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Valorization of pruned tea leaves based on the accumulated metabolites: Current techniques and prospects towards sustainable production

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ABSTRACT

China ranks first in tea cultivation (62.6%), production (49.1%), and consumption (44.2%) in 2022 over the world. Increasing output of tea leaves produces profit for China's tea farmers, however, current tea production from such prosperous market aims for premium and special tea, which results in over 60% tea leaves being wasted in tea garden after pruning. Herein, comprehensive research on the pruned tea leaves termed as tea waste biomass (TWB) is conducted to draw a balance between simple consumption and cross-frontier waste management. Current research on tea biomass is reviewed by bibliometric analysis and further investigation into the physiological accumulation patterns in TWB are concluded. Vigorous photosynthesis promotes the accumulation of valuable and characteristic metabolites in TWB such as sugars and flavonoids. The valorization of this underestimated resource is positively pronounced through three cost-effective approaches, namely two-stage enzymatic extraction, biological and thermochemical conversion. Two-stage enzymatic extraction transforms PTB into food, agricultural, chemical, and medical products. Biological fermentatation, ensiling and composting convert CTB into enzymes, feed and fertilizer. Through thermochemical pyrolysis, the fixed carbon in CTB is beneficial for soil improvement, bio-fuel production, and energy storage. This review promotes current valorization methods of TWB based on the accumulated metabolites in tea plants, and sheds light into continual production of tea plants and other C_3 cash crops.

1. Introduction

Tea is commercially manufactured from the fresh leaves of tea plant [*Camellia sinensis* (L.) O. Kunze], which is widely cultivated in more than 60 countries around the world (Xia et al., 2020). Compared to annual staple grain crops, such as wheat, maize, and rice, tea plant has different physiology as a perennial cash crop. Its nutritional and economic value is underestimated at present (Beringer et al., 2020). Various secondary metabolites, including tea polyphenols (TPP), *L*-theanine, tea saponins, and caffeine, offer extraordinary health promoting activities, including anti-inflammatory, anticancer, antivirus, neuro-protective, and refreshing effects (Shang et al., 2021). Tea production industry has grown continuously, with an output exceeding USD 250 billion in 2024 and global tea production of 6.39 million tons in 2022. China is the largest country to produce and consume tea in the world (over 45% and 50%, respectively). Depending on the degree of oxidation and/or microbial fermentation, tea leaves are processed as the six major tea categories (conventional tea), which can be further processed to reprocessed teas (herbal and scented tea), beverages, tea foods, and tea extracts for healthcare, cosmetics, and environmental remediation (Fig. 1**A**).

Tea plant is subject to ever-increasing demands for palatability and

Abbreviations: TWB, tea waste biomass; PTB, pruned tea biomass; CTB, consumed tea biomass; TPP, tea polyphenols; SC, structural carbohydrates; NSC, non-structural carbohydrates; ROS, reactive oxygen species; UV, ultraviolet; PA, proanthocyanidins; HT, hydrolysable tannins; DF, dietary fibers; NCC, nanocellulose crystal; TPS, tea polysaccharides; NP, nanoparticle; SSF, solid-state fermentation.

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quality, which makes Chinese conventional tea one of the world's most important high value-added products. Average domestic price of green tea and black tea are 153.4 and 148.1 yuan/kg respectively in China, much higher than average international price of tea (21 yuan/kg) (Food and Agriculture Organization of the United Nations, 2022). Careful field management and labor-intensive refining processing from plucking to sorting are required. In practice, regular tea pruning aims to improve cultivation. Only the tender tea shoots including buds and first-to-fourth leaves grown in spring are qualified as rarity, while fresh tea leaves grown in summer and autumn are almost abandoned (Lin et al., 2021). Such fine and extravagant consumption characteristics directly generate massive loss during fresh tea leaf plucking and production, seen from the less average tea yield per hectare in China than that in Türkiye (1117 kg and 2137 kg, respectively). Given that tea yields of China, India, and Vietnam are estimated to continuously increase (Beringer et al., 2020), pruned tea leaves and the consumed tea (tea residue) also increase. Over 5 million tons of tea buds, leaves, and pruned stems are discarded annually (Kumar et al., 2023a), and 5.8 million tons of consumed tea waste are generated (Çakmak et al., 2024). Pruned tea waste at the production end and the consumed tea waste at the consumer end have

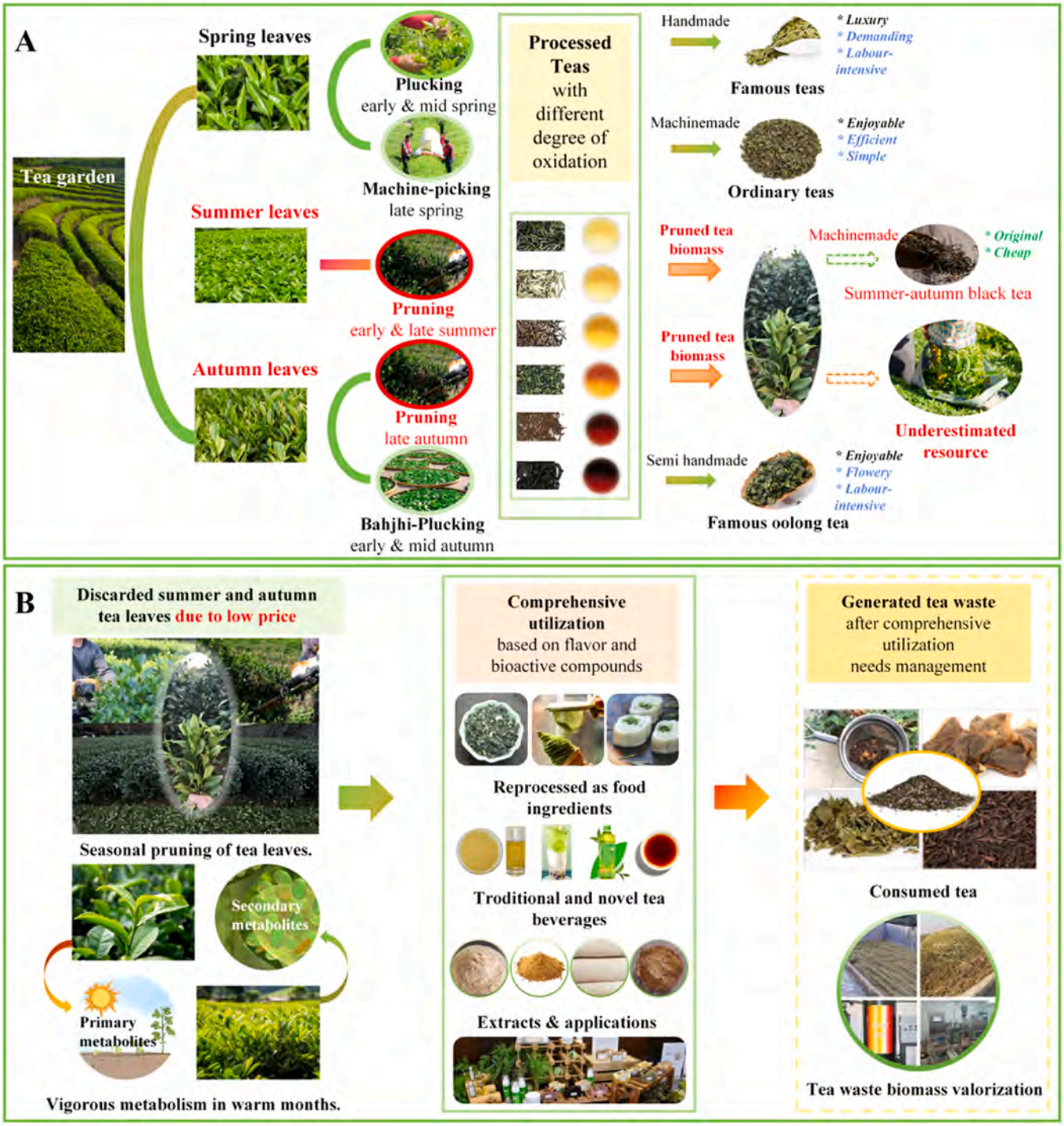

Fig. 1. Current tea production practices generate substantial amounts of tea biomass that remain largely unutilized. A, Current industrialization of *Camellia sinensis* leaves in all producing seasons causes an enormous loss of pruned tea biomass. B, Generated tea waste after comprehensive utilization needs management via current valorization techniques.

been questioning the sustainability of improving global tea industry (Fig. 1**A**) (Munasinghe et al., 2017).

These pruned tea (PTB) and consumed tea (CTB) are potentially valuable, and we defined them as TWB (tea waste biomass). As for tea wastes from pruning and consumption, progress in converting them into bio-adsorbents, agricultural compost, or animal feed by thermochemical and biological technologies has been reviewed (Guo et al., 2021). Such potential is linked to the abundant carboxyl, hydroxyl, and oxyl groups in primary metabolites (holocellulose, fatty acids, and amino acids), and phenolic hydroxyl and oxyl groups derived from secondary metabolites (lignin, alkaloids, and polyphenols) (Guo et al., 2021; Negi et al., 2022). The valorization of TWB is based on the extraction of bioactive secondary metabolites such as TPP and *L*-theanine in PTB, and the transformation of the fixed primary metabolites such as abundant holocellulose and lignin. However, the biological transformation of these secondary metabolites into food and healthcare products is less reviewed, indicating that previous concluding remarks certainly underestimate the valuable constituents in TWB (Guo et al., 2021; Guo et al., 2024). After concluding the accumulation patterns of primary and secondary metabolites in tea plants based on tea physiology, the potential of PTB in summer and autumn for functional food production has been reviewed in our previous work (Liang et al., 2024).

While extensive research has focused on the secondary metabolism of tea plants (Jiang et al., 2025), studies concerning primary metabolism such as sugars, lipids, and proteins remain limited (Zhao et al., 2024; Jiang et al., 2025). Configuring these primary metabolites in PTB presents a promising strategy to enhance the valorization of CTB. This advancement offers a strategic pathway to deal with the increasingly serious environmental pollution caused by human activities and fossil fuels and the irreversible effects of global warming. In the present work, previous literature about biomass utilization and tea biomass production are retrieved and compared. Afterwards, we perform overall investigation on the accumulation characteristics of significant metabolites derived from photosynthesis in PTB and subsequent spontaneous biosynthesis of stress inducers. Comprehensive utilization of TWB based on current extraction strategy, biological transmission techniques, and multiple thermochemical processing are introduced to gain high value from these underestimated resources and maintain the healthy development of tea industry under the circumstances of endless pursuit of premium and special tea.

2. Overview of current biomass valorization techniques

2.1. Category of biomass

Biomass is derived from contemporaneous (non-fossil) and complex biogenic organic-inorganic solid products such as plant residues (mainly stems and branches generated by wood products industry and from dedicated energy plants), agricultural residues (mainly straws and algae from crop residues), industrial biomass wastes (mainly municipal solid waste and consumed food waste). Generally, natural biomass synthesized by growing plants is seen renewable and offers no depletion to the net forest resource base. Plant biomass is mainly composed of carbohydrates (mainly cellulose, hemicellulose and lignin), which uses CO_2 and water under sunlight to store chemically combined energy (17–21 MJ/kg) through photosynthetic biochemical pathways. Initiated by the concern about rising environmental cost and global warming by combustion of fossil fuels, study of biomass has been conducted worldwide (Table 1). Among various biomass types, woody/herbaceous plants and grasses are the centre of interest due to the plant's clean productivity.

Owing to distinct genetic backgrounds, C_3 crops generally achieve light conversion efficiency of around 1–2% and C_4 crops around 3–4% under normal field conditions during the active growth phase (Éva et al., 2018). Besides, other important traits, namely the longevity, life cycle, harvest index, and stress tolerance, should also be counted for productivity. For instance, longer leaf life of perennial plant correlates well

Table 1
General classification, characteristics and treatment of biomass from various sources.

Type		Natural source	Characteristics	Basic compositions/(wt%)				Treatment	References
				C	H	O	N		
Woody biomass	General meaning	Residues from natural forest, and wood industry	Low moisture, ash and voidage, while high calorific value and high bulk density	48.15–55.50	5.40–6.70	40.8–45.90	0.06–1.60	Generate energy for power, and fertilizer for regeneration	Jafri et al., 2018
	Examples	Pinewood sawdust	A heating value of 15.10 MJ/kg, high volatiles content	50.60	6.18	43.10	0.05	Utilized as an energy source	Luo et al., 2015
Non-woody biomass	General meaning	Agricultural crops and residues, animal waste, urban and industrial solid waste	High heating value of 19.34 MJ/kg 42.47% cellulose, 44.06% lignin 12%−24% cellulose, 7%−22% hemicellulose, and 10%−56% lignin	48.55	5.88	43.57	NR	Natural fibers through biological and thermochemical conversion	Aristizábal-Marulanda et al., 2020
				50.70	6.60	42.90	1.60	Transformed into a useful product through pyrolysis	Hmid et al., 2014
			High moisture, ash and voidage, while low calorific value and bulk density	41.78–61.57	5.36–8.10	37.73–61.57	0.30–3.80	Conversion into biofertilizer and feed through composting and ensiling	Jafri et al., 2018
	Examples	Rice straw	An average calorific value of 14–15 MJ/kg, 38.44% cellulose, 27.21% hemicellulose, and18.83% lignin	46.65	6.03	41.75	1.02	Converted into biogas and by-products through or combusting	Alengebawy et al., 2023
		Bamboo	47.65% cellulose, 72.5% hemicellulose, and 26.88% lignin	46.78	6.38	46.59	0.25	A promising energy crop	Rousset et al., 2011
		Consumed tea waste (CTB)	An average calorific value of 16.19 MJ/kg, 31.05% holocellulose and 25.68% lignin	48.60	5.43	42.17	3.80	Suitable for bio-fuel production via pyrolysis	Uzun et al., 2010
		Pruned tea biomass (PTB) *	2.96–4.82% cellulose, 19.18%−22.62% lignin, and 16.48%−21.16% TPP	44.45–47.13	NR	NR	0.12–0.14	Abundant TPP for bio-extration	Yang et al., 2023; Ma et al., 2023

Note: Carbon, C; Hydrogen, H; Oxygen, O; Nitrogen, N. NR, Not Reported. *, Pruned tea biomass (PTB) refers to the reported pruned tea leaves.

with higher productivity and increased drought tolerance, which help increase the potential yield of crop plants by as high as 70% (Agarwal et al., 2006). As an evergreen perennial C_3 crop, tea plant biomass emerges as promising candidates as the current plant biomass for nutritional soil amendments, biochar and biofuel production (Table 1) (Guo et al., 2021; Liang et al., 2024).

2.2. Current biomass conversion methods

Currently biomass are often converted into soil amendments, biochar and biofules. Biomass derived from plant and agriculture contains vast organic matters, enabling it to be composted to produce fertilizers and soil conditioners for crops, promising in enhancing soil quality, nutrient availability, and plant growth (Tarashkar et al., 2023). Through various microbial actions, solid biomass is converted into stable humic substances to boost soil fertility by supplying essential nutrients, enhancing soil structure, and promoting microbial activity. Another method to utilize renewable plant biomass is pyrolysis for biochar production, which has gained growing prominence in energy platforms for its rapid, oxygen-free conversion of raw biomass into solid biochar (Jafri et al., 2018). As shown in Table 1, woody biomass yields biochar with a higher carbon content than non-woody biomass under the same pyrolysis conditions, which is attributed to its inherently higher cellulose and lignin content and the lower amount of hemicellulose. The third way is to transform lignocellulosic biomass into sustainable biofuels, an appealing renewable source to offer consistent heat and value-added chemicals (Kumar et al., 2019). Current advances in biomass conversion technologies aim to fully recycle lignocellulosic feedstocks and algae for high calorific value biofuels in solid (combustion, pyrolysis), liquid (biological conversion), and gaseous (anaerobic digestion) forms, while minimizing the consumption of scarce resources (Lee et al., 2024). Furthermore, within a sustainable production framework, some waste-derived biomass with irregular shape and high moisture content requires careful treatment to prevent adverse environmental and social impacts.

2.3. TWB requires effective ecological conversion

During planting, production, processing and consumption, the tea industry will produce many tea industry residues, such as pruned tea branches, tea stems, fragments, tea dust, and so on. PTB and the spent tea leaves (CTB) discarded after the extraction of liquid from processed teas are both characterized as non-woody biomass called TWB (Table 1). China can produce more than 20 million tons of wet TWB every year, which poses a significant challenge to the recycling of agricultural and forestry byproducts (Wang et al., 2025). Prevalent evidence shows that tea waste (termed as CTB) has the characteristics of being a low-density and low-quality solid fuel due to the lower content of cellulose and lignin (Güler, 2024). In fact, TWB exhibits unique structure and composition that distinguish it from other biomass. Its stems contain abundant lignocellulose, similar to woody biomass (Table 1), while its leafy nature also results in high moisture content and a significantly higher content of functional components than that of wood and herbaceous plants, as previously reported (Liang et al., 2024). Specifically, the content of various secondary metabolites in TWB is several times or even dozens of times that in wood and herbal plants (Gong et al., 2020).

These TPP, essential amino acids, theanine, tea proteins, caffeine, trace elements and other bioactive secondary components in TWB are insufficiently utilized waste (Fig. 1**B**), necessitating the sustainable valorization through combined ecological conversion methodologies. Improving the energy conversion efficiency of non-woody biomass remains a challenge (Widjaya et al., 2018). However, biomass valorization for bioenergy production helps maintain a healthy ecosystem for sustainable production (Kumar et al., 2023a). A comprehensive survey of tea biomass production is essential to pave the way for its high value-added utilization. This approach is grounded in the unique compositional characteristics of TWB, particularly its lignocellulosic contents and secondary metabolites.

3. Overview of the tea biomass production

Biomass accumulation is associated with carbon sequestration. Plants are adapting to newly changing climatic conditions, which could modify the empirical relationship between biomass and climate, thus reducing carbon losses (Uribe et al., 2023). Research has shown that rising global temperatures can reduce photosynthetic carbon gain and biomass productivity by destroying plant photosystem within a specific range, particularly in C_3 plants (Pascual et al., 2022). To enhance heat tolerance in summer, significant increase of secondary metabolites including catechins, flavonoids, and anthocyanidins are demonstrated to derive from enhanced photosynthetic carbon assimilation through subsequent malonic and shikimic acid pathways (Liang et al., 2024). However, no comprehensive reviews have been conducted on biomass production of tea plants. In the context of the established fact of global warming, understanding and predicting the impacts of climate change with elevated CO_2 concentration on primary carbon metabolism in tea plants become critical.

3.1. Links between tea and biomass production

Tea plants are perennial evergreen shrubs or trees consisting of variable initial metabolites from primary metabolism and specialized metabolites from secondary metabolism. Photo-captured carbon by leaf such as sugar and TPP and soil-absorbed nitrogen by root such as amino acids and proteins are strongly influenced by external environmental factors (Ruan et al., 2010). Given the dual stress of world population expansion and changing climate, it is imperative to develop and deploy sustainable biomass production pathways (Antar et al., 2021). To perform an overview, bibliometric analysis was conducted using VOSviewer (version 1.6.20) (Filho et al., 2022) to identify the interlinks between *Camellia sinensis* and biomass production research in the scientific literature published up to 2024.

Compared with research focused on biomass, China performed more research about tea biomass than other countries (Fig. 2**A&B**). Information on contributions to tea biomass utilization was obtained from the Web of Science Core Collection, identifying a total of 37 relevant countries. China ranked first in the publication with 127 documents (about 47% of the total) and 2477 citations (about 51% of the total). India has published 14% of the documents with 9.9% citations, and USA has published 3.9% of the documents with 3.0% citations. This demonstrates China's commitment, as the world's largest tea producer, to advancing scientific research in tea biomass (Fig. 2**A&B**).

Based on keywords of 656 documents that has the highest correlation with the keywords "*Camellia sinensis* * tea * biomass", we perform a visual clustering analysis (Fig. 2**C**). The documents are primarily categorized into six clusters (in different colors). The term "*Camellia sinensis*" has a central position among dark blue dots, in relation to the formation of quality attributes of green tea such as catechins and amino acids. Four other clusters are closely related to it, namely the assimilation of carbon and nitrogen (green and yellow), the stress responses during growth (purple), and black tea polyphenols biomass (red). This was consist with researches that tea biomass research is mainly conducted about carbon and nitrogen metabolism and relevant responses under stress (Lv et al., 2021; Liang et al., 2024). While further utilization of biomass into bioenergy (e.g., bio-oil) and absorption materials (e.g., biochar) is not comprehensive.

The term "biomass" is clustered with "biochar, active carbon, pyrolysis and absorption" in red, and is closely related to "*Camellia sinensis*" (dark blue) and stress responses during "growth" (purple). The red cluster is clearly focused on conversion of lignocellulosic biomass (or plant biomass) conversion into bioenergy and activated carbon through pyrolysis and gasification (Fig. 2**C**). Current analysis also shows that

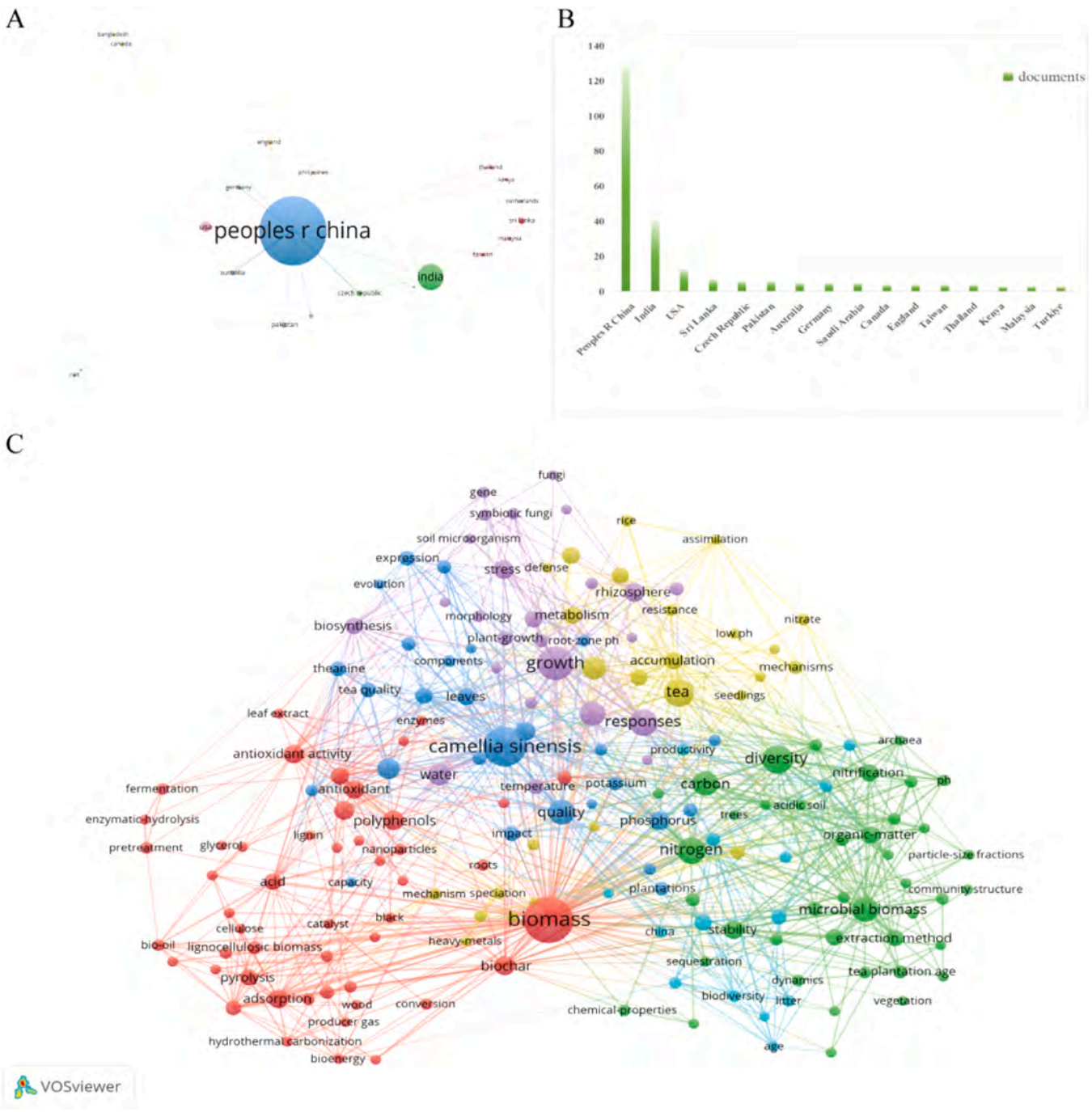

Fig. 2. Bibliometric study of *Camellia sinensis* and biomass. A, Colophony of countries or regions. B, The top twenty countries in publications more than 3. C, The output of the term co-occurrence analysis for "*Camellia sinensis*", "tea" and "biomass".

green tea is the resource of catechins and amino acids but lacks subsequent utilization, which correlates with previous research of tea catechins and peptides extraction (Harfoush et al., 2024; Cao et al., 2025). Microbial biomass has a central position in the green cluster, separated from the red cluster. The green cluster is closely related to tea plantation, specifically carbon sequestration, nitrification, mineralization, and acidification. Besides, the light blue cluster (soil acidification and fertilization) is closely related to the green cluster. The above analysis evinces the important roles of rhizosphere microorganisms for plant growth. Microbial community is closely related to biochar and mineralization, which corresponds to the research using homogenized biochar as soil amendment (Zou et al., 2023).

3.2. Physiological patterns of TWB

Tea plants originate from the cloudy primeval forest located in the Yunnan-Guizhou Plateau and Himalayan Mountains. Through long-term systematic evolution, tea plants adapt to warm and humid environments with an optimal temperature of 20–25 ℃. During warm months, sunlight provides sufficient irradiation for moderate temperature (10–40 ℃) along with necessary light intensity. Tea plants are perennial evergreen leafy cash crops, and 90–95% of their biological yield comes from photosynthesis (Sun et al., 2015). Despite benefiting carbon metabolism, however, the strong sunlight intensity inhibits nitrogen metabolism and results in the decreased amino acids and protein synthesis during summer and autumn. The accumulation of secondary metabolites (mainly

flavonoids) facilitates vascular plants' adaptation to abiotic stresses, including high temperature, intense light, and drought (Mouradov and Spangenberg, 2014), among which high light intensity and temperature are reported to accelerate the flavonoid biosynthesis, tricarboxylic acid cycle, and photorespiration of tea plants in summer (Liu et al., 2015).

3.2.1. Photosynthetic characteristics of tea plants

For C_3 plants, CO_2 enters the mesophyll through the stomata and directly joins in the Calvin cycle. As C_3 short-day leaf crops, tea plants have high photorespiration, a high CO_2 compensation point, and low photosynthetic efficiency. The quality of tea products primarily depends on the content of metabolites in the raw teas (Liang et al., 2022), highlighting the importance of elucidating photosynthetic characteristics of tea plants under external environmental factors.

Biosynthesis of tea metabolites depends on sunlight, which regulates photosynthesis and influences the growth and morphogenesis. Tea plants favor low light intensity but require high light quality. The suitable light intensity ranges from 1.67 to 2.03 $J{\cdot}cm^{-2}{\cdot}min^{-1}$. Besides, their photosynthetic rate is higher under red light than blue light, promoting the formation of carbohydrates and TPP. Excessive light intensity causes light stress and inhibition in tea plants (Sun et al., 2015). Under strong light conditions, tea plants actively increased formation of light-absorbing flavonoids to prevent sunburn.

Temperature also has a great influence on photosynthetic characteristics of tea plants. The optimal ambient temperature for tea growth ranges from 18 to 30 ℃ and the optimal soil temperature is between 20 and 25 ℃. When the average daily temperature is about 22.5 ℃, the growth rate of tea plants reaches its maximum. Temperatures higher than 40 ℃ or lower than −6 ℃ would block the electron transduction in tea leaves and cause serious damage to their growth (Li et al., 2015). The growth of new tea shoots is stunted when the average daily temperature exceeds 30 ℃, and extreme heat waves resulting from global warming threatens the output of new tea plantations.

Water supply is necessary for the functionality of photosystems. Well-distributed rainfall (150 mm per month) ensures continuous production. And water deficiency may cause significant reduction in the photosynthetic rate, stomatal conductance and transpiration rate (Maritim et al., 2015). Supplemental irrigation has been provided to reduce water stress during the dry season for stable production of Tieguanyin tea in southeastern China (Lin et al., 2014). Facing the short of water supply in some East African tea planting areas, it is important to maintain proper irrigation for tea plant growth.

In addition to light, temperature and water supply, season and nitrogen supply are worth consideration to maintain the efficient photosynthesis of tea plants. Among three growing seasons, the photosynthetic performance of tea plants is greatest in summer, as reflected by their higher average net photosynthetic rate, stomatal conductance, and transpiration rate (Zou et al., 2018). Given their high nitrogen demand for consecutive harvests, tea plants benefit from nitrogen application. Applying nitrogen (26 $kg{\cdot}667\ m^{-2}$) supports healthy growth primarily through the mechanisms of increased chlorophyll content and improved photosynthetic parameters in tea plants (Li et al., 2020).

3.2.2. Carbon capture of tea plants

Life on earth chiefly depends on photosynthesis for synthesizing high-energy sugars, concomitant with the production of oxygen. However, atmospheric CO_2 concentration has been intensified by more than 40% (from 270 to 400 ppm) since the industrial revolution (Moreira and Pires, 2016). The direct consequence is inevitable global warming. Global temperature has raised by 0.85 ℃ from 1880 to 2012 and will increase further by 1.4–5.8 ℃ in 2100, foreseeing a huge impact on the entire ecosystem (de Silva et al., 2015). Biological capture and sequestration of CO_2 as plant biomass is a sustainable and cost-effective approach to reducing atmospheric CO_2 levels (Pires et al., 2011).

Under current atmospheric CO_2 concentration that is lower than the CO_2 saturation point of C_3 plants (tea plants included), such an increase will directly promote the photosynthesis of tea plants, further promoting their growth and development. In addition, tea plants play significant role in mitigating global warming by assimilating 1243.8–2526.7 $kg{\cdot}ha^{-1}$ atmospheric CO_2 each year and sequestrate 50.8% in their biomass (Pramanik and Phukan, 2020). Through carbon capture and fundamental physiological process (photosynthetic carbon assimilation) in tea plants, substrates and energy for the synthesis of primary metabolites are produced.

3.3. Primary metabolites accumulated in PTB

Photosynthetic carbon assimilation of tea plants has always received less attention than other physiological processes (e.g., nitrogen supply) to improve production (Mohotti and Lawlor, 2002). As the energy foundation produced by photosynthetic carbon assimilation, carbohydrates are also an important part of driving the circulation and operation of the biosphere. Same as other plants, tea plants thrive in warm months when the temperature stays within 10–40 ℃ for photosynthesis, due to vigorous metabolism to produce carbohydrates for structural development. According to the forms of carbohydrates present in plants, they are usually divided into two categories: structural carbohydrates (SC) and non-structural carbohydrates (NSC). Here, we conclude the accumulation patterns of primary metabolites in PTB with an emphasis on carbohydrates.

3.3.1. Non-structural carbohydrates and amino acids

NSC mainly include monosaccharides, disaccharides, and sugar alcohols and act as important energy source involved in plant growth and important indicator involved in carbon uptake and consumption, the content of which ranges from 12% to 14% (w/w) in tea plants (Xiang et al., 2019). After transforming CO_2 into glucose in leaf and subsequent transportation to ubiquitous cells, they begin to serve as source of carbon and energy. Through different pathways, a complex mixture of primary metabolites (amino acids, organic acids, sugars, lipids and short-chain fatty acids) are formed in tea shoots, which merits the expected utilization value.

Under heat stress and high irradiation, the assimilation process of photosynthetic carbon in tea plants is inhibited. To enhance resistance to biotic and/or abiotic stresses in warm months, tea plants spontaneously evolve various morphological and physiological responses, among which the accumulation of soluble sugars, such as glucose, sucrose, and fructose in vacuole (Sami et al., 2016). A rapid accumulation of soluble sugars, soluble proteins, and osmotic proline in the cytoplasm effectively reduces high temperature induced damage to tea plants. Tea plants also produce different categories of natural inducers that can rapidly activate the defense systems and prevent cellular damage caused by the increased photosynthesis, part of which are glycoproteins, proteins, polypeptides, amino acids, lipids, and chitosan.

Tea plants usually contain less amino acids than that in winter and spring, however, they play essential roles in the growth of tea plants. In tea leaves, the concentrations of total free amino acids range from 1% to 5%, and proteins account for 21–28% of tea leaf dry weight (Wang et al., 2014). As building blocks for enzymes and proteins, amino acids are essential for tea plants metabolism and structure, serving as nitrogen donors for synthesizing many compounds critical to plant development, including chlorophyll, hormones, and secondary metabolites. As an important signaling molecule, γ-aminobutyric acid rapidly accumulates in plant cells in response to many stresses, such as heat, drought, cold, injury, herbivores, pathogens and viruses. Glutamate and proline are also considered to be stress-related amino acids, which may play a role in plant immunity. Concluding remarks are thus demonstrated: The generation of these non-structural carbohydrates and amino acids plays essential roles in regulating tea plants growth, although diverting a small portion of assimilated carbons.

3.3.2. Structural carbohydrates and lignins

Plant cell wall comprises a gel-like network of cellulose, hemicelluloses, pectin, glycoproteins, lignin, minerals, and phenolic acids. For SC (including cellulose, hemicellulose and pectin), the major macromolecules of plant morphogenesis in tea plants have barely been reported. PTB contains massive insoluble cell walls of tea leaves, mainly consisting of cellulose (>9.3%), hemicellulose (>42.5%), and lignin (>31.9%) (Ayas, and Esen, 2016). These cellulose, hemicellulose, lignin, tannins, and proteins in PTB serves as a magnificent carbon source for CTB valorization to preparing biochar and other biological processes after extracting soluble secondary metabolites such as TPP and TPS (Table 2).

3.4. Abundant secondary metabolites accumulated in PTB

Secondary metabolites are the required chemicals for plant interactions with the environment for their survival and fitness, which are derived from the assimilated carbons in primary metabolism. TPP, tea saponins, *L*-theanine, caffeine, and volatiles are characteristic secondary metabolites found in tea plants. Extremely abundant TPP (including three kinds of flavonoids namely catechins, anthocyanins and proanthocyanidins) in PTB contribute to both sensory quality and health benefits of tea products (Liang et al., 2024), which also act as antioxidants to directly remove reactive oxygen species (ROS) under biotic and abiotic stresses (Agati, Azzarello, Pollastri, and Tattini, 2012).

3.4.1. Flavonoids

Recent study demonstrates the significant roles of flavonoids accumulation through shikimate, phenylpropanoid, and flavonoid pathways in PTB to resist environmental stresses like ultraviolet (UV) radiation, heat, and drought in warm months (Wu et al., 2019a). Both high light intensity and high temperature treatments upregulate the genes of the secondary metabolism of phenylpropanoids significantly, increasing total flavonols content in PTB (Lv et al., 2021). When tea leaves are exposed to sunlight and high temperature, *Cs*MYB67 contributes to the accumulation of flavonoids via regulating the downstream pathway of flavonoid biosynthesis in PTB (Ye et al., 2024). Drought stress in warm months induces the generation of $O_2^{\cdot-}$ and H_2O_2. Similarly, TPP and total flavonoids in tea variety Zhong Cha 108 kept under drought stress for 96 h increased by 53% and 25%, respectively (Jiang et al., 2020). Anthocyanins (glycosides of anthocyanidins) and proanthocyanidins (PA, condensed tannins) are also accumulated in PTB to resist radiation stress and attacks from pathogens, microbes, and herbivores (Dixon et al., 2013; Wang et al., 2019). In general, adequate sunlight irradiation, high temperature, and drought stress promote the increase of total flavonoids in PTB in summer and autumn.

3.4.2. Tea saponins

Saponins are a class of natural triterpene or steroid glycosides containing carbohydrate chains linked via a glycosidic bond to an organic moiety (termed the aglycone), participating in plant communication and defense. As other classes of plant secondary metabolites, the level of saponins is significantly influenced by external environmental stimuli including high temperature, drought, and irradiation (Szakiel et al., 2011). Tea plants tend to accumulate saponins in PTB for adaptation to survive under adverse climatic conditions, synthesis of saponins is elevated (Wen et al., 2023). Triterpene biosynthesis in tea plants gains progress on the enzymology level with the characterization of oxidosqualene cyclase genes via genome mining and screening, and future investigations at the molecular level would demonstrate seasonal saponins variations to guide tea production and strengthen the utilization of tea saponins in PTB.

3.4.3. Lignin

Lignin is the third most abundant metabolite in plants, while in tea plants it gains less attention than polyphenols. Lignin plays a crucial role in tea plant growth and development, including providing the necessary mechanical strength for plant cells and tissues, contributing to the transport of water and nutrients in plants, and responding to various biotic or abiotic stresses (Zhao and Dixon, 2011). When tea plants are exposed to an excess of light or UV-B radiation, an increased level of lignin is observed, which protects plant cells from ROS-induced cellular damage. Under drought stress, tea plants also accumulated lignin to maintain cell osmotic balance and protect membrane integrity (Teng et al., 2020). High-temperature stress also stimulates lignin biosynthesis. Taken together, the inevitable increase of lignin in PTB contributes to the resistance against strong light, drought, and high temperature stresses.

4. Valorization of TWB through bio-extraction

Chinese tea market is in a dilemma of pursuing tender shoots (including buds and first-to-third leaves) grown in spring for traditional premium tea. Technically, there are three main tea-plucking seasons throughout the year: spring, summer, and autumn. In practice, however, over 60% of tea biomass grown in summer and autumn is typically left unharvested or abandoned because of low market price. Owing to its rich content of inherent metabolites as concluded above and massive annual output (over 20 million tons), TWB is well-suited for multistage valorization in various industries, primarily biological and thermochemical approaches aimed at achieving sustainability (Table 2). First biological approach is to extract active ingredients from PTB to produce value-added food additives, health products, adsorbents, and daily necessities (Fig. 3).

4.1. Two-stage enzymatic extraction from TWB

Regardless of season, PTB are rich in secondary metabolites, such as phenolic antioxidants, proteins, amino acids, lipids, sugars, vitamins, fiber, and minerals. In face of the large amount of TWB, one of the most effective methods is to extract the valuable bioactive components. As promising strategies for biomass valorization, enzymatic catalysis and microbial fermentation have drawn considerable interest (de Souza, and Kawaguti, 2021; Lee et al., 2023). Their appeal lies in providing a cost-effective and controlled means to support greener and more sustainable manufacture. Two-stage enzymatic extraction thus serves as an effective method to valorize the soluble extracts from PTB alongside the insoluble extracts from CTB.

4.1.1. Enzymatic extraction of soluble TPP, TPS and saponins from PTB

The potential benefits of PTB mainly depend on the pharmacological activities of TPP, accounting for 20% of soluble contents. Traditional preparation methods of TPP include solvent extraction method, ion precipitation method, resin adsorption method, and supercritical extraction method, all of which have certain limitations (Di Maro et al., 2024). It is urgent to optimize the extraction conditions, which accurately and selectively extract bioactive compounds from PTB with good operational performance and, low cost. Response surface methodology was shown efficient for obtaining the optimal conditions to yield 33.82 mg/g of TPP (Xiang et al., 2018). Further enzymatic extraction of TPP from PTB via enzymatic reactions (enzyme complex of pectinase and cellulase) at the mild reaction conditions (48 ℃) effectively decomposes the plant cell wall to release active TPP in the vacuoles, leading to the maximum yield of 82.26 mg/g (Luo et al., 2020).

TPS have merited increasing attention due to non-toxic nature and remarkable antitumor and antibacterial properties, the content of which ranges from 1% to 4.6% in different processed teas based on dry tea weight (Du et al., 2012; Chen et al., 2016). The structures of TPS are highly branched mixture of monosaccharides, sugar alcohols and proteins, and bioactivities of TPS extracts are different between the chemical compositions. Conventional TPS preparation via hot-water extraction and ethanol precipitation yields crude products with low

Table 2
Current valorization techniques of common tea waste biomass (TWB).

Technique	Product	Raw material	Crucial processing procedure	Common application	Characteristic	Application prospect	Reference
Bio-extraction of bioactive molecules	Tea polyphenols extracts (containing mainly TPP with multiple phenolic hydroxyl groups)	Spent tea after tea-making	Water bath extraction with ethanol	Industrial food products or supplements	Promising antioxidant and antibacterial potential	As candidates for use as natural health boosters in food industry	Harfoush et al., (2024)
		Green tea waste from hot water extraction (85 ℃, 10 min)	Dried and ground into 63 μm powder, then sonicated for 2 min	As a reductant for the oxidative degradation of toxic phenols and pharmaceutical pollutants	High electron donating properties with notably enhanced efficiency in degrading 4-chlorophenol	As an accelerator in Fenton-like systems for waste water treatment	Truong et al., (2025)
		Green tea waste	Extraction with 70% ethanol and 2% hydrochloric acid at 70 ℃ for 15–45 min	Acted as a plasticizer of the polymer	Improve antioxidant properties of the fabricated samples, and extend shelf life	Edible packaging material from TWB	Acquavia et al., (2024)
		Oolong tea stems were obtained from tea farmers	Ground for 1 min and extraction in an aqueous medium (87 ℃, 57 min)	As natural and promising reversible thermochromic dyes	Showing excellent antibacterial, UV-protection and oxidation resistance	Developing smart color-changing textiles to substitute synthetic dyes	Xu et al., 2025; Zhou et al., (2024)
		Post-extracted tea waste, a commonly discarded by-product	Reflux extraction (80 ℃, 20 min)	As reducing agents to synthesize zero-valent iron nanoparticles (NPs)	Facilitating 100% removal of orange G, methylene blue, and methyl orange dyes	As a promising solution for dye degradation in water decontamination	Rodríguez-Rasero et al., (2024)
	Tea polysaccharides (TPS) extracts	Green tea residues	Hot water extraction (100 ℃ for 2 h), ethanol precipitation, and steam explosion	Modified polysaccharides	Displayed more loose and porous structures, compared to the original one	Enhancing the antioxidant activity of TPS isolated from TWB,	Ge et al., (2024)
		Liubao brick tea residues	Sequential extraction method with dialysis and purification via ion exchange chromatography	Novel water-soluble polysaccharides	Four distinct cell wall polysaccharides were isolated and	An cost-effective sequential extraction method to utilize TWB as a valuable resource	Wang et al., 2024
	Microcrystalline cellulose (MCC)	Black tea waste produced in tea factories	Initial boiling to remove TPP, then heated with 5 wt% NaOH solution	For use in food packaging, cosmetics, pharmaceutical, and polymer composites	Superior mechanical strength, good biodegradability and renewability	Developing a energy efficient, time-saving and low-cost method for extracting MCC from TWB	Debnath et al., 2023
	Cellulose nanocrystals (CNC)	Black tea residues from a local tea factory	Acidolysis with 64% sulfuric acid (45 ℃, 50 min)	Potential for high-performance applications in nanocomposites and biomedicine	A 44.8% increase in the yield, exhibiting a crystallinity of 68.57%	Promising for application in reinforced composites	Wang et al., 2024
	Chlorophyll extracts	Oolong tea dreg from soft drink preparation	Stirred in ethanol for 12 h	Fluorescent ratiometric probe	Outstanding selectivity and a low limit of detection (0.8 μM) for bilirubin	Providing an environment friendly method for ratiometric probe synthesis	Bui et al., 2024
	High-quality dietary fibers (DF)	Green tea residue	Steam explosion treatment (0.3–1.0 MPa, 30–90 s)	As right food ingredients with a 20% soluble DF	Increasing the content of soluble DF to 23.03 g/100 g	Offering a method to convert insoluble DF into soluble DF	Xing et al., (2024)
Biological conversion	Fermented tea residue soluble DF	Pu-erh tea residue	Sequential fermentation with *Lactobacillus plantarum* and *Aspergillus niger*	Functional products to alleviate cardiovascular diseases	Easy to be digested due to more generated short-chain fatty acids	Improving the value of dietary fiber in TWB	Xia et al., (2025)
	Tea residue protein-derived peptides aimed at managing human health	Wuyi rock tea residue	Extracted with NaOH (66 ℃, 2 h), and enzymatic hydrolysis (neutral protease, 45 ℃, 3 h)	Producing angiotensin I converting enzyme (ACE) inhibitory peptides	Five novel ACE inhibitory peptides were found	Potential of active peptides for applications in functional food or pharmaceutical products	Cao et al., (2025)
	Ribulose−1,5-bisphosphate carboxylase/oxygenase (RuBisCO)	Tea residue, provided by a tea factory	Sequential hydrolysis with pepsin, papain, alkaline protease, and β-glucanase	Alternative protein or bioactive peptides in the food industry	RuBisCO was completely released	Offering a food-grade extraction of RuBisCO	Zhou et al., 2024
	Organic tea vermicompost	Raw tea waste from	Composting	Returned to the tea plantation to	Organic fertilizer with low level of antioxidants	Promising organic tea compost fertilizer	Kocaman et al., (2024)

(*continued on next page*)

Table 2 (*continued*)

		processing factories		increase soil organic matter	and increased levels of amino acids, organic acids and chlorophyll	from TWB for organic plant production	
	Silage with a high content of water-soluble carbohydrates	Pruned branches from tea plants	Ensiling	Ensiling preserves the main bioactive components in the raw material.	Enriched lactic and acetic acids with the well preserved tea components	PTB from tea plants is a promising bioresource for developing silage	Li et al., 2022
	Bacterial cellulose	Tea dust from local tea plantation	As a nitrogen source in fermentation medium instead of commercial teas	Growth medium for microbial consortium production	Higher SCOBY yield and growth rate with a reduced cost from $0.075 to $0.027	Cost-effective substrates for bacterial cellulose production within a short time	Selvaraj, and Gurumurthy, (2024)
	Tannase	Spent green tea leaves	As culture medium in solid-state fermentation	Great potential for hydrolyzing tannins	Optimized condition achieves a tannase yield of 246.82 (U/g)	Production of tannase with low production costs	Peña-Lucio et al., (2023)
	Cellulase	Green tea waste after brewing	Solid-state fermentation, with 3 g of dried TWB	Promoting the hydrolysis of lignocellulose to produce fermentable sugars	*A. niger* 28 A produced high titers of endocellulases (65.85 IU/g), total cellulase activity (5.44 FPU/g)	Production of cellulases by SSF with high added value with various applications	Saldaña-Mendoza et al., 2024
	Ethanol	Brewed tea waste powders or industrial tea waste	Fermented for 168 h at 30 ℃	Biofuel production	Co-fermentation of *Candida boidinii* and *Saccharomyces cerevisiae* produced 21.9 g/L bioethanol.	A promising way to produce bioethanol by fermenting the sugars prepared from TWB	Demiray et al., 2022
Pyrolysis	Activated carbon	Local tea waste	Pyrolyzed at 200–1000 ℃ for 2 h	Treatment of industrial wastewater	An average crystallite size of 15 nm, reducing 89–97% chromium (Cr)	Effectively removes Cr from tannery wastewater	Hossain et al., 2023
		Tea waste from local market	Carbonization at 550 ℃, and thermochemical activation in KOH at 850 ℃	High-performance energy storage electrode materials	Specific capacitance value of 182 F/g and a stability of 95% in 5000 charge/discharge cycles	Promising materials for cost-effective high-capacity supercapacitors production	Beissenov et al., 2024
	Modified biochar (carbonaceous solid residue)	Tea residue collected from the market	Calcined at a rate of 10 ℃/min to 800 ℃ for 2 h	Inorganic phosphorus adsorption in solution	Exhibiting a high adsorption capacity and recovery under anaerobic conditions	Reducing wastewater treatment expenses and addressing water pollution	Zhou et al., (2025)
	Pruning litter derived biochar	Pruned tea litter from tea plantations	Pyrolyzed for 2 h at 500 ℃ in an oxygen-restricted environment	Significantly mitigated soil organic carbon mineralization	Reducing *O*-alkyl C, β-glucosidase/ cellobiohydrolase activities	Maintaining soil carbon stock and mitigating the C emission	Zhang et al., (2025)
	Co-pyrolytic bio-oil (condensable vapours)	Tea waste from a tea factory	Pyrolyzed at 500 ℃	Obtaining bio-oil between light and heavy petroleum products	30.4% yield of alkanes, alkenes, and branched hydrocarbons	Renewable fuel for power generation, and production of value-added chemicals such as resins	Uzun et al., 2010
		Spent black, green, white tea grounds	Pyrolyzed at 400 ℃ with sodium and calcium carbonates as catalysts	Renewable fuel	A bio-oil yield of 18% without unsaturated aldehydes or ketones compatible with diesel and kerosene fuel in water heating applications	Producing net profit of about 338.15 $/ton, while reducing annual greenhouse gas emissions by 2104.29 tons	Rijo et al., 2021; Hossain et al., 2025
Combustion	Pellets with a diameter of 0.5–6 mm and a length of 30–40 mm.	Tea waste or tea leaves collected from tea factories	Pelleting, further modified by torrefaction	As a sustainable solid biofuel	The calorific value of tea waste pellets was above 18.5 MJ/kg, exhibiting a high carbon content of 45%	Easily pelletized and increasing energy parameters comparable to conventional wood pellets	Güler, (2024); Jezerska et al., 2025
Gasification	Syngas	Spent green tea waste	Two-step pyrolysis and catalytic cracking (first 550 ℃, second 700 and 800 ℃)	Biofuel	Syngas yield (56.5 wt%) and its potential were greatly enhanced, reaching a H_2/CO ratio of 1.5	Potential to produce diverse biofuels and chemicals	Ben Abdallah et al., (2023)
	High quality hydrogen-rich syngas	Spent tea waste generated by restaurant	Gasification at 800–900 ℃	Generated energy	Co-gasification of TWB with agricultural residues enhanced the volumetric gas composition of H_2 and CH_4 with a relatively constant CO gas composition	Increasing gasification potential, aiding effective implementation of bioenergy while reducing CO_2 emission	Santhappan et al., 2024; Saini et al., 2024

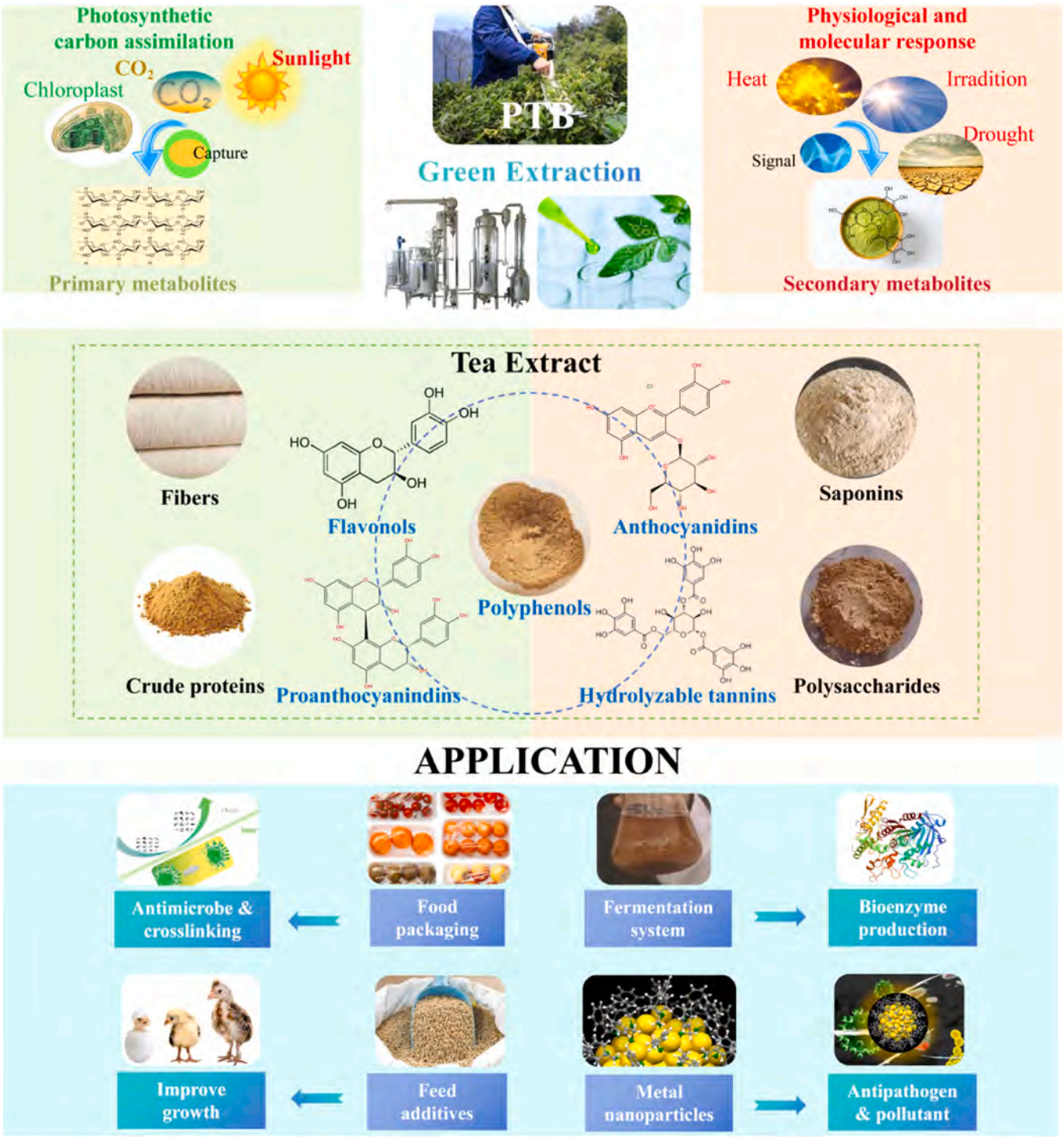

Fig. 3. Employing enzymes for two-stage extraction of pruned tea biomass (PTB) into resources. Green bio-extraction, mainly based on the maceration method combined with enzymatic treatment recover both the water-soluble bioactive components (especially polyphenols, polysaccharides, etc.) and the water-insoluble ones (especially fibers, proteins, etc.) based on the accumulation patterns of PTB for the production of food packaging films, enzymes, feed additives and health-promoting metal nanoparticles.

recovery rate due to the high sensitivity of TPS to extraction conditions. Advanced methods including ultrasound-, microwave-, and enzyme-assisted extraction combined with chromatographic purification are thus necessary to improve efficiency (Huang and Yu, 2024). By using synergistic pectinase, cellulase, and protease to modify the chemical composition of TPS for enhanced bioactivities and to disrupt cellular structures for thorough material release, enzyme-assisted extraction is distinguished by its ability to significantly boost yield, selectively enhance effective compositions, and lower energy consumption via mild thermal conditions.

Due to the anticancer, anti-inflammatory, and antioxidative effects, tea saponins can be extracted from PTB for pharmaceutical and healthcare products and natural non-ionic surfactants. The common way of extracting saponins from PTB is maceration with water, and increased duration and temperature benefits the saponin extraction rate by promoting more saponins released into water (Fan et al., 2021). Although

inorganic solvents like methanol and ethanol have been used to assist the hot water extraction of saponin for improved efficiency, the yield remains limited to 25.8% (Ribeiro et al., 2013). Enzymatic extraction produces a high-purity tea saponin extract through the enzymatic hydrolysis of polysaccharides and proteins using specific enzymes (e.g., protease, cellulase, lipase) and subsequent purification, which achieves an enhanced yield compared to traditional hot water extraction (de Souza and Kawaguti, 2021).

Although meriting the enhanced yields than common methods, enzymatic extraction methods for soluble TPP, TPS and saponins from PTB were neither cost-effective for foods nor capable of yielding purity levels sufficient for medical purposes. To advance the valorization of PTB, future research should pursue the recovery efficiency while enhance product purity via combining other promising techniques, including deep eutectic solvent extraction and aqueous two-stage extraction. Future elucidation on the structure-activity relationship will pave the way for the selective enzymatic modification of TPP, TPS, and saponins from PTB using integrated chemical and physical methods, thereby facilitating their high value-added utilization.

4.1.2. Bio-extraction of insoluble fibers and proteins from CTB

Previous research mainly focused on water-soluble components (TPP, TPS, etc.) in tea leaves, without enough attention been paid to water-insoluble fibers and proteins within PTB and CTB. After enzymatic extraction of the soluble constituents in PTB, the resulted CTB contains many insoluble fibers and proteins. These compounds can be converted into forms suitable for industrial valorization by bio-extraction.

Insoluble fibers from CTB can be used as cellulose-based biomass materials due to a underestimated fact that PTB contains more insoluble fibers than water-soluble carbohydrates (less than 10 g/kg of dry matter) (Lai, Doan, and Nguyen, 2021). Controlled acid hydrolysis helps remove the amorphous region of CTB cellulose, and ultimate dialysis cuts off molecular weight of 8–14 kDa crystalline particles (also termed nanocellulose crystals, NCCs), which are promising bionanoparticles owing to their unique advantages of more biocompatibility and biodegradability but lower cost than commercial wood NCCs and microcrystalline NCCs (Guo et al., 2020). A significant economic issue, however, lies in the high consumption of reagents, notably organic acids like H_2SO_4 and acetic acid, and oxidants such as H_2O_2. Bio-extraction of insoluble fibers often uses cellulases, hemicellulases and pectinases to randomly hydrolyze the β−1,4-glucosidic bonds and α−1,4-glucosidic bonds in cell wall to organize the long chains of tea fiber, simultaneously partially crystalline structure are cut, facilitating the production of functional ingredients and soluble or insoluble dietary fibers (DF) (de Souza, and Kawaguti, 2021; Xing et al., 2024). Conversion via fermentation strains such as *Cochliobolus kusanoi*, *Aspergillus puulaauensis*, *Lactobacillus plantarum* and *A. niger* significantly changes the microstructure of DF, which advances phytochemistry properties and valorization of PTB (Si et al., 2022; Xia et al., 2025).

So far, proteins from two major sources (i.e. milk and soybean) are most widely used in the food industry. Tea proteins in PTB (18–20% of dry matter) have gained much attention for their nutritional parity with soybean proteins (Kumar et al., 2023b). Their role as a sustainable and safe plant-based source positions them as a key solution for alleviating the global malnutrition issues (Hadidi et al., 2023). The functional properties of proteins depend on how they are extracted, isolated, and concentrated. Tea proteins are traditionally extracted with high-pH solutions, with an optimal yield of 20.73% extracts from PTB (Zhang et al., 2015). Howerver, such alkali method poses challenges to both food safety and environment sustainability because of nutritional concern about the generation of noxious substances, in addition to the poor emulsification properties for food applications (Lin et al., 2022). Biological hydrolysis is preferable for tea proteins extraction primarily through co-fermentation of *Lactiplantibacillus plantarum* and PTB, tea proteins and peptide fractions were recycled from CTB into renewable resources (Lee et al., 2023). Combining enzymatic hydrolysis, ultra-filtration, mass spectrometry identification and molecular docking screening further provides guidelines for developing novel hypolipidemic peptides (Ye et al., 2023), promoting the high-value utilization of tea proteins in CTB.

4.2. TPP from TWB used for food packaging

Bio-based packaging materials derived from biopolymer matrices are highly biodegradable and renewable, posing no risk to consumers or ecosystems (Acquavia et al., 2024). This makes them ideal alternatives to traditional petroleum-based plastics for food packaging.

4.2.1. Polymer cross-linking agents

Commonly used chemical cross-linking agents (including glutaraldehyde, glyoxal, and formaldehyde) have high toxicity and are not suitable for food packaging applications. The use of cross-linking agents such as TPP enhances the interfacial adhesion between the layers of composite films (Lei et al., 2019; Debnath et al., 2023). Under alkaline conditions, diphenol moieties of TPP go on oxidization to produce quinone intermediates and form a crosslink (covalent C-N or C-S bonds) with the side chains of proteins (Strauss, and Gibson, 2004). These bio-extracted TPP from PTB, regarded as non-toxic plant metabolites with bulk density, function as a cross-linker in aqueous solution to form abundant hydrogen bonds and modify protein- or polysaccharide-based food packaging films, which significantly improve the tensile strength and barrier properties of biopolymer films against water vapor and oxygen (Ozdal et al., 2013; Lei et al., 2019).

4.2.2. Antibacterial agents

Owing to its antioxidant and antibacterial properties, TPP serves as a valuable active ingredient in food packaging. The antioxidant effect, which delays lipid oxidation, is attributed to its initial oxidation upon exposure to oxygen and light (Wang et al., 2013), while its inherent antibacterial nature inhibits pathogen growth. These dual functions are leveraged in materials like modified TPP-based edible packaging, where TPP acts as a plasticizer and enhances antioxidant properties, thereby extending shelf life (Acquavia et al., 2024). Consequently, exogenous TPP from PTB effectively controls pathogens, improves quality, and regulates oxidation during the storage of agricultural products.

4.3. Promising ingredients in TWB as feed additives

Tea leaves have the potential to be used as animal feed primarily because of their higher crude protein content (21%−28%), especially for animals utilizing low-quality forage in protein-deficient areas (Kondo et al., 2007). When byproducts from PTB with bioactive TPP, saponins, and *L*-theanine were supplemented in the feed, the conversion ratio and crude protein got improved in many livestocks.

TPP are a promising ingredient in PTB as the feed additives. Adding tea catechins to goats' diet improved daily weight gain and increased protein content and dry matter in goat meat (Tan et al., 2011). TPP addition enhanced the fattening performance of pigs and promoted central nervous excitement, which significantly increasing their daily weight gain. In the last few decades, the role of tannins in animal fodders has been recognized, and researchers have demonstrated that PA could potentially be used as natural alternatives to in-feed antibiotics, exhibiting more significant activity against gram-positive than gram-negative bacteria (Huang et al., 2017a). In addition to production benefits, adding PTB with tannins to feed also brings ecological benefits through alleviating bloat and reducing methane and ammonia production, which helps reduce greenhouse gas emissions and mitigate climate changes (Vasta et al., 2009; Kolling et al., 2018).

Similar as TPP, tea saponins and *L*-Theanine in PTB act as promising feed additives for meat production. Addition of tea saponins helps improve the quality of ruminant products such as milk and meat in terms of increased rumenic acid and polyunsaturated fatty acids while

decreased saturated fatty acids (Zhou et al., 2012). The supplementation of dietary *L*-theanine enhances both the immune and antioxidant functions of livestock, which may be attributed to its positive influence on lipid metabolism (Zhang et al., 2018; Yang et al., 2022).

4.4. Extracts from TWB used to produce metal nanoparticles (NPs)

Recent studies have shown that some plant extracts including tea, cola, and corn bran can improve the synthesis and surface properties of metal NPs, conferring greater stability through surface organic coatings than conventional physicochemical synthesis. Over the past decade, extracts from TWB have been widely used to synthesize metal NPs, notably in drug modification and the efficient remediation of contaminants (Dou et al., 2021; Kumar et al., 2022).

4.4.1. Against diseases and bacteria

TPP extracted from PTB have been widely applied as eco-friendly reducing and stabilizing agent for the synthesis of novel copper NPs. The resulting NPs exhibit cytotoxic effects on gastric and ovarian cancer cell lines (Liu et al.,2022; Dou et al.,2021). Based on the coordination metal-phenolic networks that TPP forms with metal ions on various substrates, these NPs are also promising for antimicrobial application. Natural TPP mixed with metal ions (e.g., Cu^{2+}) in aqueous solution lower the working concentrations of Cu^{2+} and show comparable antimicrobial activity with no observed safety issues in cell models such as blood, zebrafish, and mice (Yu et al., 2023). The combination of enhanced antimicrobial efficiency and a lack of safety concerns makes these NPs an important model for the green synthesis of TPP-based materials with biomedical applications.

4.4.2. As pollution detergents

Extracts from TWB is an ideal plant litter-based materials that meriting the advantages of convenient, low cost, and sustainable adsorption over various chemically synthesized materials, since the inherent various functional groups such as hydroxyl, nitro, carbonyl, and amino groups act as good binding sites for pollutants adsorption (Praveen et al., 2022). Catechins and other TPP recovered from TWB extracts can used as reducing agents to synthesize MgO NPs via facile green approach, showing over 97% photocatalytic degradation efficiency of methylene blue dye (Kumar et al., 2022).

5. Valorization of TWB through biological conversion

Currently, most lignified tea stems to be discarded cause environmental pollution and waste a lot of potential biomass resources. Using plant by-products as raw materials to produce high-value products like

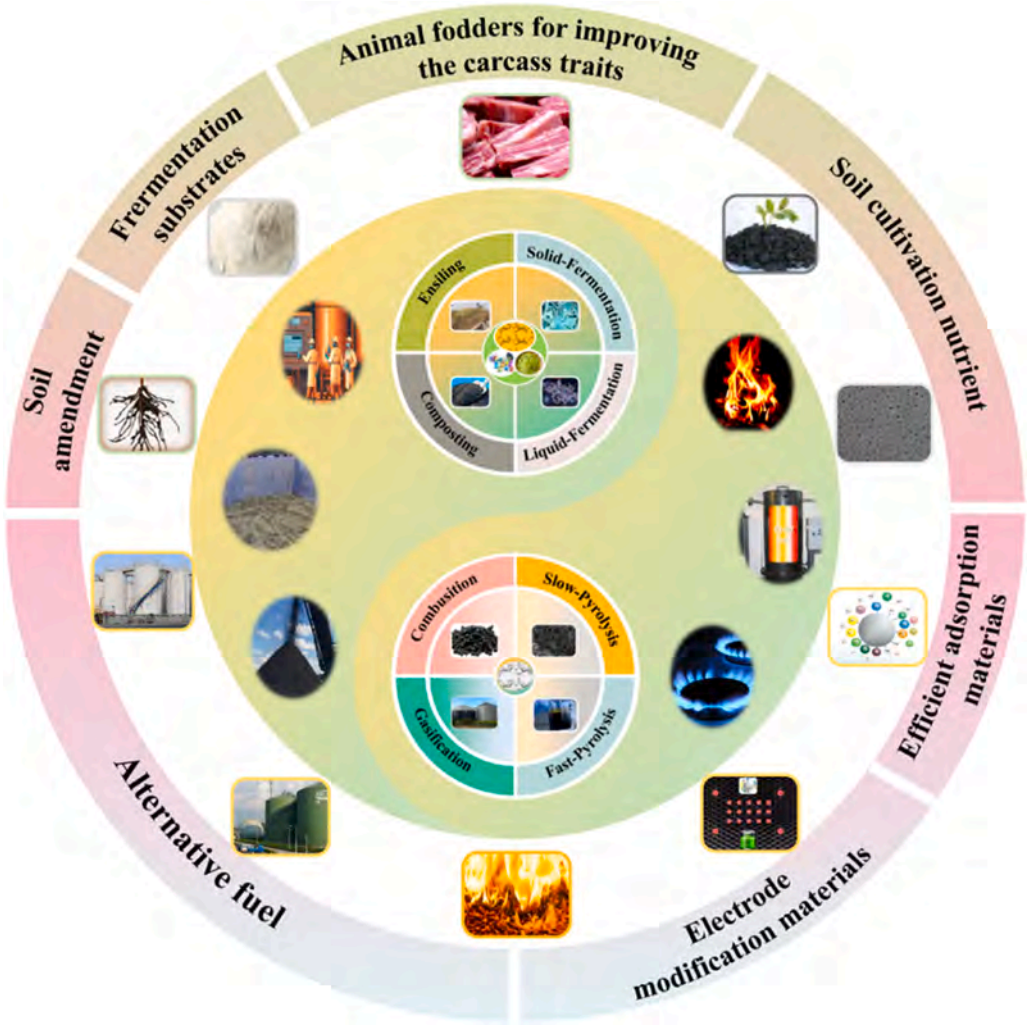

Fig. 4. Biological and thermochemical transformation as two complementary forces for the valorization of TWB. The first force is biological transformation ways including compost, ensilage and fermentation to convert the residue before and after extraction (PTB & CTB) into animal fodders, cultivation nutrients and bioactive fermentation substrates. The second force is the thermochemical ways including combusting, pyrolysis and gasification to convert them into biochar and biofuels for environment protection, remediation, and sustainable production.

feed additives, fertilizers, and low-cost absorbents, achieves interests and diversified utilization (Sui et al., 2019). Herein, another pathway to valorize TWB is to integrally process the induced residue before and after extraction (PTB & CTB) by biological conversion into animal fodders, cultivation nutrients or fermentation substrates (Fig. 4).

5.1. Using TWB-based SSF for enzyme production

Research in tannase (EC 3.1.1.20) production from agricultural residues have remarkably increased in the last decade because of its low cost and critical applications in various industries. Microorganisms such as *Aspergillus* secret tannase when induced by tannin substrates (Xiao et al., 2015). As tannin-containing substrates, PTB has been proven to be excellent for large-scale production of valuable tannase (Table 2). Solid-state fermentation (SSF) is preferred for tannase production because of its lower cost and higher enzyme activity than submerged liquid fermentation (Wu et al., 2018). Optimized condition using TWB as culture medium in SSF is a cost-effectiv method for the production of tannase, achieving a tannase yield of 246.82 (U/g) (Peña-Lucio et al., 2023). The cellulose remaining in TWB after TPP bio-extraction serves as an ideal raw material for producing fermentable sugars. These sugars can then be used by *A. niger* 28 A to synthesize cellulases, which promote the hydrolysis of lignocellulose into high-value products with diverse applications (Saldaña-Mendoza et al., 2024).

5.2. Ensiling PTB for fodders

Ensiling is a prevalent process for utilizing agricultural residues due to its ability to preserve nutrients. Through microbial degradation of water-soluble carbohydrates, silage is obtained with abundant organic acids and reduced pH, which inhibits the proliferation of decaying bacteria (Muck et al., 2018). Besides, the microorganisms involved in anaerobic fermentation produce metabolites to improve the original nutritional structure. The characteristic components, including caffeine, TPP, and *L*-theanine, were well preserved in silage by ensiling PTB for 60 days, paving the way of ensiling PTB for silage (Lin et al., 2021). Silage produced from PTB contains the main bioactive components in the raw material including a high content of water-soluble carbohydrates and also enriches lactic and acetic acids (Li et al., 2022).

5.3. Composting PTB for soil

5.3.1. As soil amendments

PTB has been applied as soil amendments through the mesophilic composting process. A controlled ambiance is provided for microorganisms and earthworms to mineralize complex substrates in a complementary manner, recycling various organic substrates in PTB into nutrient-rich soil amendment. The application of PTB in soil not only improves the physical and chemical properties but also improves the growth of tea plants (Sarmah et al., 2023). Shredding process helps improve decomposition rate of PTB as soil amendments, which dismisses the hard nature of tea stems and had potential to replace up to 15% of recommended urea during tea cultivation (Pramanik et al., 2018). In addition, the amendment to PTB alone and PTB mixed organic fertilizer significantly reduces the absorption of heavy metals and organic pollutants, because of the inherent large amounts of TPP to act as metal-chelating substances (Chen et al., 2016). Therefore, PTB is good for ecological balance of metal ions in soil and can be used as a cultivation fertilizer.

5.3.2. As allelochemicals to modulate rhizosphere microbiome

When using PTB in tea gardens, we need to look out for the issue of allelochemicals, because TPP are one of the most critical and common allelochemicals. They regulate the rhizosphere microbiome in tea garden, causing changes in microbial community structure and composition. In conventional tea plantations, a large amount of PTB returns to the soil surface, which leads to regeneration problems and soil sickness due to the increase of TPP (Borgohain et al., 2020). In the tea garden growing consecutively for 30 years, the growth of plant-promoting bacteria (e.g., *Bacillus*) decreased significantly, along with increased catechin-degrading bacteria (e.g., *Pseudomonas*). However, allelochemicals may act as a chemical facilitator for plant species at low concentrations, and plant co-occurrence may alter the production and release of allelochemicals into the environment (Delavaux et al., 2017). It is recommended to pretreat PTB, such as immersion with hot water to reduce TPP content or mixed amendment with bacterial fertilizer before applying them as fertilizer.

6. Valorization of TWB through thermochemical conversion

In addition to fodders and fertilizers, carbohydrates such as cellulose, hemicellulose and lignin derived from vigorous photosynthesis in PTB represent an excellent carbon source for thermochemical conversion, laying the foundation for valorization of TWB into biochar and biofuels (Biswa Sarma et al., 2024). The third valorization pathway offers an efficient alternative to simple incineration by transforming the highly lignified TWB into value-added products such as cost-effective activated carbon (for adsorption), biochar (for novel functional materials), and biofuels (including bio-oil and biogas), realizing the comprehensive utilization of biomass energy.

6.1. Pyrolyzing TWB for biochar

In recent years, biochar has received worldwide attention due to its promising applications in various areas such as excellent adsorbents to remove contaminants from the environment and global carbon sequestration (Pal and Maiti, 2019). PTB contains more than 10% of fixed carbon content, which is higher than that in generated CTB after bio-extraction, and similar to the commercialized coconut shell or walnut shell (Asadi-Sangachini et al., 2019). Furthermore, the production of TWB keeps at approximately 20 million tons annually in China, suggesting a steady supply of the raw materials for biochar. Processing TWB-based biochar can solve the problem of solid waste treatment and obtain valuable biochar materials to be used as soil cultivation nutrient, efficient adsorption materials and electrode modification materials (Fig. 4).

An easy and convenient way to produce TWB-based biochar is described as follows. PTB is sun-dried, chopped, and packed as feedstock, then the feedstock is pyrolyzed at a temperature of 300–550 ℃ for 8 h under oxygen-limited conditions with an increasing rate of 25 ℃·min^{-1}. Such method often gains profit due to biomass pyrolysis at relatively low temperatures (300–700 ℃).

6.1.1. As soil cultivation nutrient

The positive impact of biochar on the improvement of soil physicochemical properties includes tea plant growth and development, reducing smoke emissions, and improving the recovery rate of soil microorganisms. Biochar application generally resulted in higher macronutrient contents in tea plants, with increases in nitrogen (N), phosphorus (P), and potassium (K) (Zou et al., 2023). With 500 kg·ha^{-1} TWB-derived biochar amendment, tea plant sugar, starch, and amino acids increased. Within the context of sustainable management practices, TWB biochar amendment is cost-effective to maintain soil integrity and increase photosynthetic rate and water use efficiency for tea cultivation (Shi et al.,2019; Borgohain et al., 2020). As to the possible characteristic allelochemicals in TWB, the pyrolysis reaction of TPP begins at about 200 ℃ and is drastic between 200 ℃ and 350℃, which are totally destroyed during general biochar pyrolysis. Applying TWB-derived biochar in tea garden not only prevents the possible damage of allelochemicals but also has a mitigation effect on the tea rhizosphere soil sickness.

6.1.2. As efficient adsorption materials

The remarkable characteristics of biochar, including large specific surface area, unique pore structure, abundant surface functional groups, and high surface charge density, make it an efficient and cheap adsorbent (Li et al., 2018). Alternative use of PTB as a raw material for biochar production is a feasible method to reduce the uptake of heavy metals in different crops and alleviate the economic and environmental burden. Prepared by the pyrolysis at 700 ℃, the adsorption property of PTB-derived biochar to Cd^{2+} maximized at 74.04 mg/g (Han et al., 2021). Tea products from the tea gardens imposed 500 $kg{\cdot}ha^{-1}$ PTB-derived after two months showed a decrease in the concentration of arsenic (As), cadmium (Cd), and chromium (Cr) by 36.73%, 16.22%, 13.96% over control, respectively (Borgohain et al., 2022). Therefore, chemisorption of PTB-derived biochar provides an effective management strategy of TWB for sustainable tea plantations.

6.1.3. As electrode modification materials

As a carbon-rich material with a porous structure, TWB-based biochar possesses abundant oxygen-containing functional groups (-COOH, -OH) and shows a superior electrical conductivity. Through thermochemical functionalization with various oxidizing agents (e.g., ozone, KOH, nitric acid, and sulfonitric mixtures), low-cost and environmentally benign TWB-based biochar can be developed into hydrophilic biochar materials. These oxygen-containing functional groups provide a foundation for inner-sphere interaction towards metallic ions. The combination of nickel oxide/hydroxide with TWB-based biochar help improve the electric conductivity and enhance the capacity and surface wettability, and contributes to the fabrication of pseudo-supercapacitors, thereby expanding applications to catalysis, water remediation, CO_2 capture, soil remediation, and energy storage (Bhoyate et al., 2017; Parsimehr et al., 2021). TWB-based biochar deserves further research to reduce energy cost and protect the environment.

6.2. Biofuels from TWB

Biofuel is a green fuel derived from bio-based resources and waste biomass, and can be used as transportation fuel with almost no modifications. Owing to the economic and environmental attractiveness of biofuel, methods for converting biomass into bio-oil have received widespread attention. During the pyrolysis process, the biochar from CTB can be further carbonized to produce activated carbon, while the volatiles are condensed to produce oil. Controlled pyrolysis converts TWB into biofuels, such as liquid bio-oil and biogas, enabling efficient biomass energy recovery. Although TWB is easily pelletized for combustion and gain more energy parameters comparable to conventional wood pellets for biofuel use (Güler, 2024; Jezerska et al., 2025), pyrolysis of TWB is often preferred over direct combustion due to the ease of storage and transportation of the resulting fuels (Veses et al., 2014). Liquid bio-oils have advantages over solid biomass due to their higher volumetric energy density. Through anaerobic digestion, which involves decomposing organic matter in the absence of oxygen, TWB energy is recycled as bioethanol (Demiray et al., 2022). While gasification at 700–800 ℃ is currently the most efficient way of recovering lignocellulosic biomass energy, and typical conversion efficiencies are higher than 50% (Widjaya et al., 2018; Ben Abdallah et al., 2023). The yielded syngas is a mixture of H_2, CO and CH_4 with the enhanced the volumetric gas composition and can also be used to produce diverse biofuels and chemicals, aiding effective implementation of bioenergy while reducing CO_2 emission (Santhappan et al., 2024; Saini et al., 2024). Combining pyrolysis and gasification, the several drawbacks including high water content, high viscosity, and poor igniting properties that hinder the large-scale use of TWB as feedstocks can be solved, thus increasing the prospects of using TWB as profitable biorefineries.

6.3. Carbon quantum dots from TWB-based biochar

Carbon quantum dots (CQDs), also known as carbon nanodots, are a new kind of zero-dimensional carbon-based nanomaterials with remarkable optical properties and excellent water solubility. They can be produced from wide source of raw materials and have advantages of low toxicity, low cost, good biocompatibility (Wen et al., 2023). TWB is an appropriate starting material for CQDs because of the inherent various active substances such as aromatic compounds, phenols, amino acids, proteins, and essential oils. The promising TWB-based CQDs synthesis is based on a simple hydrothermal method using a Teflon-lined hydrothermal reactor to transfer TWB-based biochar at 200 ℃ for 8 h (Ye et al., 2025). CTB such as tea waste bag and tea leaf residue have been reported to be transformed into fluorescent sensors for gefitinib determination and acrylamide detection (Hu et al., 2020; Sharma et al., 2024). With the combination of bioactive compounds like curcumin, the constructed TWB-based CQDs have the improved antioxidant performance and retained antibacterial activity (Wen et al., 2023). As an inexpensive and abundant biomass resource, TWB-based CQDs are endowed with potential application prospects in many fields such as biological imaging, organic analysis, and clinical medicine.

7. Research perspectives

Traditional tea industry faces the contradiction of the oversupply of common-quality tea and the pursuit of premium tea and specialty tea. Current plucking standards are shortening the harvest period for tea, ultimately leading to higher prices of fresh leaves in the near future. Meanwhile, the tea plantation area will continue to grow to meet the demand for fresh leaves. The dilemma inside the tea industry have become more severe in recent years, such as imbalance between supply and demand, low utilization rate of middle or low-grade tea and PTB, and enormous quantities of CTB generation, which hamper the sustainable development of tea industry (Liu, 2019). The whole society should pay attention to the coordination between tea production and environmental protection, promoting the green development of tea industry.

Though tea plants show stress resistance through primary and secondary metabolisms, the damage of seasonal stresses (namely cold spell in spring, high temperature in summer, drought in autumn, and freeze injury in winter) on tea production is highly underestimated. Regions in southeast China, particularly those along the Yangtze River, experience reductions in tea yields ranging from 14% to 26% due to high-temperature stress (Yan et al., 2021). The cellular damage-induced physiological changes under heat, strong irradiation and drought stress all have direct influence on the quality and price of tea leaves. Herein, it can be speculated that more and more tea leaves will be abandoned. The paramount goal of planetary health is the ecological transformation of all industrial sectors. Comprehensive utilization of accumulated flavonoids, phenylpropanoids, and other secondary metabolites in tea leaves under heat, irradiation, and drought stress is inevitable for the healthy development of the future tea industry. In views of increasing production and consumption of tea around the world, efficient utilization of tea byproducts (PTB and CTB after production and drinking) from both tea cultivation and processing is the key to improving economy value of tea industry.

Currently, over 90% of TWB is improperly managed, being largely disposed of in landfills, incinerated, or composted, leading to significant environmental issues such as soil, air, and water pollution (Debnath et al., 2021; Altaf et al., 2021). Continuous sustainable tea production should balance the growing output and its waste biomass which adversely influences local ecosystems. Within framework of sustainable production, TWB is valorized through three promising and cost-effective approaches aimed at achieving sustainability (Fig. 4).

The first strategy, two-stage enzymatic extraction, utilizes enzymes to dissolve the boundary between usable biomass and disposable waste

by targeting both soluble components and insoluble fibers and proteins. This process offers an energy-efficient, time-saving, and low-cost route for the green utilization of TWB as a renewable and abundant resource (Debnath et al., 2023; Wang et al.,2024).

The second approach leverages microbial factories to convert tea waste into high-value products such as cellulase, tannase, fertilizers, and animal feed at an extremely low cost. These outputs hold broad industrial applicability, and the resulting enzymes can be directly employed in the bio-extraction of insoluble fibers (Peña-Lucio et al., 2023; Saldaña-Mendoza et al., 2024).

The third valorization pathway involves synthesizing biochar and biofuels from TWB, which not only yields a net profit of over $300 per ton but also mitigates carbon emissions (Hossain et al., 2025; Saini et al., 2024). The resulting biochar serves as an inert organic carbon source that can be sequestered long-term in tea plantation soils, effectively reducing greenhouse gas emissions. Additionally, TWB-based CQDs show high overall profitability, with significant savings in production costs and promising applications in biological imaging, organic analysis, and clinical medicine (Ye et al., 2025). The co-gasification of TWB with other agricultural wastes has emerged as a key strategy in waste management, facilitating the effective implementation of bioenergy and contributing to the reduction of environmental hazards (Santhappan et al., 2024; Saini et al., 2024).

8. Conclusion

TWB, with fixed carbon and accumulated metabolites, has great potential for high value-added utilization. Current water extraction combined assistant with enzymes is adequate for the two-stage enzymatic extraction of TWB valorization to obtain soluble TPP, TPS and insoluble fibers and proteins. The second way of TWB valorization is to biologically convert the residue before and after extraction (PTB & CTB) into animal fodders, cultivation nutrients or fermentation substrates with the introduction of microorganisms. The third way of TWB valorization refers to thermo-chemical pyrolysis and gasification to convert lignified TWB into biochar, biofuels and carbon quantum dots for environment protection, green energy, and sustainable tea production. Accumulation patterns of TWB agree with the current cost-effective biomass valorization techniques in terms of the application of primary and secondary metabolites. The massive amount of TWB generated from seasonal trimming, tea manufacture, deep-processing, and consumption is presented as an environmentally friendly biomass source, suitable for two-stage bio-extraction as well as biological and thermochemical conversion into novel industrial products.

CRediT authorship contribution statement

Yong-Quan Xu: Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Jun-Feng Yin:** Writing – review & editing. **Weibiao Zhou:** Writing – review & editing. **Jian-Hui Ye:** Writing – review & editing, Conceptualization. **Granato Daniel:** Writing – review & editing. **Chun Zou:** Writing – review & editing. **Ying Gao:** Writing – review & editing, Conceptualization. **Shuang Liang:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation, Conceptualization.

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Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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