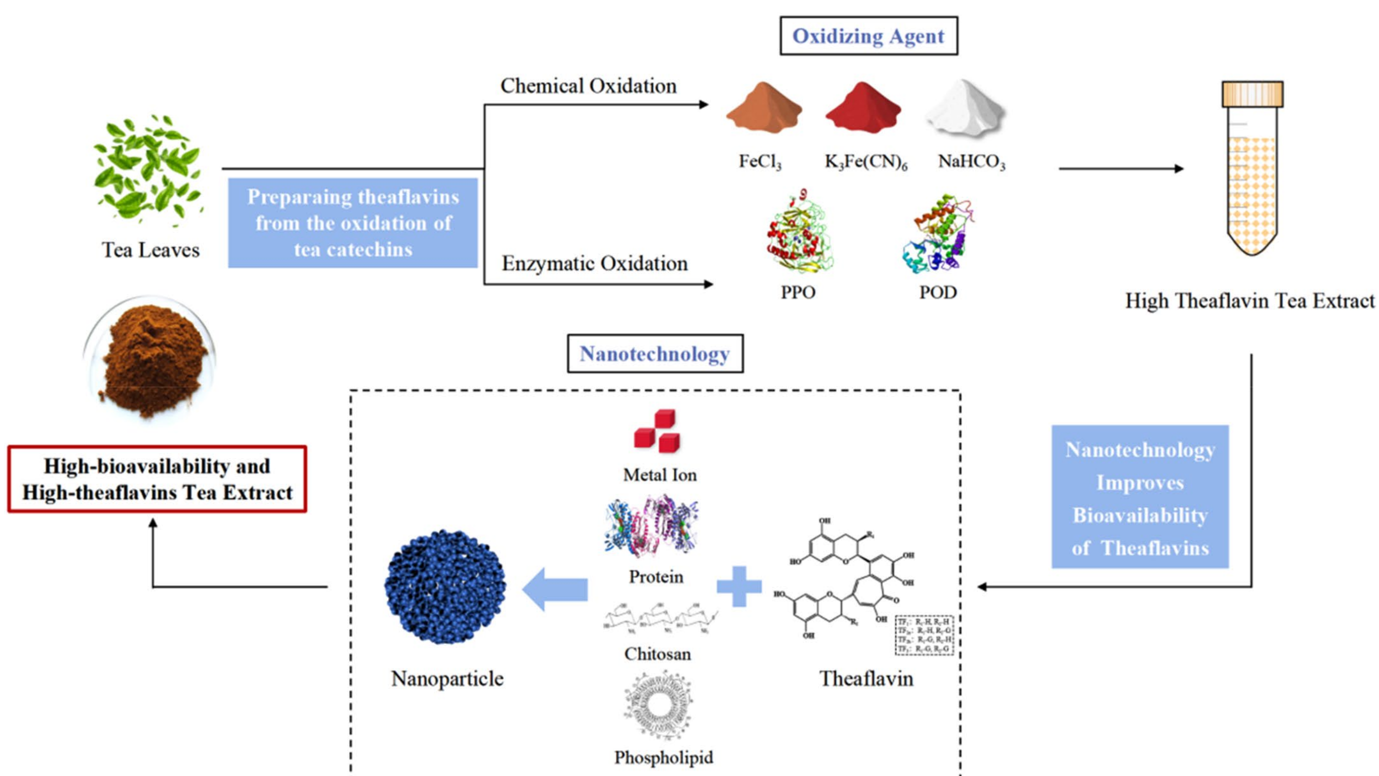

Figure 4. The flow chart of the preparation of tea extract with high bioavailability and high theaflavins.

4.3. Nanotechnology improves bioavailability of theaflavins

Theaflavins have shown high biological activities in different models, such as inhibiting pro-inflammatory cytokines, preventing DNA damage in lymphocytes, and reducing the formation of reactive oxygen species (ROS) (Pereira-Caro et al. 2017). Nevertheless, there are few studies on the bioavailability of theaflavins in human, indicating that theaflavins are undetected in the upper and lower digestive tracts after oral administration, which are also not easily absorbed and transported in the intestinal tract with a poor bioavailability (Chen, Parks, et al. 2011). Since theaflavins are the oxidation products of catechins, many studies have proved that the preparation of catechin loaded delivery system can also improve the bioavailability of catechins. Therefore, combining theaflavins with nanomaterials to improve their bioavailability can maintain the unique biological activities of theaflavins. Li, Xiao, et al. (2019) combined SM^{3+} with EGCG to obtain metal nanoparticles by self-assembly, which effectively inhibited the proliferation of B16F10 cells without harming the activity of other normal cells. Maity et al. (2019) combined gold nanoparticles AuNPs with theaflavins to form nanocomposites to enhance the anticancer properties of theaflavins against ovarian cancer, showing that the nanocomposites exhibited a stronger inhibitory effect than theaflavin alone to cancer cells. In addition, different delivery carriers can be developed and constructed to improve the stability and bioavailability of natural active ingredients such as theaflavins (Wei et al. 2018). Some studies have proved that the stability and bioavailability of bioactives *in vitro* and *in vivo* can be effectively improved by modulating the physicochemical properties, molecular interactions and microstructure of composite nanoparticles with the aid of high pressure mircofluidization, thermal treatment and other extra processings (Wei, Wang, et al. 2022; Wei et al. 2020).

5. Functional preparation technology of high antioxidant and high tea polysaccharide tea extract

Tea polysaccharide (TPS) is a plant polysaccharide extracted from tea leaves, which is a kind of heteropolysaccharide combined with protein. TPS has shown various biological activities such as antioxidant, anti-diabetes, and anti-obesity (Chen et al. 2018; Fan et al. 2022; Li, Xiao, et al. 2019). Nevertheless, previous studies have shown that the content of TPS in low-quality teas is generally higher than that in high-quality teas. The content of TPS in low-quality tea leaves is 0.8% to 1.5%, while the content of TPS in high-quality tea leaves is 0.4% to 0.9% (Xiao et al. 2011). Therefore, efficiently extracting TPS from low-quality tea and strengthening their functions will promote the high-value application of low grade tea resources, which will turn "waste" into "treasure" (Figure 5).

5.1. Preparation technology of high-purity tea polysaccharide tea extract

5.1.1. Tea polysaccharide extraction

Presently, the most used method for extraction of TPS is water extraction and alcohol precipitation, which has the advantages of facile operation, low cost, and pollution-free.

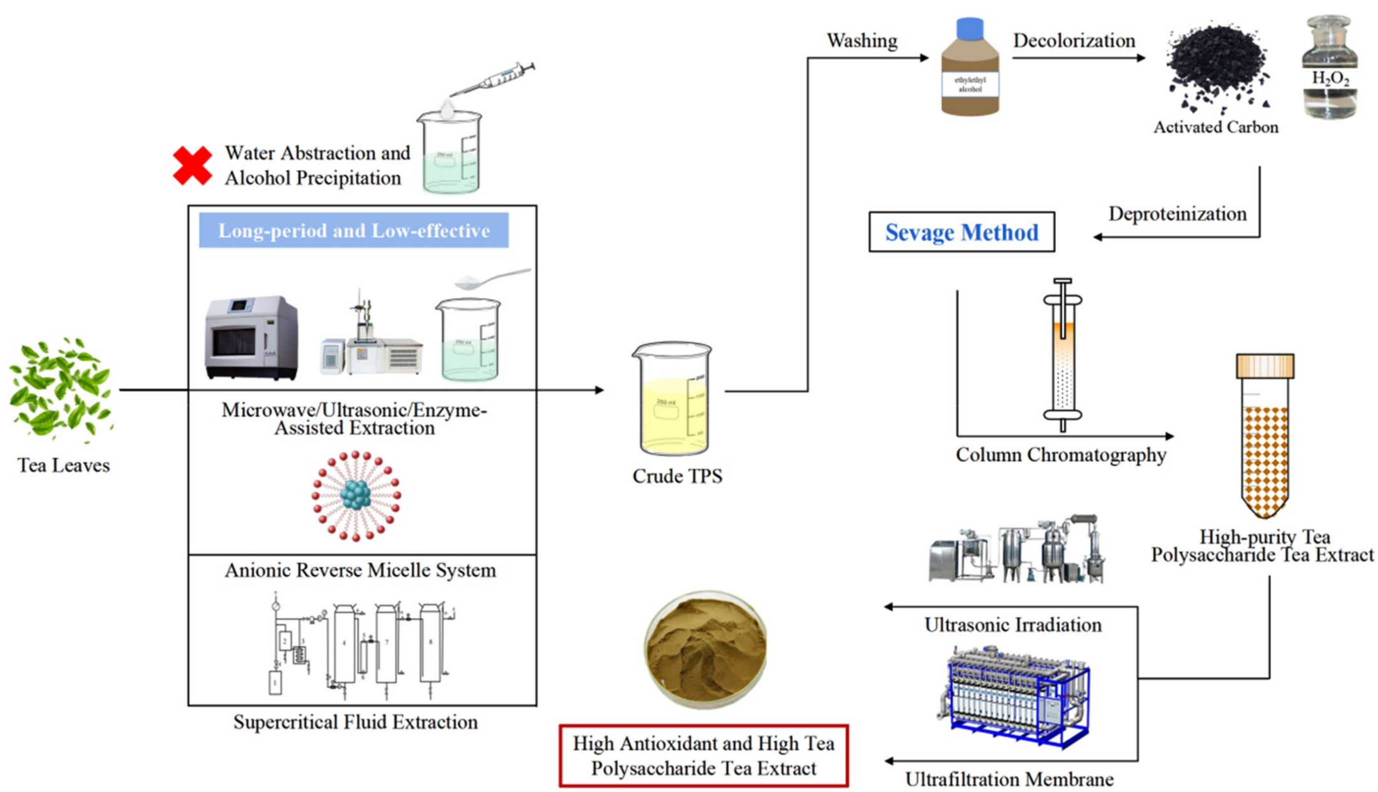

Figure 5. The flow chart of the preparation of high antioxidant and high tea polysaccharide tea extract.

However, the lengthy extraction time and low extraction rate restrict the industrial application of this method. Therefore, auxiliary methods such as microwave-assisted extraction, ultrasonic-assisted extraction, and enzymatic hydrolysis-assisted extraction are considered to improve the extraction efficiency. Tsubaki et al. (2008) used microwave-assisted extraction to obtain TPS from tea residues of different teas (green tea, black tea and oolong tea). Under the conditions of solid-liquid ratio of 1:20, extraction temperature of 200–230 °C and extraction time of 2 min, the yield of TPS was 40–50%. Karadag et al. (2019) optimized the ultrasonic-assisted extraction conditions of low-quality green tea polysaccharides, and made the recovery rate of TPS reach 4.65 ± 0.29%. Zhu et al. (2020) compared the effects of water extraction, ultrasonic-assisted extraction, microwave-assisted extraction and enzymatic-assisted extraction on the extraction rate of TPS, and the highest total sugar content of crude TPS obtained by enzymatic-assisted extraction was 71.83% and the polysaccharide yield was 4.52%. The auxiliary extraction technology can effectively shorten the extraction time of TPS with the elevated extraction rate under the condition of ensuring the economic cost and safety. In addition, TPS can be extracted through related high-tech, such as supercritical CO_2 extraction technology and anion reverse micellar system. Li and Xiao (2014) used anion reverse colloid beams to extract TPS and elevated the extraction rate of TPS to 34% under the optimized conditions. Chen, Parks, et al. (2011) used supercritical CO_2 technology to extract TPS, and the optimal parameters were 2 h of extraction time, 45 °C of extraction temperature, 35 MPa of extraction pressure, and 20% of absolute ethanol, which elevated the extraction rate of TPS to 92.5%. Except for ensuring efficient extraction of TPS, these technologies show the advantages of good selectivity, fast mass transfer, environmental protection, high safety, and low cost (Table 1).

5.1.2. Separation and purification of tea polysaccharide

As a type of macromolecular heteropolysaccharides, TPS contain polyphenols, proteins, pigments, inorganic salts and other small molecular substances (Chen et al. 2016). After extracting TPS from tea leaves, further separation and purification are required to improve the quality of TPS to remove substances that may interfere with subsequent qualitative and quantitative analyses. Ethanol washing is currently the easiest way to remove small molecular substances and inorganic salts in TPS. Mao et al. (2014) extracted TPS by water extraction and alcohol precipitation, washed them three times with absolute ethanol, acetone, and ether to remove small molecular substances and inorganic salts, and then further separated and purified them by column chromatography. Common decolorization methods mainly include activated carbon decolorization and H_2O_2 decolorization. Chen, Parks, et al. (2011) used H_2O_2 to bleach TPS at 30 °C for 1 h to decolorize them. Quan et al. (2011) used 5% (g/L) activated carbon to decolorize TPS. Qin et al. (2021) used the Sevag method to remove the protein in TPS, and used polyamide resin for dynamic adsorption decolorization. After washing, decolorization, deproteinization and other treatments, TPS are further purified by column chromatography according to molecular weights and polarities. Zhao et al. (2022) eluted TPS through DEAE-cellulose 52 column and Sephadex G-100 column in turn, and the total sugar content of the components with high recoveries in the three groups were 90.04 ± 2.46%, 78.28 ± 2.35% and 87.32 ± 1.47%. The TPS purified by column chromatography can be used for further research on physicochemical properties and biological activities.

5.2. High antioxidant functionalized tea polysaccharide extract

The antioxidant properties of polysaccharides are one of the main action mechanisms for their anti-tumor, anti-inflammatory, hypoglycemic, and lipid-lowering effects (Hao et al. 2022). Therefore, the natural antioxidant properties of TPS have become the focus of research and the use of functional enhancement technologies can improve the antioxidant capacity of TPS. In a recent study, Wang, Chen, et al. (2021) reported that the ultrasonic radiation could enhance the antioxidant properties of yellow tea polysaccharides with different molecular weights. Since the natural hydrogen bonds of polysaccharides are destroyed during sonication, the DPPH radicals generated by sonication can obtain more hydrogen atoms from the degraded polysaccharides to improve the scavenging ability of yellow tea polysaccharides on DPPH radicals. Wang, Gong, et al. (2012) studied the effect of ultrafiltration membrane technology on the antioxidant activity of crude TPS in low-quality tea. Among the obtained three groups of polysaccharide fractions with different molecular weights (TPS1, TPS2, TPS3), TPS1 showed the strongest free radical scavenging activity with the highest antioxidant activity. Therefore, TPS with high antioxidant activity can be screened out from tea samples by different extraction techniques to achieve high functionalization of TPS extracts.

Tea polysaccharide extract has exhibited abundant biological functions due to its antioxidant activity, such as anti-tumor, regulating the gut microbiota, and hypoglycemic effects. Recently, Liu, Liu, et al. (2022) investigated the anti-tumor activity *in vitro* of a water-soluble polysaccharide (DTP-1) from dark tea, indicating that DTP-1 could suppress the activity of the cancer cells through induction of cell apoptosis and inhibition of cell migration. Chen et al. (2020) studied the effect of TPS from tea flower (TFPS) on regulating the intestinal health, showing that TFPS contributed to the maintenance the intestinal barrier. The analysis of gut microbiota showed that TFPS increased probiotic *Lactobacillus* and decreased the risk of *Akkermansia*, indicating that TFPS can improve the intestinal health. Li, Fang, et al. (2020) reported the effect of TPS on diabetes and hypoglycemic activity in a type 2 diabetic rat model, suggesting that TPS can restore the reduced abundance of some bacterial genera. Furthermore, TPS exerted the hypoglycemic and hypolipidemic effect on type 2 diabetes *via* the modulation of gut microbiota and the improvement of host metabolism.

6. Green preparation of tea extract with high umami and low bitterness

With the continuous development of tea industry, the consumption demand of modern society is gradually changing to specialization, precision and individualization, and the quality of tea products should be more targeted. The taste of tea is the feeling produced by stimulating the taste organs after the taste substances in tea soup are integrated in the mouth (Xu, Wang, and Gu 2019). Tea has a unique strong bitter taste, but some people have low acceptance of this taste substance and have a high acceptance of umami in tea. Therefore, the specific preparation of high-freshness and low-bitterness tea extracts can realize the product specialization and individualization.

6.1. Taste substances

The taste substances in tea extract are composed of catechins, alkaloids, anthocyanins, saponins, organic acids, amino acids and soluble sugars (Figure 6). These taste substances interact with each other under different proportions to form five distinct flavors, namely bitterness, astringency, sourness, sweetness and umami. Thereinto, the main flavors of tea extracts are bitterness, astringency and umami.

6.1.1. Main bitter substances

The bitter taste originated from the mediation of the second taste receptor family (TAS2Rs) (Zhang et al. 2020). The major bitter substances include catechins, caffeine, anthocyanins, and tea saponins. Catechins is one of the most important compounds in tea extract contributing to bitterness, and EGCG is the crucial monomer in catechins. The content of caffeine is the highest of total alkaloids in tea. Different types of teas have similar range of caffeine content, indicating that caffeine is adapted to various extraction techniques. Moreover, there is a certain synergy between EGCG and caffeine in increasing the bitterness of tea extracts (Yin et al. 2014). Anthocyanins are mainly found in the purple tea leaves, which increase the bitterness of tea extract, but anthocyanins can easily be oxidized due to its instability.

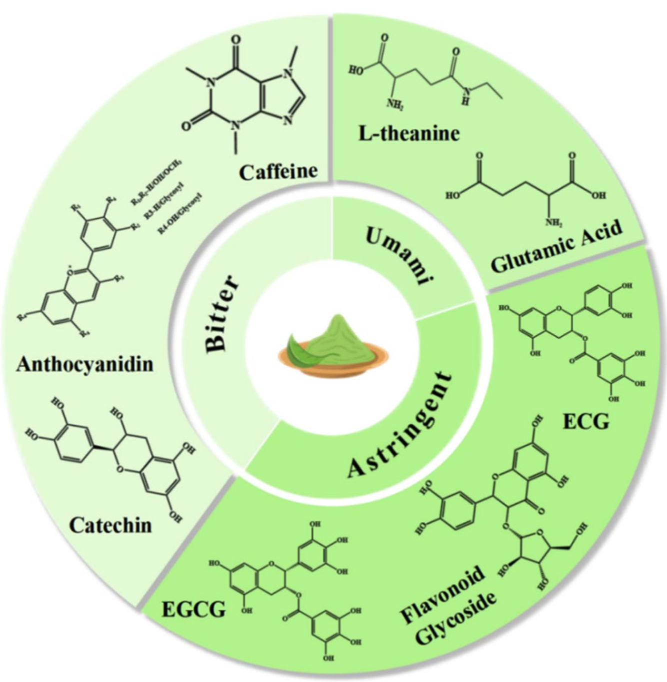

Figure 6. The main flavoring substances in tea extracts.

6.1.2. Main astringent substances

Astringency, which is generally accepted as a tactile sensation of the tongue caused by the interaction of polyphenols and salivary proteins, has been found to greatly influence the taste of tea (Xu, Ji, et al. 2018). Galloylated catechins, flavonoid glycosides, and phenolic acids containing galloyl groups are main astringent compounds. The spatial structure is the main reason for the astringency of different galloylated catechins, which is positively correlated with the number of hydroxyl groups on the benzene ring (Ye et al. 2022). Flavonoid glycosides have extremely low taste threshold values, which more easily contribute to the astringent taste (Scharbert, Holzmann, and Hofmann 2004). Moreover, the existence of flavonoid glycosides may also increase the bitterness caused by caffeine (Scharbert and Hofmann 2005). Phenolic acids are regarded as important taste substances in tea extract because of their high solubilities, which are associated with the astringency taste. Phenolic acids in tea mainly include gallic acid, tannic acid and chlorogenic acid (Yin et al. 2018).

6.2. Extraction technology

6.2.1. Biological enzyme extraction

Compared with other bitter taste substances, catechin has the highest content in tea extract and the ester catechin EGCG is the main monomer. Therefore, reducing the total amount of catechins and galloylated catechins in tea extract can prepare the tea extract with low bitterness and astringency. Presently, the most extraction technology for reducing bitterness and astringency is biological enzyme extraction. As the most widely used enzyme, tannase can break the ester bonds in galloylated catechins to degrade them into non-galloylated catechins and reduce the total amount of catechins. Zhang and Zhao (2015) used laccase and α-galactosidase to assist the extraction to reduce the bitterness and astringency of oolong tea. The results showed that the content of catechins and total polyphenols after enzyme treatment decreased by 11.9% and 13.3%, respectively, and the content of total soluble sugar and water extract increased by 19.4% and 6.6%, respectively. The reduction of catechin and total polyphenol content reduced the bitterness and astringency of summer tea, while the increase of soluble total sugar and water extract content improved sweetness and mellow taste. Li et al. (2017) sprayed different concentrations of tannase on the surface of tea samples to assist the preparation of tea extracts. The results showed that the content of three non-galloylated catechins

EGC, EC, GC increased from 308.7 μg/mL, 47.6 μg/mL, 28.3 μg/mL to 359.6 μg/mL, 54.3 μg/mL, 79.8 μg/mL, respectively, which proved that tannase-assisted extraction technology could degrade galloylated catechins into non-galloylated catechins to prepare the tea extract with low bitterness and astringency.

6.2.2. Subcritical water extraction

As a new extraction technology, subcritical water extraction (SWE) used subcritical water as solvent and controlled the corresponding conditions to extract the target components from raw materials (Cheng et al. 2021). SWE has ben widely used in the extraction of natural active components, which has the advantages of low solvent residual, low cost, low pollution, high safety, and high extraction efficiency (Table 1). Miyashita and Etoh (2013) used SWE technology to improve the bitterness and astringency in green tea, showing that SWE reduced the bitterness and astringency in green tea extract while retaining the original fragrance.

6.2.3. Superfine grinding

Superfine grinding is an emerging technology in the field of food processing, which can alter the structure and surface area of the raw material to improve its physical or chemical properties, biological activity, and flavor (Gao et al. 2020). Peng et al. (2020) compared the effect of superfine grinding technique with traditional extraction on the aroma of tea extract, showing that the superfine grinding technique can effectively restore 16 different kinds of amino acids in the tea extract. Meanwhile, the amino acids of Arg and Ala, which contributed to the bitterness of tea, were significantly reduced by the superfine grinding instead of traditional extraction.

6.2.4. pH regulation technology

To improve the special taste of tea extract to meet consumers' demand, a novel pH regulation technology was developed to reduce the astringency of tea extract. Wan et al. (2021) studied the mechanism of astringency in tea extract, revealing that the combination of tannic components and salivary proline-rich proteins in the mouth form a precipitate, which reduced the lubricity of the mouth and produced the feeling of astringency (Ma et al. 2016). Different ranges of pH can break the hydrogen bond of the combination and improve the aroma of tea extract. The results showed that adjusting pH to 4.9 could decrease the astringency of tea extract, and this astringency masking technology can be widely used in the tea industry.

6.2.5. Dynamic extraction

Dynamic extraction means that under the action of pump, the water at constant temperature is pumped into the extraction column containing tea, and the tea extract is obtained from the extraction column through the continuous dynamic flow of water. Static extraction technology is only to soak tea in constant temperature water to extract its active components. Comparably, dynamic extraction technology has higher extraction efficiency and is helpful to improve the sensory quality of tea extract. Xu, Ji, et al. (2018) compared the effects of static and dynamic extraction on the chemical composition and sensory characteristics of green tea extract, and showed that dynamic extraction improved the extraction rate of polyphenols and free amino acids. Dynamic extraction technology can reduce the bitterness and enhance the umami of green tea extract to improve its sensory properties. Chen et al. (2022) explored the effects of dynamic extraction conditions on chemical substances and sensory quality of green tea extract, and showed that extraction temperature and water flow rate were the main factors affecting sensory quality. Notably, the higher quality of tea raw materials used for extraction made the higher extraction efficiency and better flavor. When different flow rates were used for extraction, high umami extract could be produced, which is suitable to produce functional food ingredients.

6.3. Quantitative analysis technique

6.3.1. Chromatographic technology

Chromatographic technology can separate nonvolatile substances from complex food extracts, and finally obtain a single flavor compound with high purity, which can be further quantitatively analyzed (Zhai et al. 2022). It is characterized by high separation efficiency, wide application range, fast analysis speed and high sensitivity. Presently, the common chromatographic technologies mainly involves liquid chromatography (LC), gas chromatography (GC), high-performance liquid chromatography (HPLC) and ultra performance liquid chromatography (UPLC). Xu, Ji, et al. (2018) used HPLC to analyze the taste substances of catechins, gallic acid and caffeine. The concentration-taste intensity curves of catechins showed that catechins are the main source of the bitterness and astringency in tea infusions. The taste of tea can be improved by quantitative analytical methods. Flaig et al. (2020) used different types of GC/MS to quantize the changes of key aroma compounds in tea. A quantitation of 42 aroma compounds by means of stable isotope dilution assays followed by the calculation of odor activity values (OAV; ratio of concentration to odor detection threshold) showed 27 key aroma compounds with OAVs ≥ 1.

6.3.2. Biomimetic sensors

Biomimetic sensors refer to a sensor modified by a specific bionic material to simulate the function and performance of biological organs, which quantifies the taste substances by receiving a variety of taste signals transmitted by different matters (Lu, Hu, and Zhu 2017). The types of biomimetic sensors mainly involve in potentiometric sensor, voltammetric sensors and impedance spectrum sensors, which have been widely used in the characterization and identification of tea or tea extracts. Hayashi et al. (2013) used a biomimetic sensor to objectively evaluate and quantize the bitter and astringent taste intensities of black and oolong teas. The standard solution prepared by EGCG was used to calibrate the sensor, which can effectively evaluate the bitterness and astringency intensity with high accuracy.

7. Risk assessment of high-quality tea extract

During the processing of tea extracts, there are still safety issues of tea extracts caused by pesticide residues that cannot be completely dissolved and separated, mechanical equipment, and illegal addition. The green preparation of high-quality tea extract can efficiently enrich the functional components of tea, while reducing the organic solvent residue caused by traditional extraction technology. Although traditional food safety detection technology can effectively detect pollutants, when multiple pollutants simultaneously exist, there are still limitations such as incomplete separation and low detection rate. It is necessary to quickly identify the pollutants in the tea processing by expanding traditional detection technologies and developing emerging rapid detection technologies, which performs efficient separation and analysis to ensure the safety of high-quality tea extracts (Figure 7).

7.1. Exogenous risk substances in tea extracts

7.1.1. Pesticide residue

Pesticides refer to chemical agents used in agriculture to prevent and control plant diseases and insect pests as well as regulate plant growth. Nowadays, the pesticide residue is the major negative factor to threaten the export trade of tea products and green development of tea industry. Taking European Union as an example, the exceeding standard rate of pesticide residues is the main factor of notified item from tea products transporting to Europe. Presently, the main pesticides used in agriculture are organic pesticides, which are divided into organochlorine pesticides (OCPs), organophosphorus pesticides (OPPs), organic nitrogen pesticides (ONPs) and carbamate pesticides (CBPs) (Miao et al. 2023). Pesticides used in the cultivation and processing of tea mainly include herbicides and insecticides. Unfortunately, due to the high toxicity of organic pesticides, their large-scale use can lead to safety problems of pesticide residues, especially in the tea industry. Most tea leaves and tea extracts are brewed with drinking water, resulting in a higher risk of pesticide transfer from tea leaves or tea extracts to the human body (Merhi et al. 2022). In addition, both the unreasonable establishment of maximum residue limits (MRLs) and the low efficiency of detection technology are the reasons leading to safety problems caused by pesticide residues. Notably, long-term ingestion of pesticides can pose serious threats on human health, which are mainly manifested by severe headaches, dizziness, and nausea, even leading to cancer and life-threatening conditions.

7.1.2. Heavy metal

As an exogenous risk substance, heavy metal can penetrate the growing environment of crops through the medium of

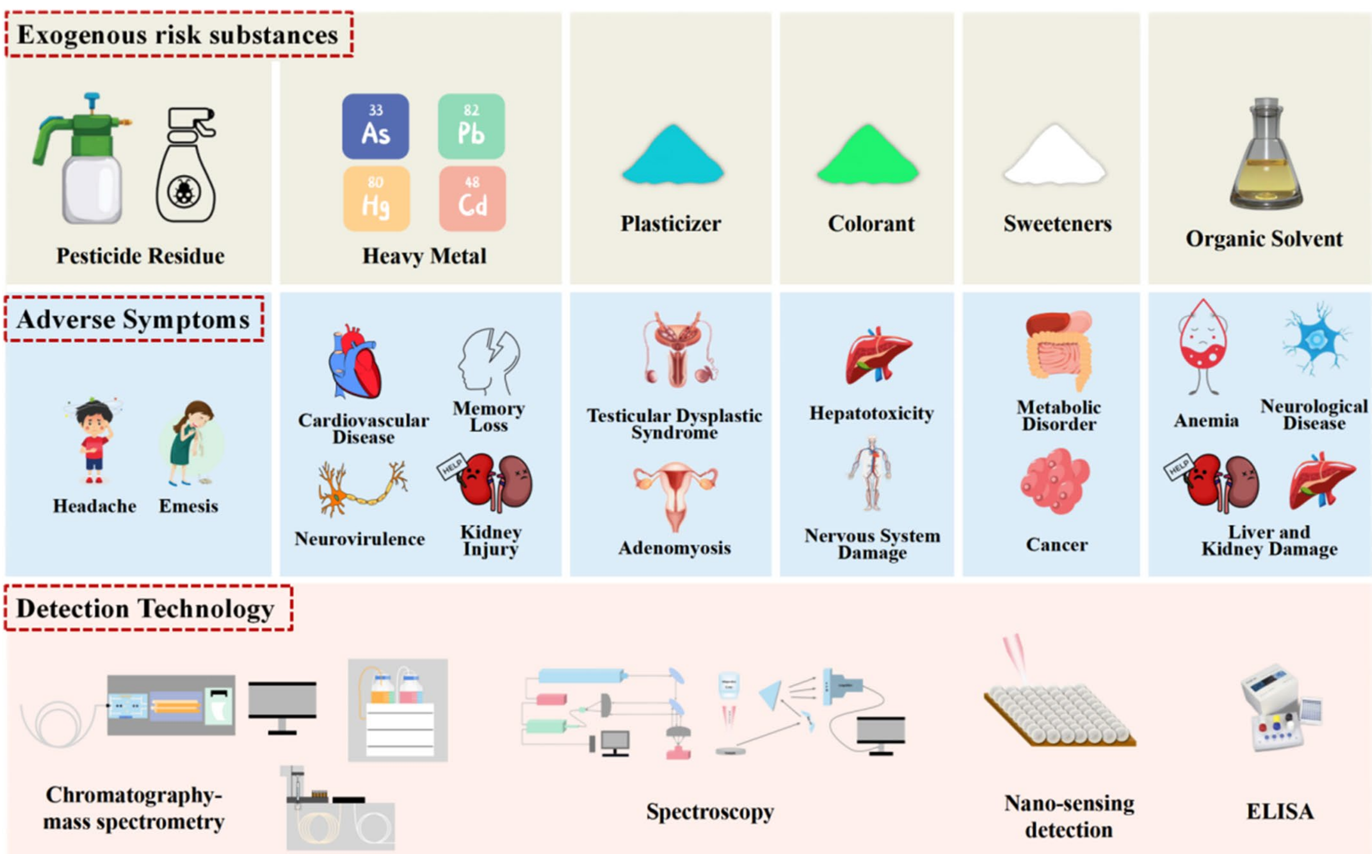

Figure 7. Adverse effects and detection technologies of exogenous risk substances in tea extracts.

soil, atmospheric deposition, rainfall, and irrigation, which affects the physiological activities, growth, yield, and quality of plants. Heavy metals in tea extracts mainly come from atmospheric and soil pollution. Atmospheric pollution is usually found in tea plantation near cities and highways. During the planting of tea trees, heavy metals in soil and water sources will migrate to tea leaves (Sui et al. 2023). In the manufacture of tea extracts, related technologies cannot completely remove heavy metals, which are accompanied by several safety issues. Heavy metal pollution in tea mainly includes plumbum, cadmium, arsenic, mercury, etc. Among them, the content of plumbum has become the key unqualified item in the safety assessment of tea products by the state department. Chinese standard stipulates that the maximum standard limit of plumbum in tea is 2 mg/kg. Long-term intake of toxic heavy metals can cause serious impact on human health. Specifically, long-term intake of lead may cause memory loss, prolonged reaction time, and decreased comprehension; cadmium intake can easily cause kidney damage; arsenic intake can cause skin cancer, cardiovascular and nervous system diseases; and mercury has high neurotoxicity (Cao et al. 2010).

7.1.3. Plasticizer

Plasticizers refer to polymer material additives that are widely used in industrial production. Any substance added to a polymer material that can increase the plasticity of polymers is called a plasticizer. Presently, there are thousands of compounds that can be used as plasticizers in the world, among which phthalic acid esters (PAEs) are the most used, accounting for 80% of the total amount of plasticizers. The possible sources of plasticizers in foods are mainly concentrated in four aspects: illegal artificial addition, environmental pollution, processing links, and packaging materials. During the planting and production of tea and the processing of tea extracts, soil pollution leads to the infiltration of plasticizers into tea trees and some plastic packaging leads to the migration of plasticizers, which are the two most important food safety threatens. Long-term intake of plasticizer-contaminated food may lead to diseases such as adenomyosis and leiomyoma in women, and testicular dysplasia syndrome and reproductive tract abnormalities in men (Li and Ko 2012).

7.1.4. Colorant

Colorant, also known as food pigments, is a substance whose main purpose is to color food, to impart color to food and to improve food color. There are more than 60 kinds of food colorants commonly used in the world, and 46 kinds are allowed to be used in China. Since color is one of the most important indicators in the sensory evaluation of tea, some unscrupulous businessmen illegally add talcum powder, lead chrome green or other colorants to tea for profit, which generates potential safety risks during the processing of tea extract. For instance, long-term consumption of talcum powder will cause symptoms such as malnutrition, gastrointestinal discomfort, and liver poisoning (He et al. 2023). Lead chrome green contains substantial heavy metals such as lead and chromium. Therefore, long-term consumption of tea leaves dyed by lead chrome green will cause the lead in the body seriously exceeds the safety level, thus damaging the human nervous system. It is necessary to monitor the colorants in tea extracts through emerging technologies to ensure the food safety.

7.1.5. Sweeteners

As a non-energy substitute for sucrose, sweeteners have been widely used in food and beverages (Ma et al. 2021). It is estimated that 28% of the global population consumes sweeteners daily. Traditional sweeteners include cyclamate, saccharin sodium, acesulfan, aspartame and sucralose. In recent years, new sweeteners, such as neotame and stevioside, have been emerged. During the processing of tea extracts, sweeteners are usually added to improve the flavor of tea products and mask the bitterness of tea. Some studies have shown that high consumption of sweeteners may have adverse effects on human health, such as metabolic disorders, renal dysfunction, and cancers (Harpaz et al. 2018).

7.1.6. Organic solvent

Organic solvents have been widely used in industrial production, which are usually used to dissolve some organic compounds that are insoluble in water. Common organic solvents mainly include styrene, perchloroethylene, trichloroethylene, ethylene glycol ether and triethanolamine. During the processing of tea extracts, the extraction of organic solvents and the use of cleaning agents for mechanical equipment may lead to the residue of organic solvents. Undoubtedly, long-term intake of organic solvents in humans can lead to several adverse symptoms such as neurological diseases, liver and kidney damage, and anemia.

7.2. Emerging detection technology

7.2.1. Chromatography-mass spectrometry

Chromatography-mass spectrometry technology refers to the ability to combine the advantages of high-efficiency separation of gas phase (or liquid phase) chromatography with the advantages of high-sensitivity detection of mass spectrometry to obtain better detection results (Table 2). Although traditional chromatography-mass spectrometry technology can achieve rapid detection of pesticide residues, it still has the limitation of being unable to achieve efficient separation and detection due to co-elution effects or variance of pesticides. It is worth noting that these problems can be overcome by increasing the chromatographic dimension or adopting high-tech mass spectrometry techniques. Nevertheless, the analytical costs of these technologies still need to be further considered. Lo Turco et al. (2015) used solid-phase extraction-gas chromatography-mass spectrometry (SPE-GC-MS) to evaluate the residues of 27 plasticizers in teabags and non-bag teas. Thereinto, di(2-ethylhexyl) phthalate (DEHP), di-n-butylphthalate (DBP) and DEP were detected in all analyzed samples. In another study, Wu

Table 2. The advantages and disadvantages of detection technologies in the exogenous risk substances

Detection technologies	Advantages	Disadvantages
LC-MS	High separation efficiency, good selectivity, high detection sensitivity, automatic operation, wide application	High cost, expensive maintenance charge, long analysis time
GC-MS	High separation efficiency, high sensitivity, less sample consumption, good selectivity, facile separation with similar boiling points, wide application	Analysis objects that can be vaporized or ionized. In qualitative analysis, known substances or data should be compared with corresponding chromatographic peaks, or combined with other methods. In quantitative analysis, the output signal after detection needs to be corrected with known pure samples.
Near-infrared spectroscopy	Accurate and objective results, unpretreated samples, real-time detection	Unsuitable for trace analysis, high cost, the applicability problems of prediction models
FT-IR spectroscopy	Fast scanning speed, high resolution, high sensitivity, and precision, allow higher energy to pass through	High equipment price and maintenance costs, single transmission mode, real-time detection cannot be performed under glass, liquid or gas conditions, difficult sample processing
Raman spectroscopy	Non-contact measurement, rapid analysis, suitable for the conditions of high or low temperature and high pressure, fast spectral imaging, high resolution, instruments of moderate size, low maintenance cost, facile operation	Weak raman scattering signal, easy to be disturbed by impurities in the environment or samples, only to analyze the vibrational patterns of molecules, high sample requirements
Laser-induced breakdown spectroscopy (LIBS)	Remote non-contact measurement, no requirement for pretreatment, rapid analysis speed, simultaneous multi-element detection, no pollution	High cost, complex operation, hard to obtain the standard reference material with perfect matrix matching, large matrix effect, high energy laser pulses cause great damage to vision
Nano-sensing detection	Portable and practical, fast response speed, high sensitivity, no complicated pretreatment	Interference by environmental factors, limited tolerance and environment recognition ability of sensor components
Enzyme-linked immunosorbent assay	High sensitivity, strong specificity, low cost, simple operation, wide application, no radioactive pollution	Poor repeatability, prone to false positives, many interference factors, easy to be affected by temperature and time

(2017) used gas chromatography-triple quadrupole tandem mass spectrometry to rapidly detect pesticide residues in oolong tea. The detection limit and quantification range of 89 pesticides were 1–25 $\mu g \cdot L^{-1}$ and 10–50 $\mu g \cdot L^{-1}$, respectively, and the effective separation was achieved within 36 min, and the recovery rate was between 60% and 120%. In another study, Jia, Chu, and Zhang (2015) detected multiple pesticide residues in green tea by comprehensive two-dimensional gas chromatography-time-of-flight mass spectrometry (GC × GC-TOFMS), which could simultaneously analyze 423 pesticides, isomers and pesticide metabolites, and the recovery rate of sample addition was 81.6%–113.0%.

7.2.2. Spectroscopy

Spectroscopic technology refers to the technology of identifying substances and determining their chemical composition according to the characteristic spectral lines of molecules or atoms themselves. The spectroscopic techniques used in the safety detection of tea extracts mainly include near-infrared spectroscopy, FT-IR spectroscopy, Raman spectroscopy, and laser-induced breakdown spectroscopy (LIBS). The general determination process includes four basic steps: sample preparation, spectrum acquisition, spectrum processing and model building, which exhibits the advantages of facile operation, rapid detection, and high sensitivity (Table 2). Li et al. (2015) used Raman spectroscopy to quickly detect lead chrome green in tea, which collected Raman spectra in the range of 2804 cm^{-1} to 230 cm^{-1}, and then used wavelet transform to extract different time domain samples from Raman spectra. The information in the frequency domain proved that the low-frequency approximate signal was the most important information for establishing the lead chrome green measurement model. SPA was used to select the characteristic wavenumbers and 8 characteristic wavenumbers were obtained, which proved the feasibility of Raman spectroscopy in the nondestructive detection of chrome green lead in tea. Wang et al. (2017) used LIBS to compare the performance of external standard method, internal standard method and multiple linear regression method in the quantitative analysis of Pb in Pu-erh tea, showing that the combination of LIBS technology and multiple linear regression method is a feasible method to analyze the lead content in Pu'er tea. Zhu et al. (2021) used surface-enhanced Raman spectroscopy (SERS) combined with chemometrics to quickly detect chlorpyrifos pesticide residues in tea, which synthesized AuNPs as SERS-enhanced substrates with a good enhancement effect. The characteristic peaks of chlorpyrifos were optimized from the full spectrum by CARS. On this basis, the performances of the PLS linear model and the SVM nonlinear model based on characteristic variables were compared through CARS. The established SVM was superior to PLS, indicating a nonlinear relationship between Raman intensity and chlorpyrifos pesticide concentration. The predicted and measured values of SVM for 5 tea samples with unknown concentrations showed that SERS is feasible for rapid detection of chlorpyrifos residues in tea.

7.2.3. Nano-sensing detection

Nano-sensing detection technology refers to the detection of target analytes using nanomaterials as signal transducers combined with sensor recognition components. Due to the advantages of large specific surface area, high conductivity, strong magnetism, and structural controllability (Miao et al. 2023), nanomaterials can amplify the detection signal and provide higher sensitivity (Table 2). Moreover, the nano-sensing detection also has the advantages of portable and practical, fast response speed, and high sensitivity, which has been widely used in the safety detection of tea extracts (Li, Xiao, et al.

2019). Hassan et al. (2019) established an ultrasensitive and selective detection platform based on SERS for the simultaneous determination of the pesticides acetamidoamidine (AC) and 2,4-dichlorophenoxyacetic acid (2,4-d) in matcha. The LODs of the prepared SERS Au@Ag nanosensors for AC and 2,4-d in matcha were 2.63×10^{-5}μg/g and 4.15×10^{-5}μg/g, respectively, which were far below the MRL stipulated by the EC. The method has satisfactory recoveries (99.85%~116.0%) and RPD values (<4.85%), indicating that the established sensor-coupled GA-PLS can be used for rapid monitoring of pesticide residues in matcha. Gao et al. (2022) developed AIEgen nanosphere-labeled biosensors to detect Pb^{2+} in tea. AIEgen nanoparticles were immobilized on the surface of Zr-MOFs and the fluorescence of AIEgen NPs was quenched, and PEG was added to remove nonspecific adsorption. Subsequently, Pb^{2+} was added to cut the DNA sequence containing the cleavage site, and the AIEgen NPs and part of the DNA sequence were separated from the Zr-MOFs surface to restore fluorescence. Through comparing the fluorescence changes before and after adding Pb^{2+}, the detection limit of Pb^{2+} can reach 1.70 nM, which can be applied in the detection of Pb^{2+} in tea extracts.

7.2.4. Enzyme-linked immunosorbent assay (ELISA)

Enzyme-linked immunosorbent assay (ELISA) refers to a qualitative and quantitative detection method that combines soluble antigens or antibodies with solid phase carriers like polystyrene and uses specific binding of antigens and antibodies to detect immune responses. Due to its high sensitivity and strong specificity, ELISA has been successfully applied to the rapid detection of pesticide residues in tea extract, which exerts a vital role in ensuring the safety of tea extract (Table 2). Song et al. (2011) investigated a novel ELISA to rapidly detect fenvalerate (FA) in tea samples. FA and aminocaproic acid methyl ester (AME) were used to synthesize haptens, and then a polyclonal antibody against fenvalerate (FEN) was produced by the hapten with the characteristic moiety of FA. The results showed that the sensitivity of detection is 9 μg L^{-1} for IC_{50} and 0.5 μg L^{-1} for IC_{15}, and the detection limit of FA was 0.16 mg L^{-1}, which represented the establishment of an effective method for detecting pesticide residue in tea extract. Lu et al. (2010) developed a new approach for hapten synthesis using pyrethroid metabolite analogue to detect pesticide residue in the green tea sample, and the recovery of tea sample was about 86–107%. Furthermore, the correlation between immunoassay and GC/ECD data in the green tea (R^2 = 0.9968) indicated that this method can be reliable in detecting pyrethroid insecticides in green tea.

8. Key technologies for intelligent control of tea extract processing

Tea extracts contain various active ingredients that contribute to their physicochemical properties, flavor quality, and health benefits. Monitoring the content of these active components in real-time is crucial for the development of high-quality tea extracts. Traditional detection methods rely on manual control and analysis of parameters and sensory characteristics, which are time-consuming and labor-intensive. To address these limitations, gas chromatography mass spectrometry (GC-MS) and high-performance liquid chromatography (HPLC) have been developed for the determination of quality components in tea (Pongsuwan et al. 2008). While these techniques have provided accurate measurements, they are still not ideal for rapid detection and real-time monitoring. Currently, the intelligent control technology of tea extract processing has been widely explored, mainly including computer vision, near-infrared spectroscopy, electronic nose, electronic tongue, and data fusion technology integrating multiple sensors (Chen et al. 2015). The effective combination and practical application of these new technologies and traditional methods can intelligently control the parameters in the manufacturing process and monitoring the nutritional and sensory characteristics of the product to realize the green and efficient production of high-quality tea extracts (Figure 8).

8.1. Computer vision

Computer vision is a multidisciplinary field that integrates mechanics, optics, electromagnetic sensing, digital video, and image processing techniques. Its primary objective is to enable computers and machines to perceive, interpret, and understand visual information from images or videos. Once computer vision systems collect images, a series of image processing techniques are applied to enhance the quality and prepare the images for further analysis. These preprocessing steps aim to improve the effectiveness of subsequent analysis algorithms and extract meaningful information from the images. Computer vision can analyze the textural characteristics of tea leaves, including parameters such as density, roughness, and linearity, through colorimetry and spectrophotometry, and then judge the color and texture of tea leaves based on statistical and modeling methods (Gill, Kumar, and Agarwal 2011), which shows the advantages of rapid detection, facile operation, and accurate determination (Table 3). Nevertheless, the rapid growth of data amount will urgently need the constant upgradation of algorithm of computer vision. Jin, Xiong, and Lei (2021) established a tea sorting system based on computer vision technology, which can extract feature information from the shape and color of tea. The tea sorting system can classify 10 kinds of tea to realize intelligent, fast, and accurate sorting of tea varieties. Wang, Ren, Chen, et al. (2023) used computer vision to detect the fermentation steps in the process of black tea manufacturing, and extracted color variables and key quality indicators in tea samples from the images. A partial least squares regression model based on color variables accurately predicts the contents of catechins, theaflavins and chlorophyll in tea. Furthermore, the visualization of fermentation quality can be realized based on the drawn spatiotemporal distribution map of each index in the fermentation process.

8.2. Machine learning-based spectroscopic analysis

Machine learning-based spectroscopic analysis, such as FTIR, has provided valuable insights into the tea extraction

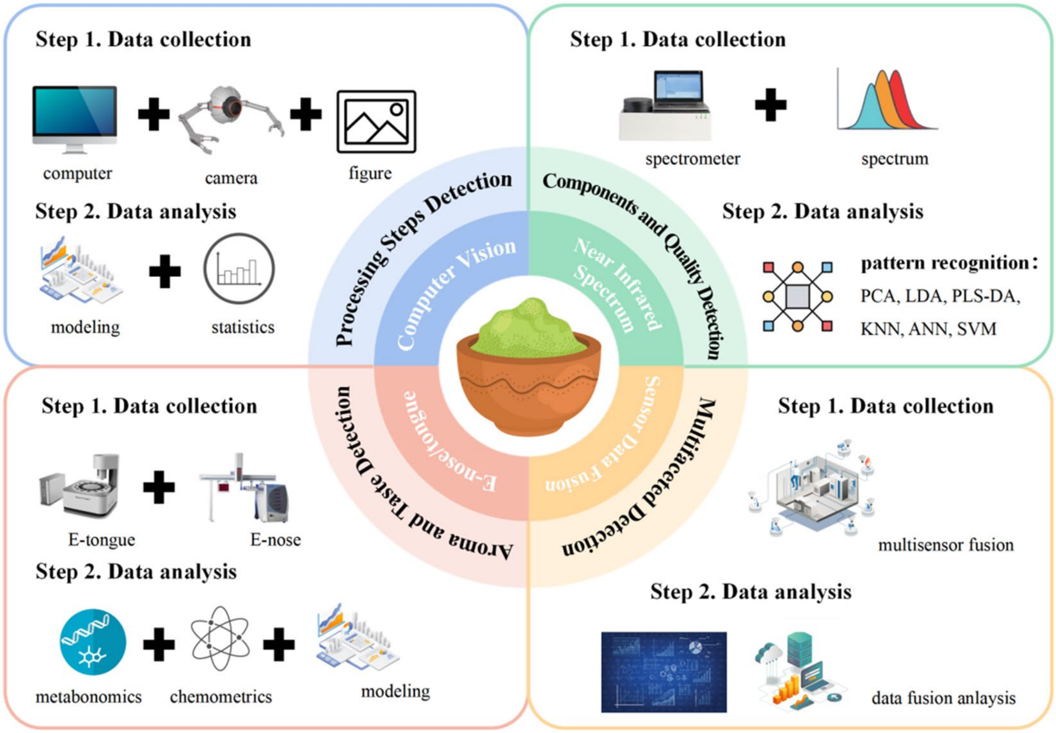

Figure 8. Application of intelligent technology in the processing of high-quality tea extracts.

process. Near-infrared spectroscopy operates on the principle that when a sample is exposed to infrared light, distinct chemical bonds within the organic matter absorb or emit light at specific wavelengths. This characteristic absorption or emission pattern enables the detection and analysis of chemical components present in the sample. By leveraging near-infrared spectroscopy, researchers can gain a deeper understanding of the chemical composition of tea and its extraction process. The detection process of near-infrared spectroscopy usually includes the following four steps: data acquisition, data preprocessing, calibration model establishment with a set of samples, and model validation with a set of independent samples. In the process of model establishment and verification, a variety of pattern recognition methods have been used for qualitative and quantitative analysis of near-infrared spectroscopy, which can improve the accuracy and objectivity of the results but along with high cost (Table 3). Principal component analysis (PCA) is the most commonly used linear supervised analysis method in pattern recognition (Yang, Qi, et al. 2020), which can not only give clustering trends, but also perform data dimensionality reduction. Other pattern recognition can be divided into linear methods and nonlinear methods. Linear methods include linear discriminant analysis (LDA), partial least squares discriminant analysis (PLS-DA) and k-nearest neighbor (KNN). Nonlinear methods include artificial neural network (ANN) and support vector machine (SVM). Recently, near-infrared spectroscopy has been widely applied in tea analysis, which can be used to detect the moisture content in the tea processing or analyze the functional components, such as catechin, theaflavin, theanine and polysaccharides (Wang, Ren, Chen, et al. 2023). Wang, Li, et al. (2022) combined the sensor array based on pH indication and near-infrared spectroscopy to detect the withering status of tea leaves during black tea processing, which obtained effective data analysis through low-level data fusion and PCA dimensionality reduction, and provided bright prospects for intelligent processing of high-quality tea extracts.

8.3. Electrochemical sensor array

An electronic nose is composed of a sampling device, a sensor array, and a data processing system that mimics the human sense of smell by producing a unique composite response to odors (Yu, Wang, and Wang 2009). Currently, common sensor arrays include piezoelectric sensors, electrochemical sensors, optical sensors, and thermal sensors. The electronic tongue is a typical chemical sensor array combined with chemometrics for characterizing complex samples. When the sensor interacts with the sample, electrical signals can be generated to facilitate analysis. Similar to the near-infrared spectroscopy, the working steps of the electronic nose and the electronic tongue are to preprocess the relevant data after collecting them, and then identify and analyze the data through modeling. Yang, Dong, et al. (2022) used GC-electronic nose to characterize the aroma compounds with sweet or floral aroma in different kinds of black tea, and identified 15 important volatile aroma compounds in total through partial least squares analysis. Liu, Liu, et al. (2022) combined electronic nose and GC-MS to characterize the chemical composition and sensory properties of instant sweet tea, suggesting that there were significant differences in 88 volatile compounds among different sweet tea samples. In the evaluation of the sensory properties, 9 aroma compounds were analyzed, showing that the instant sweet tea had a stronger caramel flavor. Ouyang et al. (2020) combined electronic tongue with chemometric analysis to detect the content of free amino acids in black tea, which exhibited a good ability in predicting the total free amino acid content with the advantages of facile pretreatment process, fast detection speed, and low operation cost (Table 3).

8.4. Multimodal tea data fusion

Sensor data fusion technology refers to the fusion of vision, smell, taste, and other data captured by sensors such as computer vision, electronic tongue, and electronic nose, which provides supplementary interpretation of sample data to ensure the real-time and comprehensive results by processing substantial multivariate signals from different sensors (Wang, Li, et al. 2022). The main limitation is that the huge signals require powerful algorithms to support data processing with high economic cost (Table 3). Sensor data fusion technology is divided into three stages: low-level fusion, intermediate fusion, and high-level fusion (Yang, Qi, et al. 2020). Low-level fusion refers to building a single data vector with fused signals from different sensors to form a super-sensor system. Intermediate fusion refers to extracting and fuzing features from the signals of each sensor. Advanced fusion refers to building classification models for each sensor technology separately, and then combining the classification results to generate the final classification. Liu, Liu, et al. (2022) combined near-infrared spectroscopy and computer vision to detect moisture in black tea processing, and used sensor data fusion technology to fuze and analyze the

Table 3. Applications of intelligent processing technologies in tea analysis

Intelligent Processing Technology	Type of Tea	Purposes	Data Analysis	Advantages	Disadvantages	References
Computer Vision	Black Tea	Identify tea quality according to the texture characteristics of tea grains under different light conditions	PCA	Rapid detection, facile operation, accurate determination	Large amounts of data to analysis, interference of complex environmental background, upgradation of algorithms	(Laddi et al. 2013)
	Black Tea	Visualization of black tea fermentation and processing steps	PLSR			(Wang, Ren, Chen, et al. 2023)
	Green Tea, Longjing Green Tea, Jasmine Tea	Tea sorting according to the shape and color	CNN			(Jin, Xiong, and Lei 2021)
Near Infrared Spectrum (NIR)	Darjeeling Black Tea	Identify and sorting Darjeeling black tea and other types of black tea	PLS-DA, SIMCA	Accurate and objective determintion, facile pretreatment, real-time detection	Unsuitable for trace analysis, high cost, difficult application of prediction models	(Firmani et al. 2019)
	Green Tea	Quantitative determination of active components and antioxidant capacity in green tea	PLS, Si-PLS, GA-PLS, ACO-PLS, SA-PLS			(Guo et al. 2020)
	Black Tea	Visualization of the moisture content of tea leaves	SPA, CARS			(Sun et al. 2019)
E-nose	Longjing Green Tea, Dark Tea	Identify tea quality by aroma detection	PCA, LDA	Short response time, high detection speed, simple sample pretreatment, wide range of determination	Low sensor sensitivity, poor repeatability	(Yuan et al. 2019)
	Black Tea	Classify seven brands black tea by the quality	PCA, LDA, QDA, SVM			(Hidayat et al. 2019)
	Congou Black Tea	To study the aroma characteristics of tea in the final burning process of variable temperature	PLS-DA			(Yang, Qi, et al. 2020)
	Instant Sweet Tea	Effects of spray drying and freeze drying on chemical, sensory and volatile characteristics of instant sweet tea	PCA, PLS-DA			(Liu, Liu, et al. 2022)
E-tongue	Dark Tea	To study the chemical changes and taste characteristics of five typical dark tea	PCA, HCA, OPLS-DA, PLS, ANOVA	Short response time, high sensitivity, good repeatability, fast detection speed, close rolerance	Interference of complex environmental background, the types of sensors cannot cover all kinds of tea flavor substances	(Cheng et al. 2021)
	Indian Black Tea	Improve the accuracy of tea classification	ANN, OVO-SVM, VVRKFA, PCA			(Saha et al. 2016)
	Green Tea	Quickly evaluate the bitterness and astringency of green tea	MLR, PLSR, BPNN			(Zou et al. 2018)
	Black Tea	Measurement of total free amino acids content	Si-VCPA-PLS			(Ouyang et al. 2020)
Sensor Data Fusion	Black Tea	Evaluate the wilting degree of black tea based on pH indicator sensor and NIR	PCA, SVM	Fast detection speed, high accuracy of results	High cost, powerful algorithms to support data processing	(Wang, Li, et al. 2022)
	Black Tea, Yellow Tea, Green Tea	Evaluate the content of tea polyphenols	RF, Grid-SVR, XGBoost			(Yang, Qi, et al. 2020)
	Longjing Green Tea	Rapid identification of tea quality based on electronic nose and computer vision system	PCA, KNN, SVM			(Xu, Wang, and Gu 2019)
	Green Tea	Detection of moisture content in green tea processing based on computer vision and NIR	PLSR, SVR			(Liu, Liu, et al. 2022)

collected data. The results showed that low-level data fusion performed poorly on moisture detection, while medium-level fusion showed the best prediction accuracy for moisture during black tea processing. Therefore, machine vision combined with near-infrared spectroscopy can realize quantitative prediction of moisture content during black tea processing, which effectively improves the poor prediction accuracy of a single sensor.

9. Application of high-quality tea extract in different fields

Due to the targeted biological functions of the high-quality tea extracts, it can be used in various food to satisfy the specialized demand of consumers. Up to date, high-quality tea extracts has been used in the fields of instant tea, concentrated tea, foods, health products and others (Figure 9).

Instant tea is a kind of powder, fragmented or granular tea product, which is made from finished tea, semi-finished tea, tea by-products or fresh tea leaves. The water-soluble components of high-quality tea extract are obtained through filtration, concentration, drying and other processes (Bai et al. 2022). While the only difference between concentrated tea and instant tea is the lack of a drying processing step. According to the types of tea raw materials, processing technologies, solubility, particle size and applications, they can be divided into dozens of different products. Through innovative extraction and processing technology, the high-quality tea extract can be found in the form of instant powder or concentrated juice in tea products, which can produce the complex flavor and improve the stability of tea infusion (Wang, Li, et al. 2022).

For food products, the incorporation of high-quality tea extract can provide a unique flavor to different foods, including bakery food and dairy products, such as cake, bread, ice-cream, cheese, and milk powder. Moreover, high-quality tea extract can be prepared as the cling film of meat products due to its excellent antioxidant activity (Zhang et al. 2023). The development of high-quality tea extract in the food industry will continuously expand in the future to improve the added value of tea and consumer satisfaction. For tea health products, high-quality tea extract can be designed and developed into tablets, gels, or capsules to enhance its bioavailability and biological functions (Yang et al. 2023). Noah et al. (2022) explored the effect on chronically stressed healthy individuals with the tablets containing L-theanine, indicating that the tablets can effectively relieve the pressure of healthy people, but the beneficial effects on sleep and pain perception require further investigation. Han et al. (2020) added green tea powder, soluble tea, and tea polyphenols to improve the quality of dough. The results showed that tea polyphenols presented the most effective improvement with highest dough stability, resistance, and noodle chewiness. Jamróz et al. (2019) explored a new film with pigskin gelatin and tea extracts to improve the antioxidant and antibacterial properties, which can be used in packaging of food products.

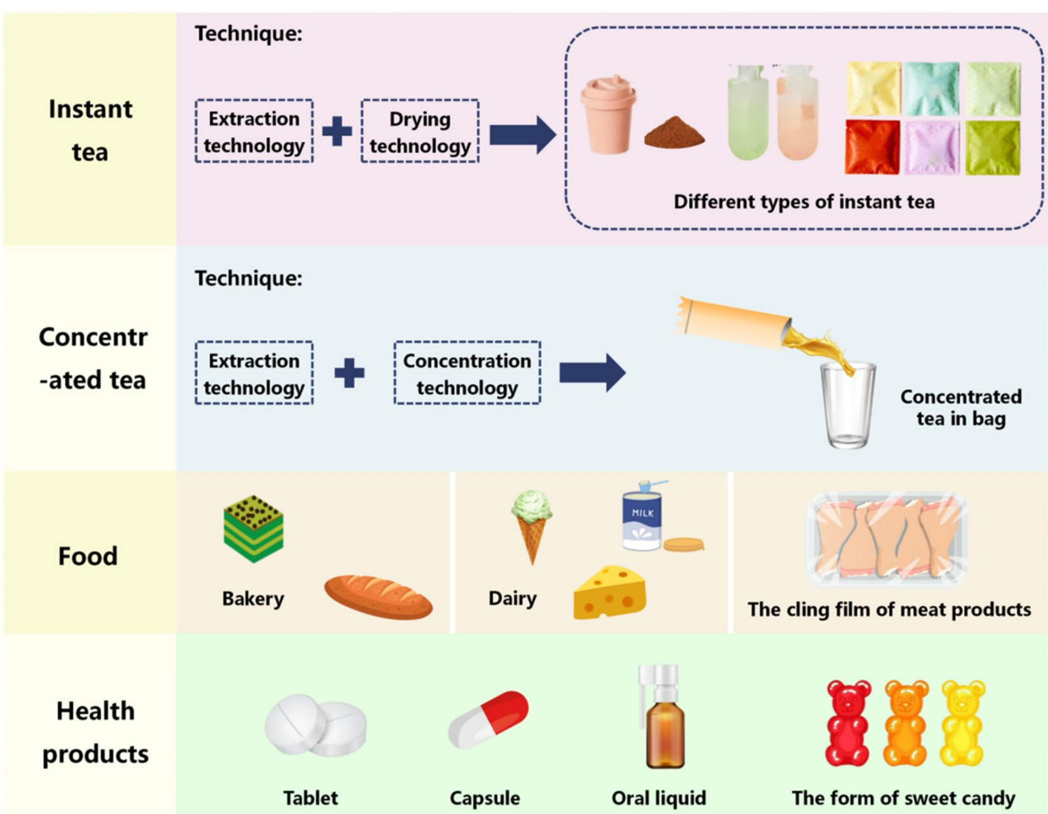

Figure 9. Application of high-quality tea extract in different fields.

10. Conclusion and perspectives

By optimizing key parameters in different manufacturing processes combined with green and efficient extraction technology, the functional components in tea extracts can be effectively retained and enriched with enhanced bioavailability. The safety of the manufacturing process can be ensured through rapid detection technology. Meanwhile, the manufacturing parameters are precisely regulated in combination with intelligent control to realize green, efficient, and intelligent preparation of various high-quality tea extracts, which promotes the efficient utilization of tea resources, especially the summer and autumn tea resources (Most have been wasted). Nevertheless, for the entire tea industry, innovation breakthroughs in key technologies are still in the minority and the research on the stability of products are scarce. With the development of modern society, the consumption demand and quality pursuit of tea-related products are increasing, and therefore the research on key technologies of high-quality tea extracts will put forward higher requirements. Four main suggestions are proposed for the development of the tea extract industry.

10.1. Innovation of key extraction technology of high-quality tea extract

The optimization of key processing technology can improve the quality of tea extract. Through the innovation of high-tech extraction and aroma backfilling technology, the high-efficiency separation technology and the energy-saving equipment should be used to prepare tea extract. The pollution-free extraction of high-quality tea extract will be realized through rapid and safe detection technology. Furthermore, based on the functional characteristics of tea, the extraction and application of active components in tea extracts should be oriented and strengthened, while the shortcomings of high pollution and low efficiency caused by traditional manufacturing procedures should be abandoned. The industrial application of high-tech such as supercritical extraction and enzymatic hydrolysis-assisted extraction should be optimized and applied in the extraction process. While satisfying the functionalization of tea extract terminal products (such as instant tea and concentrated tea juice), the stability, moisture resistance and instant solubility of tea extract should be improved.

10.2. Intelligent processing technology innovation of high-quality tea extract

The integration of computer vision, near-infrared spectroscopy, and bionic sensor technology into the traditional tea extract manufacturing production line will realize the combination of intelligent processing equipment and quality perception monitoring technology (Shen et al. 2022). Meanwhile, during the preparation of high-quality tea extracts, the judgment of product quality and the adjustment of processing parameters need to be more accurate. Particularly, it is essential to overcome the shortcomings of weak applicability of sensors and mathematical models, signal drift, signal noise, and high cost. Besides, through the internet of things, the processing data is transmitted to the cloud in real time. Producers can use software to monitor the quality and safety of tea extracts during processing, which improves the digital system to realize the precise, digital, and intelligent processing of high-quality tea extracts.

10.3. Guarantee the safety of high-quality tea extract

Given that tea-related products are consumed primarily in the form of tea soup or aqueous solution, the application of highly water-soluble pesticides should be avoided in the selection and use of pesticides. Meanwhile, it is necessary to construct a new principle of establishing MRLs standard based on effective risk quantity and reconstruct the international standard of MRLs in tea extract. Moreover, the development of miniaturization and high sensitivity technologies such as nanomaterials and SERS should be sequentially improved. The intelligent techniques can be combined with pollutant traceability and rapid detection technology to improve the accuracy of safety detection. In the process of supervision, the relevant law enforcement agencies need to clearly implement the relevant laws and regulations to make full investigation and confiscation.

10.4. Market regulation in the process of commercialization

Presently, tea extract has been used as dietary supplement or food additive in food or health care products, but the regulations and market supervision on its dosage have not been consummated. For instance, catechin is the most abundant bioactive ingredient of green tea. Although catechins have a variety of physiological functions beneficial to human body, excessive intake can lead to liver poisoning (Hu et al. 2018). The European Commission has published a new regulation in 2022, which added green tea extract containing EGCG to the list of restricted substances. Furthermore, Canada also limits daily intake of EGCG to 300 mg and total intake of catechins to 600 mg because of its potential damage to the liver. Currently, China has not established relevant laws and regulations on the safe use threshold of tea extract, which still lacks certain market supervision. Before regulations and standards are consolidated, the use of tea extract as food additives or dietary supplements can be printed in the way of reminders to avoid adverse effects on some people with intolerance or liver dysfunction.

In summary, the research breakthroughs and product development of high-quality tea extracts have become the focus of the global tea deep processing industry. Through the optimization and innovation of these technologies, the development of high-quality tea extracts will contribute to the sustainable development of the tea industry. The precise functional positioning and scientific formulation of high-quality tea extract can be utilized to reduce the homogeneity of tea-related products and develop high value-added functional terminal products. More importantly, the development and utilization of high-quality tea extract in cross-border fields such as food, medicine, personal care products, plant pesticides, animal health products will be promoted through interdisciplinary and cross-field technical cooperation.

Disclosure statement

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ORCID

Yang Wei http://orcid.org/0000-0001-8302-8903

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