BEYOND SURPLUS: A REVIEW OF CULTURAL, ECOLOGICAL, AND TECHNOLOGICAL DRIVERS OF SUSTAINABLE TEA DEVELOPMENT IN YUNNAN, CHINA

FU, C. X.[1,3#*] – MAO, Z. Q.[2#] – ZHANG, Q.[1,3] – XU, S. T.[1,3] – YANG, J. D.[1,3] – JAMIL, A.[1*] – LIU, S. F.[1,3] – YUAN, Y.[2]

[1]*Institute of Agricultural Resources and Environment, Yunnan Academy of Agricultural Sciences, Kunming 650205, China*

[2]*Institute of Agricultural Economy and Information, Yunnan Academy of Agricultural Sciences, Kunming 650205, China*

[3]*Yunnan Society of Plant Protection, Kunming 650205, China*

[#]*These authors have contributed equally to this work*

**Corresponding authors*
e-mail/phone: 632600725@qq.com/+86-138-8829-1203; arslan_aspsr@yahoo.com/+86-131-8786-8208

(Received 14th Jun 2025; accepted 1st Sep 2025)

Abstract. Yunnan Province, the ancestral home of Pu'er tea (*Camellia sinensis var. assamica*) and a vital node in China's tea (*Camellia sinensis* (L.) O. Kuntze) heritage, faces multifaceted sustainability challenges amid expanding national tea inventories and evolving global market dynamics. This review critically synthesizes recent advances and persistent bottlenecks affecting Yunnan's tea sector, encompassing ecological degradation, socio-economic inequities, cultural preservation, and supply-demand imbalances. Rapid land-use shifts, especially monoculture expansion in biodiversity hotspots like Xishuangbanna, exacerbate deforestation, soil erosion, and biodiversity loss, compounded by climate-induced stressors such as drought and temperature volatility. The tea sector faces challenges such as market saturation, price volatility, and rising production costs, which threaten the livelihoods of smallholder farmers and rural communities dependent on tea production. Simultaneously, inventory surpluses and post-pandemic consumption shifts drive price volatility and market saturation, destabilizing profitability and supply chain resilience. The review highlights integrative strategies, agroecological innovations (IPM, agroforestry, regenerative agriculture), digital commerce platforms, blockchain traceability, and climate-resilient breeding technologies (genomics, CRISPR) as pivotal for sustainable transformation. Comparative lessons from global tea-producing regions and frameworks like Rainforest Alliance certification inform potential pathways toward environmental stewardship, socio-economic equity, and enhanced global competitiveness. Circular economy principles that add value to tea by-products and support low-carbon logistics further underpin sustainability credentials. Policy imperatives, including infrastructure development, green subsidies, and legal protections for cultural heritage, are essential to reinforce these measures. By bridging interdisciplinary research, policy, and industry perspectives, this review offers a holistic blueprint to realign Yunnan's tea industry with sustainable development goals and secure its long-term ecological, economic, and cultural viability.
Keywords: *Pu'er tea, agroforestry, traceability, smallholders, climate-resilience, circularity*

Introduction

The Yunnan tea industry, deeply rooted in centuries-old traditions and renowned globally for its signature Pu'er tea, holds a unique position in both China's cultural heritage and the international tea economy. By virtue of being one of the original centers of ancient Chinese tea cultivation, Yunnan, as one of the original centers of ancient

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

Chinese tea cultivation, has developed a unique tea culture shaped by its mountainous terrain, endemic biodiversity, and distinct ethnic populations. Historically, Pu'er tea cultivation has served the Bulang ethnic group's efforts to reconstruct their ethnic identities and cultural traditions while highlighting the role of tea as a material means to engage with state power and enter commercial markets (Han, 2023). The area is a major player in rural livelihoods, particularly through smallholder-based production systems, and it boasts historical significance, such as the ancient Tea Horse Road, to elevate its branding. However, the modern context is fraught with challenges as old-world farming practices intersect with industrial-scale expansion and new consumer preferences (Li et al., 2023). Furthermore, the cultural meaning of Pu'er tea, which emphasizes living in harmony with nature, is paramount to Yunnan's national tea culture and brand essence (Qiang, 2024; Fan et al., 2024). Looking at the history of tea in China, especially during the 19th century, reveals a response to global capitalism that created a pivot to cultivation for export, affecting current market trends and the socio-economic aspects of tea production in Yunnan more recently (Guan, 2022). As evidenced by national strategies like the Tea Revitalization Plan, there is a national focus on elevating quality, sustainability, and competitiveness on the world stage. However, Yunnan is facing pressure with domestic inventories growing and market saturation. Integrating sustainable practices to balance domestic consumption and strengthen export potential is critical to the future viability and socio-economic resilience of Yunnan's tea sector in the new global market context (Ru, 2022).

Objectives and scope of the review

The purpose of this review is to systemically address sustainability issues and opportunities in the Yunnan tea industry with an emphasis on China's overall expanding tea fleet. This review is geographically based in Yunnan Province and thematically related to sustainability, which encompasses environmental, economic, and social sustainability within the tea value chain, primarily through the identified literature of the last five years. It includes substantive areas of interest such as ecological degradation, smallholder profit, cultural heritage issues, saturated markets, and global competitiveness while also revealing pertinent gaps in literature, critical resilience in tea production systems and the supply chain (Omer et al., 2025). Of particular concern is the multidimensional aspects of sustainability in regional tea industries, how traditional knowledge can inform contemporary agronomic practices, policy framing, and digital marketing interventions (Shekarian et al., 2022). This review draws together disjointed academic, policy and industry perspectives, contributing a unique perspective that demonstrates an academic synthesis contributing to multidisciplinary solutions for informing future research, science-policy interjection, and strategic decisions for a resilient and sustainable tea industry in Yunnan.

Methodology and data sources

This review utilizes a rigorous and integrated approach to synthesize existing knowledge on the Yunnan tea industry's sustainable development that has emerged under the constraints of China's expanding tea inventory. The authors conducted a comprehensive literature review of peer-reviewed articles, government reports, trade publications, and policy documents, all published from the past ten years, by searching

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

several database repositories, including Web of Science, Scopus, CNKI (China National Knowledge Infrastructure), and Google Scholar. Keywords included "Yunnan tea industry," "tea production and sustainability," "tea supply chain China," "current trends in the Pu'er tea market," and "climate-resilient agriculture." The authors included both qualitative and quantitative studies to ensure a multi-perspective robust analysis from an environmental, socio-economic, technological, and policy perspective. Inclusion criteria were high-quality, recent studies with a clear link to tea sustainability, while exclusion criteria removed dated or irrelevant publications (Arhin et al., 2022; Wong, 2022). The authors' structure of the review was primarily thematic coding and trend analysis, which allowed them to capture sustainability bottlenecks, innovation, and policy-related gaps for the tea industry in Yunnan.

Overview of the Yunnan tea industry

Well-known as the original home of tea, Yunnan Province is important to the tea industry in China because of its biodiversity, ancient tea trees, and the unique variety of tea produced in the province, including Pu-erh. A unique climate, biodiversity, and cultural heritage have made Yunnan a significant region for domestic consumption and international export.

Historical development and cultural relevance

Yunnan's tea industry has strong cultural and historical roots, distinguishing it from the other regions of tea production in the world. Yunnan is in the unique position of being the cradle of the tea plant known as *Camellia sinensis var. assamica*, and the origin and domestication of tea, as far back as the beginning of tea cultivation, can be traced to the geographical space we refer to today as Yunnan over 2000 years. The Yunnan tea industry has deep roots in the historical development of the Ancient Tea Horse Road, an essential trade route and the relationship between cultural and economic exchange among various ethnic groups, including the Han, Zang, Brown, Dai, and Lahu (Wang et al., 2023; Qiang, 2024). The ancient tea horse route facilitated the trade of tea, but also cultural integration of diverse cultural values. For example, whole villages and communities around Jingmai Mountain have developed their own unique cultivation practices based on the ecological context, and are now recognized for their cultural landscape and cultural heritage landscapes (Sigley, 2021). The tea industry is supported by historical and cultural traditions of labor practice, and the ecological and cultural diversity found in the region has been shaped by generations of cultural interaction among unique ethnic communities (Zhiyang, 2020). Additionally, the role of local chieftains' relationship to trade and promoting cultural/ethnic integration as directed by the ancient tea horse road further demonstrates the role of tea in socio-political contexts of trade, and the role of tea and tea in the growing notion of Chinese national identity and heritage (An and Pe, 2021). Integrating the cultural, historical, and creative values in tea through sustainable innovations, is a pathway for maintaining a sustainable tea industry in Yunnan, as China strives to manage the growing tea inventory and supply chain.

Tea types and regional characteristics

The tea industry of Yunnan is recognized for its varied tea types—including Pu'er, black tea, and green tea—each of which is influenced by specific regional ecological

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

settings and tea-processing traditions (*Table 1*). Pu'er tea, as a regional specialty of Yunnan, can be found in different versions: raw (sheng) and ripe (shou), which have gone through post-fermentation processes that influence the microbial community, as well as polyphenolic content, and flavor development over time (Ma et al., 2024; Devos et al., 2021). Terroir, or factors such as elevation, climate, and soil composition, determines the quality and sensory properties of tea, and certain regions at high elevations, namely Xishuangbanna, Lincang and Pu'er prefectures, are known for producing high-quality tea leaves (Wang et al., 2023). The mechanism by which a pile ferments plays a key role in the quality of Pu'er tea and allows for microbial diversity, specifically certain genera of microbes such as *Aspergillus* and *Penicillium*, to work together to generate composite compounds like theabrownins and flavonols (Li et al., 2024b; Ma et al., 2024). Recent studies have shown various ecological zoning and classification of regions for tea growth in Yunnan and agroclimatic parameters have been incorporated to grow varieties for specific microenvironments. In addition, studies have incorporated a significant phytochemical structure and secondly found phytochemical variation, such as catechins, flavonoids, alkaloids, and aroma compounds, between tea regions, indicating genotype - environment interaction (Devos et al., 2021; Assad et al., 2023). Therefore, knowing the regional importance and pile fermentation processes are useful advantages for improving the production process of Pu'er tea, its quality, and ultimately its market value.

Table 1. *Overview of tea types, regional origins, processing characteristics, and key features in Yunnan's tea industry*

Tea type	Regional origin	Key processing characteristics	Distinctive features/notes
Pu'er (Raw/Sheng)	Xishuangbanna, Lincang, Pu'er Prefectures	Natural post-fermentation (aging)	Microbial shifts over time; flavor maturation
Pu'er (Ripe/Shou)	Xishuangbanna, Lincang, Pu'er Prefectures	Pile fermentation involving microbial consortia (Aspergillus, Penicillium)	Formation of theabrownins and flavonols
Black tea	Various Yunnan regions	Complete oxidation of tea leaves	Robust flavor influenced by terroir
Green tea	High-altitude zones (e.g., Xishuangbanna)	Minimal oxidation; pan-firing or steaming	High catechin and flavonoid retention
Terroir factors	Altitude, climate, soil	Ecological zoning based on agroclimatic parameters	Affects sensory attributes and phytochemical profiles
Microbial community	Pu'er tea fermentation zones	Dominated by Aspergillus, Penicillium, and others	Drives polyphenol transformation and flavor development
Phytochemical variation	Different tea-growing regions	Variation in catechins, flavonoids, alkaloids, aroma compounds	Result of genotype–environment interactions

Contribution to national and global tea markets

Yunnan holds a vital position in the domestic tea economy, as well as the emerging international perspectives towards China's tea economy. While China remains the largest producer of tea in the world, Yunnan specialty teas, especially Pu'er, have

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

entered the high value export arena, gaining traction and traveling throughout Southeast Asia, Europe, and North America due to health benefits and cultural value. The most up-to-date export statistics report that China exported over 360,000 metric tons of tea in 2023, where Yunnan represented a small, yet significant, premium high-value tea exporter, often not fully captured by the market share due to the limitations of entering into niche markets, which often requires established branding in western markets (Qin and Zhou, 2024). Recent research findings have shown that China's tea exports have benefited from increased gross domestic product (GDP) in importing nations, as well as the Belt and Road Initiative (BRI) that has improved trade relations with many its partner countries. Yunnan's market share of growing tea consumption worldwide, especially in emerging economies, is hampered by fluctuating international demand for tea, logistics, and intense competition from Sri Lanka, India, and Kenya (Fan and Liu, 2022). Trade policies—specifically tariff fluctuations, phytosanitary standards, and bilateral agreements—also significantly affect export viability. Internally, Yunnan's overall market bargaining position is further weakened by oversupply and a lack of regional or quality-based differentiation of teas within China. Additionally, the potential market for the tea export industry is significant for China's economy, having already identified potential markets in 39 countries, which makes international relations to build export capacity a sensible strategy (Suroso et al., 2025; Liu et al., 2018). Ultimately, the tea industry in Yunnan must adapt policy support to building value-added products to keep pace with global consumption patterns, as the country continues to experience upward inventory pressure.

China's national tea inventory: status and impact

In recent years, China's national tea inventory has increased to high levels and led to market saturation as well as a downward trend in tea prices. This inventory poses serious problems for producers in Yunnan with potential impacts on their profitability and the relationship of supply and demand. A significant increase in China's national tea inventory, driven mainly by a production-consumption imbalance, but propelled even more by shifts in demand from the pandemic, has contributed to changes in the national tea inventory. China's tea industry has had more issues with oversupplying tea in recent years, especially in Yunnan with an increasing production consumption imbalance that creates larger inventory backlogs. Despite projections of a rebound in the new tea market with sales in excess of 300 billion yuan in 2022, the underlying structural challenges remain as consumer preferences have shifted toward health-promoting and aesthetically pleasing options (Tan, 2022).

Rising inventory levels: causes and trends

Currently, China's tea industry faces a major inventory issue stemming from both oversupply and changing consumption (*Fig. 1*). In 2023, China produced more than 3.3 million metric tons of tea, with an estimated national inventory exceeding 2.1 million metric tons, representing a year-on-year increase of 6.4% accounting for over 50% of total world production. Exports decreased roughly 2% from the previous year, while domestic consumption growth was curtailed to 2.5%, resulting in excess inventory that remained unsold (Suroso et al., 2025). In addition, local sales environments for tea—such as cafes and restaurants—confirmed that the COVID-19 pandemic affected traditional ordering patterns and hastened the shift to online channels of sales and consumption.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

Changing production versus consumption patterns spilled excess tea inventory back into the supply chain, creating downward pricing pressure and diminished profitability for growers and their supply chain partners (Dodd and Liao, 2025). The prospects of exporting tea to stimulate economic growth are beneficial to the industry; however, the industry is still challenged by brand recognition and quality standards necessary to improve global competition (Qin and Zhou, 2024). Therefore, improvements in inventory management and brand, while utilizing sustainability and evidence-based methodologies within the transportation, trade, and retail markets, is the way forward for the tea industry in China. The industry is also confidant that diversifying product lines, enhancing quality, and exploring new markets will better position the industry to match supply with market demand.

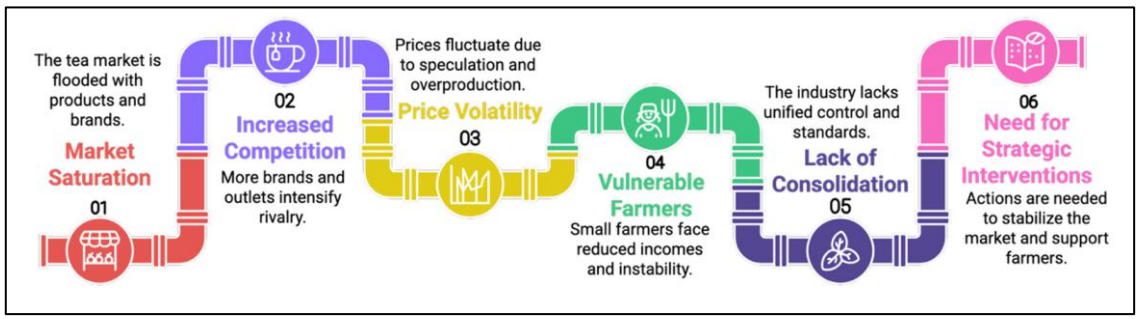

Figure 1. *Yunnan tea market dynamics*

Market saturation and price volatility

The tea sector in Yunnan has increasingly faced obstacles associated with market saturation and pricing shocks seen through the channels of China's tea market. The entry of tea brands and retail outlets, particularly with more than 500,000 milk tea shops in the country, drives additional competition, compelling tea outlets to engage in price-cutting strategies to gain customers (Wu and Li, 2022). Price variability has exhibited itself by pushing the price of Yunnan teas, particularly Pu'er, from quick rises and falls in price due to speculation and product surplus. Pu'er tea auction prices fluctuated between 210–350 RMB/kg during 2021–2023, compared with a more stable average of 280 RMB/kg in 2018–2019. Tea producers, especially smallholders, make up the majority of Yunnan's tea producers and are even more vulnerable to these market shocks, often facing decreased income and lack of financial security (Pan and Zheng, 2023). The absence of industry consolidation, with the largest 100 tea-producing enterprises holding only 20% total market share, presents further challenges for price stabilization and standardized quality control in an industry with less consolidation. Competition in China adds one more layer of difficulty to the ecosystem, as competition can exert downward pressure on prices; this downward pressure disproportionately impacts small producers (Heid et al., 2021). Moreover, overproduction can harm small farmers, as overproduction typically results in lower prices and lower profit margins, which have the potential to jeopardize the economic survival of small producers and farmers (Dou et al., 2021). In order to address the issues faced by small-scale producers and farmers, it is clear there is a need for strategic interventions targeting brand development, improving quality, and creating sustainable value chains that can assist with market shocks and support small-scale tea farmers for their livelihoods.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

Supply chain and distribution bottlenecks

The tea supply chain faces considerable inefficiencies and bottlenecks, especially in countries like China and Sri Lanka, resulting in reduced productivity and quality. One of the major inefficiencies in tea supply chains is inadequate storage technologies, with approximately 70% of the tea produced in any given year potentially ruined by incorrect storage conditions (Lv et al., 2023). The tea supply chain in Yunnan has serious problems with the overall tea supply chain and distribution networks that inhibit possibilities for sustainable development under pressures of increasing tea inventories for China. The worthless, perishable characteristics of tea leaf/commodity and a lack of transport methods and logistics technologies have increased wastage in tea crop systems—especially in remote areas (Fernando et al., 2024). From the perspective of value chains, smallholder farmers often do not have the existing resources necessary to access markets or distribute tea consistently for optimizing production and distribution, resulting in farmers with unsure income and limited market competition. The COVID-19 pandemic exposed the vulnerabilities of tea supply chains and logistics as actors in tea supply chains experienced the fragilities of transport and input availability affecting their operations (Das and Mishra, 2020). In addition to these problems, integrating the logistics and cold chain would provide improved inventory control and lower losses in tea supply chains. In addition to these issues, the key component in this process is the adoption of modern technologies related to tea traceability and integrated storage, investing in infrastructure development, and facilitating development of cooperative models of processing and logistics among coffee supply- chain stakeholders (Qin and Zhou, 2024). These all seek to improve overall efficacy of whole tea value chains and lower potential losses while also improving the sustainability of the tea sector in Yunnan Province, China.

Sustainability challenges in the Yunnan tea sector

The tea industry in Yunnan is confronted with critical sustainability challenges. These challenges are mainly rooted in environmental pressures, notably land use changes, water scarcity, and biodiversity loss. The development of tea areas has caused deforestation and decreased local biodiversity that is already under threat from climate change, which is predicted to impact tea yields and quality through increased drought and temperature variability, as illustrated in *Figure 2* (Omer et al., 2025).

Environmental pressures (land use, water, biodiversity)

Yunnan's tea industry is increasingly challenged by sustainability issues derived from environmental pressures on both ecological service integrity and productivity in the long term. To cultivate high-value Pu'er tea, for example, tea plantations have been expanded, resulting in some deforestation in protected areas (e.g., trees illegally felled or poisoned for land clearing in Yiwu Nature Reserve, Xishuangbanna), causing biodiversity loss and violations of conservation legislation and conservation outcomes. Traditional agroforestry systems were monotropically converted to monoculture systems that rely on agrochemicals, resulting in reductions in soil productivity, soil health, and ecosystem services (Omer et al., 2025; Yang et al., 2024). The problems are compounded by climate change, with temperature rise and changes in precipitation resulting in extreme drought years that can postpone harvests and impact yields by as much as 50%. The increased use of agrochemicals in raising teas has raised concerns about soil health and the integrity of

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

the surrounding ecosystem where the tea farm is located, leading to a mode of change to sustainable tea farming methods—eco-farming practices, regenerative agriculture practices—that focus on reducing pesticide use and improving soil health (Bera et al., 2024). Research shows that extreme weather events and temperature fluctuations can reduce yields of tea cultivation by 14 to 26%, which reveals the susceptibility of tea production to climate volatility. Also, indigenous knowledge is a major element of biodiversity management in tea forests that are definitive of local practice and should ultimately be integrated as part of new methods and technologies in agriculture (Yang et al., 2024; Raj et al., 2023). Sustainable practices, such as agroforestry, organic farming, and efficient water management plans will be exploited to demonstrate potential solutions to these issues. Adopting these practices will not only improve resilience to climate change, but aid in the maintenance of ecological system balance, which is required in order to promote sustainable development in tea production in Yunnan.

Economic constraints (smallholder profitability, market access)

Smallholder tea producers are notably economically constrained, affecting both profit and access to markets, including Yunnan and Sri Lanka. For instance, although smallholders are involved in agribusiness in Yunnan, their involvement is limited by issues like a lack of organization and access to markets, which is perpetuated by urbanization and constraints on land (Zhu et al., 2022). In another example of barriers to smallholder involvement, Sri Lankan smallholders produce 75% of the country's tea, but are impeded by issues of high production costs, and limited options for markets, which aggravates their income instability (Fernando et al., 2024). The shift to organic tea production in areas such as Pu'er has had economic perceived benefits; however, farmers living in conditions of low income often struggle to pay for all of the certification and market access costs (Li et al., 2024a). Access to effective agricultural extension services, as well as improved infrastructure, is essential for accessing more profitable markets for these farms, as evidenced by studies indicating education and training are critical factors of market involvement (Adams et al., 2020).

Social aspects (labor, traditional knowledge, community livelihoods)

The social aspects of Yunnan's tea industry are important to its sustainability, entailing labor relations, traditional knowledge, and community livelihoods. Rural labor, mainly women and ethnic minorities, are crucial to tea cultivation and production. Women from ethnic groups such as the Bulang, Hani, and Dai, are engaged in each stage of tea production, from plucking leaves to post-harvest processing (Das and Karmakar, 2024). Their roles, however, are often underappreciated, even when they have an indisputable impact. Ethnic communities not only preserve traditional tea cultivation practices and rich cultural heritage, but they also matter in the marketing and tourism elements of the industry. For example, women from Yaoqu Township (in Yunnan) used tea tourism to grow their economic ground, but there are still ongoing aspects of socioeconomic gendered norms and limited access to these resources (Jumi et al., 2021). Ethnic minority women play a vital role in the production of Pu'er tea in regions like Southwest China, yet their role is often objectified in the marketing of the tea, complicating their empowerment and reconsolidating hegemonic gender roles (Ma, 2024). Gendered ethnicity complicates issues even further, such as during the Covid-19 pandemic, where there were increased job insecurities which lead to the precarious status of Adivasi women

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

workers in India (Barhoi and Dayal, 2024). Community-based solutions such as agro-cooperatives or diversifying livelihoods show promise of improving income and social cohesion. These also further support the need to incorporate social considerations into a broader strategy for the sustainable development of Yunnan's tea.

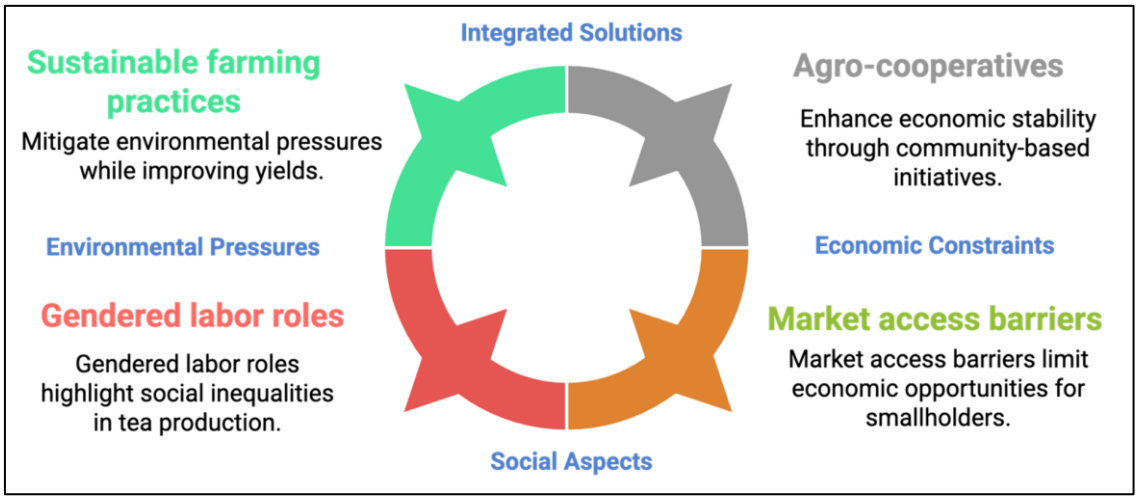

Figure 2. *Sustainability challenges in the Yunnan tea sector*

Strategies for sustainable development

In order to reach sustainable development in the tea industry, adopting value-added processing, diversifying their tea products, and engaging in eco-friendly growing practices will be critical. Enhanced branding, optimal supply chain productivity, and the opening of international marketplaces to help alleviate domestic inventory pressure will be important (*Table 2*).

Agronomic innovations and organic cultivation

The ongoing sustainability of the Yunnan tea industry relies more on agronomic innovations and organic cultivation to address environmental challenges and remain economically viable in the face of rising inventory pressures. Sustainable tea production practices, such as promoting soil health, providing water-efficient irrigation, and decreasing chemical input, have shown stable yields and improved tea quality while maintaining ecosystem health (Roy et al., 2024; Qaim, 2020). Organic tea certification programs have developed to allow tea farmers to access premium markets, however, there are still challenges surrounding certification costs and requirements. For example, in Yunnan, tea–shade tree agroforestry currently accounts for approximately 22–25% of total tea cultivation area (Li et al., 2023). Studies have shown that such systems can increase soil organic carbon by 18–30% and enhance biodiversity, with up to 40% higher pollinator diversity compared to monocultures. Additionally, carbon sequestration in tea–tree systems is estimated at 1.5–2.3 tons C/ha/year, supporting climate mitigation goals (Idris et al., 2020; Zhou et al., 2024). Furthermore, integrated pest management (IPM) strategies, which combine biological controls, cultural practices, and reduced pesticide application, can reduce pest damage and chemical residues to meet the growing consumer demand for safe and environmentally friendly products. Field studies in Yunnan indicate that IPM adoption can reduce pesticide use by 35–50%, while maintaining yields at

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

comparable levels to conventional systems. Biological control measures, such as the release of *Beauveria bassiana* and *Trichogramma spp*., achieved up to 70% suppression of key pests like the Tea Mosquito Bug (*Helopeltis theivora*). Farmers implementing IPM reported cost savings of 15–20% per hectare and improved compliance with organic certification standards. (Sharma, 2023; Fahad, 2023; Deguine et al., 2021). Together, these agronomic innovations are critical for building resiliency and long-term sustainability in Yunnan's tea sector to adapt to China's changing market conditions.

Table 2. *Key strategies for sustainable development of the Yunnan tea industry: components, benefits, and challenges*

Strategy	Key components	Benefits	Challenges/considerations
Agronomic innovations & organic cultivation	Soil conservation, water-efficient irrigation, reduced chemicals, agroforestry, IPM	Improved yield and quality, ecosystem health, carbon sequestration	Certification costs, compliance, pest management complexities
Digitalization & e-commerce transformation	Smart agriculture tools, e-commerce platforms, live streaming sales, rural digital infrastructure	Market expansion, rural revitalization, direct farmer-consumer link	Infrastructure gaps, digital literacy needs
Branding, certification & value addition	Geographical indications (GIs), traceability systems, organic certification, advanced authentication tech	Enhanced brand value, market differentiation, cultural heritage protection	Maintaining authenticity, standardization, consumer trust
Policy support & government interventions	Infrastructure investment, subsidies for sustainable practices, stricter environmental regulations	Encourages green practices, market connectivity, rural development	Policy implementation, balancing economic and ecological goals
Agroforestry systems	Integration of shade trees and biodiversity conservation	Soil fertility improvement, carbon sequestration, habitat protection	Requires training and investment
Integrated pest management (IPM)	Biological controls, cultural and mechanical methods	Reduced pesticide use, safer products, pest control	Adoption barriers, farmer awareness
Supply chain efficiency enhancements	Cold storage, blockchain, cooperative models	Reduced losses, improved transparency and quality	Infrastructure investment, cooperative governance

Digitalization and e-commerce transformation

The agricultural sector is undergoing a large-scale transformation with the introduction of digital technologies, especially in China, redefining the rural economic environment as well as the rural e-commerce environment and a well-recognized example is tea production and sales. Smart agriculture, or the use of digital technologies in agriculture, is vital in addressing today's challenges of climate change and resource scarcity. Digital technologies use online platforms or tools to enable real-time decision making and enhance productivity and sustainability in agricultural production systems (Abashidze, 2023). In China, the digital transformation of rural management of agricultural companies is accelerating rapidly. In rural areas, small and medium enterprises (SMEs) are adopting new business models, especially different forms of e-commerce, to improve their operational processes and reach new markets (Yu et al., 2022). E-commerce in rural revitalization of poverty alleviation in rural China usefully provides new economic opportunities for e-commerce, using platforms like Alibaba (He, 2021). The tea sector, traditionally reliant on offline sales methods, is innovating ways to reach new consumer audiences with e-commerce, especially through methods like live streaming. E-commerce and live streaming are changing to eliminate the constraints of physical sales context and the preferences and habits of younger generations of consumers. In 2023, over 65% of Yunnan tea sales by value were transacted via online platforms, with live-streaming sales increasing by 42% year-on-year (Xie and Nallaluthan, 2024). Live-streaming e-

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

commerce enhances visibility, sales, and income for farmers, and increases the development of rural industries (Zhu et al., 2024). Constraints still exist in the forms of limited infrastructure or capability, which may require us to invest in both digital infrastructure and capacity-building to adequately realize the opportunities presented by digital agriculture (Duc et al., 2024). Overall, the digital transformation of agriculture in China, as seen through the cases of e-commerce and smart agriculture for the tea industry, represents a transformative sector leading economic development and rural enhancement, as well as greater integration and innovation (Fang and Fang, 2022).

AI and precision agriculture in tea cultivation

The convergence of artificial intelligence (AI) and precision agriculture in tea cultivation offers promising future paths and directions for supporting research, as noted by many researchers. AI technologies, such as machine learning and computer vision, are transforming tea farming into a more productive, efficient, and sustainable process. With precision agriculture technologies, farmers can monitor their tea plantations in real-time and make informed decisions about plant health, disease detection, and water management with the help of drones, remote sensing, and Internet of Things (IoT) sensors (Bhat and Huang, 2021; Adewusi et al., 2024). AI-supported precision irrigation systems, for example, have been reported to improve crop yields by a margin of 5-15% while using up to 25-40% less water (Hoque and Padhiary, 2024). As this relates to tea production, AI can provide considerable support for pest and disease management, the next most important variable in the challenge of ensuring quality tea yields. Predictive analytics and AI models can potentially predict pest outbreaks and changing environmental conditions to prompt a farmer's response (Berna et al., 2024; Jeyalakshmi et al., 2025). Additionally, AI can improve the reliability of crop monitoring and health evaluations in remote sensing technologies, both of which are integral for ensuring tea leaf quality (Agrawal and Arafat, 2024). Precision irrigation systems, driven by real-time data on soil moisture levels and weather forecasts, enhance water-use efficiency and provide protection from drought stress, both of which are essential in the context of climate variability. In addition, remote-sensing applications, such as drones and satellite imagery, can provide fine-scale monitoring of tea plantation vigor and support early identification of pest outbreaks, nutrient deficiencies, and land degradation (Dakir et al., 2022). AI applications in the tea sector also extend to supply chain monitoring and traceability to enhance transparency and quality in production processes (Wei et al., 2024). However, high costs, data privacy concerns, and the need for expert training remain a barrier to widespread adoption (Basa, 2024). Future research directions include the integration of AI with new technologies, such as 5G, blockchain, and cloud-computing, to enhance decision-making and data management in precision agriculture (Hoque and Padhiary, 2024). Overall, the integration of AI in tea growing offers the possibility to radically change and support the demands of sustainable, high-quality production by improving efficiency and utility in dealing with environmental issues that are becoming increasingly pressing (Wei et al., 2024; Adewusi et al., 2024).

Branding, certification, and value-addition (e.g., geographical indications)

Geographical indications (GIs) are an effective branding strategy used for tea in regions like Yunnan that relies on the distinctive characteristics and cultural significance of products associated with geographical origin (*Fig. 3*). Currently, 18 Yunnan tea

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

products are registered under geographical indications, accounting for 12% of China's GI-certified teas. GIs not only build brand value through provenance, but also protect the product produced by local people as indigenous products, which encourages rural economy and cultural protection Devos et al., 2021). For example, Enshi Yulu and Deng Village Green Tea are both protected as GI products that include establishing national standards and protecting traditional production methods that contribute to the authenticity and reputation of the tea (Li, 2023). The use of traceability systems (e.g., Longjing Tea GI system) has further enhanced GI products through product authenticity and quality control, both important elements for consumer trust and maintaining market competitiveness (Li, 2024; Tripathi, 2024). The organic tea market is also increasingly driven by these branding strategies, as consumers are looking for products that provide the promise of quality through origins and connection to place and traditions (Santhosh, 2022). Thus, high-value tea branding easily relies on GIs as they provide competitive advantage through product differentiation based on origins and cultural significance. Furthermore, advanced identification methods (near-infrared spectroscopy and Fisher's discriminant analysis) have also advanced the traceability of GI teas, further helping market positioning as premium products (Zhou and Afla, 2024). Overall, incorporating GIs into tea branding allows value added tea products and allows for rural revitalization through increased economic viability and sustainability (Wong and Elbegsaikhan, 2020).

To expand the number of local tea brands, practical solutions include:

1. Regional cooperatives and producer alliances that jointly invest in brand development, packaging, and marketing to strengthen collective visibility.
2. Government-supported incubator programs providing subsidies, training, and legal support for registering new geographical indications and trademarks.
3. Integration of digital platforms (e.g., Alibaba, Douyin live-streaming) to help smallholder producers establish independent brand identities and directly reach niche consumer markets.
4. Public–private partnerships with cultural tourism initiatives (e.g., Tea Horse Road branding) to promote terroir-specific and ethnic-community brands.
5. Certification-linked branding, where organic or fair-trade certification is paired with local identity to differentiate products internationally.

Collectively, these measures could increase the number of recognized Yunnan tea brands, enhance consumer trust, and strengthen the sector's global competitiveness.

Policy support and government interventions

Policy support and government interventions are a fundamental force in directing the sustainable development of the Yunnan tea industry especially in the face of national tea excess. Modernization of agriculture and high-quality development has been established through national and provincial policies to make tea a strategic crop within China's national rural revitalization strategy (Hao et al., 2023; Hasddin et al., 2025). In Yunnan, targeted programs promote infrastructural development, marketing, and branding for tea producing areas, many of which are located in ethnic minority communities. Agriculture sustainability programs that support sustainable agriculture practices including subsidies for organic transition, organic pest control, and reforestation have promoted farmers to choose a greener ecological practice. These policies do and would require institutional innovation, technological support, and legal standing to promote and protect practices that advocate for sustainable rural development (Guo and Li, 2024; Alidu et al., 2025).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

When it comes to subsidies, China's agricultural policy has started to shift to a more sustainable direction, namely increasing "Green box" subsidies and providing revised subsidy options to reflect sustainable development objectives (Xia et al., 2024). At the same time, new environmental regulations have also been established to limit deforestation and pollution driven by high-intensity tea cultivation, incentivizing tea producers to comply with environmental standards. Furthermore, government-subsidized digital rural commerce and technology platforms have improved market connectivity as well (Han et al., 2024). This all-encompassing intervention is necessary for stress-testing systemic risks, increasing resilience for producers, and supporting a more sustainable and financially fair tea economy in Yunnan.

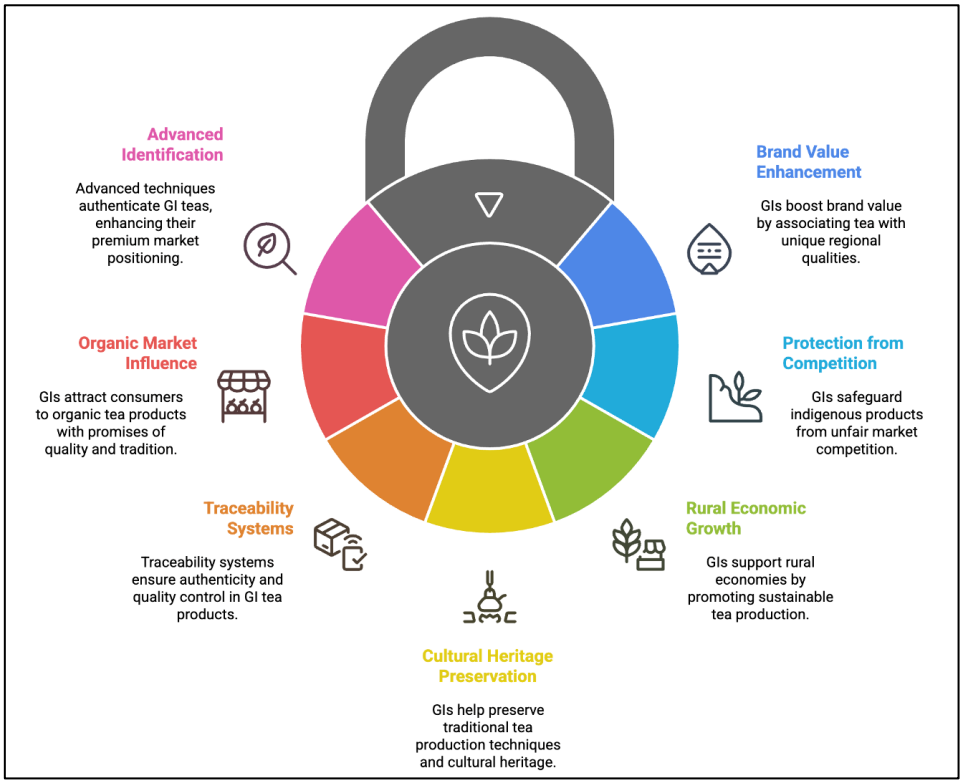

Figure 3. *Enhancing tea value through geographical indications (GIs)*

Comparative insights from other global tea regions

The global tea sector, or industry, features various development models and, sustainability practices, as evidenced by the tea sectors of India, Sri Lanka, and Kenya. In India, the tea industry is a major economic driver, facing challenges of stagnant production growth and competition from imports with potentially lower cost bases, resulting in plantation closures and the socioeconomic plight of workers.

Global comparative insights

Global comparative perspectives provide distinct lessons for sustainable development in Yunnan's tea sector, which is currently dealing with problems of overproduction and over-inventory. Countries including India, Sri Lanka, and Kenya have implemented various models of tea development that have focused on smallholder integration,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

cooperative models, and quality-oriented market segmentation. In Kenya, tea development models have been largely driven by the Kenya Tea Development Agency (KTDA), which organizes over 600,000 smallholder farmers into cooperatives, providing centralized services such as input supply, extension, processing, and marketing. Kenya also relies on an auction-based trading system in Mombasa, which ensures transparent price discovery and facilitates bulk exports (Bera et al., 2024). Additionally, Kenya has emphasized Fairtrade certification, improving labor conditions and providing community development funds. These models offer useful lessons for Yunnan: cooperative-based organization could empower fragmented smallholders in Yunnan, while a transparent auction platform might reduce speculative pricing of Pu'er tea. Similarly, adopting certification-linked branding could enhance market access for Yunnan teas, particularly in premium markets. However, adaptations are required to fit Yunnan's cultural heritage context and terroir-based differentiation rather than purely bulk exports, aligning with both domestic and international demand for high-value, identity-linked teas (Mutea et al., 2024; Subba et al., 2024). Industry is vital for foreign exchange and employment, especially for women, in Sri Lanka, but sustainability is a challenge, particularly related to climate change, productivity decline, and sociological issues (Jagadeesh et al., 2024; Thomas, 2021). Sri Lanka's Ceylon tea brand and India's Darjeeling Geographical Indication system help demonstrate how value addition can occur by establishing a connection with the origin of the product, while Kenya's auction-based trading model demonstrates how efficiently price discovery and bulk exports can take place. Fair trade practices in the above-mentioned regions have also enhanced social sustainability by improving labor conditions, community support, and re-distribution of profits. The principles of sustainable tea farming highlighted in the Darjeeling context focus on environmental, economic, and social dimensions and include the goal of increasing sustainability through mindfulness of the appropriateness of interventions (Mutea et al., 2024; Subba et al., 2024). In addition, examples of global best practices in sustainable tea farming, including organic conversion support in India, water conservation programs in Kenya, and biodiversity-friendly agroforestry in Sri Lanka, provide models for replication in Yunnan. By applying these comparative practices, Yunnan can improve environmental stewardship, enhance farmer livelihoods, and strategically reposition its tea sector in a competitive global marketplace adjusted toward sustainability (Bera et al., 2024).

Adopting best practices for sustainable tea development

In the Yunnan tea industry, it is crucial to adopt best practices for sustainable tea development to respond to market saturation and ecological degradation attributed to China's tea inventory surcharge (*Fig. 4*). Sustainability certifications for tea products, like Rainforest Alliance certification, are international frameworks that provide a rigorous model for engaging environmental, social, and economic standards in the production of tea, while supporting biodiversity and climate smart farming practices (Zhang et al., 2023). Furthermore, the growing response of tea consumers to eco-labeling provides opportunities for sustainably and ethically sourced teas in the premium market, which encourages producers to implement greener production practices. At the same time, providing measurement and reduction of the carbon footprint of tea production—including the use of renewable energy resources, low carbon transportation, and sustainable packaging—has become indispensable in indicating value chain transparency and accountability to sustainability. The carbon footprint of tea production is a critical issue, with cultivation and processing being the main contributors (Yu et al., 2024;

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

Bhattacharyya et al., 2023). Life cycle assessments (LCA) of tea production show that both the use of synthetic fertilizers and energy-intensive processing methods contributed the greatest to carbon footprints. Transitioning to a low-carbon ecological tea production process will assist in lowering carbon footprints, which is essential for addressing climate change (Premalatha et al., 2024; Bera et al., 2024). The alignment of these environmental and social ideals with sustainable sourcing certification criteria would enable Yunnan to improve its competitive standing, reach higher value markets, and provide a sense of positive participation in global sustainability initiatives, while also maintaining long-term resilience during rapid oversupply of domestic tea, in practices based on ever-increasing consumer preferences.

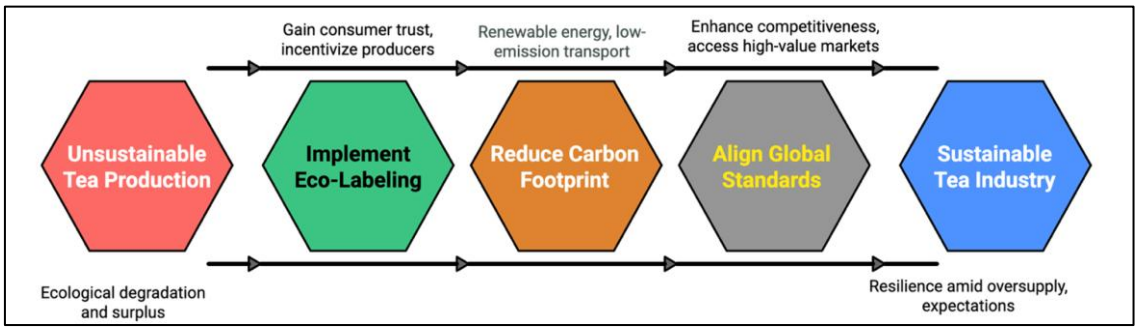

Figure 4. *Sustainable practices for Yunnan tea*

Future prospects and research directions

Yunnan's tea industry has an optimistic future, focusing on climate-resilient farming, artificial Intelligence-based pest and disease control, and low-carbon production and processing approaches. It is also important to develop and design digital tools, along with appropriate brands, to improve market value and sustainability. Continuous research is required to underpin integrated development in these areas.

Climate-resilient tea breeding and conservation

Breeding and conservation of climate-resilience tea have become strategic imperatives in order to sustainably develop the Yunnan tea industry, particularly under the dual pressures of climate change and a tea inventory surplus in China. There is rapid advancement in developing drought-tolerant and heat-resistant tea varieties through conventional breeding and molecular breeding techniques creating options to mitigate reduced yield and quality during periods of extreme weather. While traditional breeding practices have provided the foundation, they are being increasingly supplemented with molecular and genomic approaches (e.g., genomic-assisted breeding and modern gene editing techniques, i.e., CRISPR/Cas9) that provide a more precise approach to developing stress-tolerant varieties (Koshariya, 2022; Ramakrishnan et al., 2023; Prabhu et al., 2023). In particular, research enabled by genomic resources has facilitated the identification of genes associated with drought and heat tolerance, allowing for the development of elite tea genotypes with strong adaptational capabilities. For example, transcriptional profiling has identified heat shock proteins (HSPs) and transcription factors associated with thermotolerance, resulting in a better understanding of the molecular mechanisms regulating heat stress in tea (Seth et al., 2021; Nurhayati et al.,

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

2025). There is substantial research development in China directed towards the selection of genotypes with improved resilience to abiotic stress, such as temperature variation and water availability that is increasingly prevalent across tea-growing regions of Yunnan. The conservation of wild tea genetic resources and landraces are also a key focus on mapping trait reservoirs important for long-term adaptation and resilience. Interdisciplinary approaches that include molecular, ecological, and socio-economic research will also be necessary for responding to the multiple impacts of climate change on tea cropping systems, as well as for continuing production and farmer livelihoods (Omer et al., 2025; Cvejić et al., 2022). Adoption of resilient cultivars, in sustainable production systems, both provides stability in production and reduces reliance on irrigation and chemical inputs. Breeding innovations are important to ensure Yunnan remains competitive, as well as securing ecological and economic viability in tea during changing environments.

Sustainable export models and circular economy approaches

Circular economy models and sustainable export strategies are becoming increasingly prominent tensions to transform the Yunnan tea economy, as it stares down growing inventory levels and global user expectations for environmental sustainability. Circular economy models and sustainable export strategies in the tea economy are looking particularly at reusing tea waste, circular agricultural, and sustainability in packaging (*Table 3*).

Table 3. *Future prospects and research directions for sustainable development in Yunnan's tea industry*

Future prospect/focus area	Key features	Benefits	Challenges & research directions
AI and precision agriculture	Use of machine learning, drones, IoT sensors, remote sensing for monitoring and irrigation	Increased yield (5–15%), water savings (25–40%), improved pest and disease management	High costs, data privacy, need for technical expertise; integration with 5G, blockchain, cloud needed
Climate-resilient tea breeding	Conventional and molecular breeding, CRISPR/Cas9, genomics-assisted breeding, conservation of wild types	Development of drought and heat-tolerant cultivars; stable yield and quality under climate stress	Need for interdisciplinary research; genomic insights into stress tolerance mechanisms
Digital tools and branding	Digital marketing, e-commerce, AI-enabled supply chain monitoring	Enhanced market reach, transparency, consumer trust	Infrastructure gaps, digital literacy, need for capacity building
Circular economy & waste valorization	Reuse of tea waste for bioactive compounds, biochar, biofertilizers, sustainable packaging	Reduced waste, added value products, environmental benefits, rural job creation	Adoption of circular practices; need for policy and market incentives
Sustainable export models	Low-carbon logistics, traceability, sustainability certifications	Market differentiation, global consumer trust, compliance with international standards	Aligning export practices with global sustainability requirements
Precision irrigation systems	Real-time soil moisture data, weather-based irrigation	Water use efficiency, drought protection	Improving adoption and technology integration
Integrated pest management (IPM)	Biological controls, cultural practices, reduced pesticide use	Safer products, ecosystem health, pest damage reduction	Training farmers, monitoring pest dynamics, balancing control methods

Tea waste, a major waste product of the tea economy, is being valorized for several applications including, the production of bioactive compounds, environmental remediation, and as an energy source (Debnath and Purkait, 2023; Choudhury et al., 2021). This waste product is rich in polyphenolic compounds and companies are finding ways to harness tea scrap, such as to produce activated carbon, biochar as well as

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

biodegradable plastics in environmental remediation and energy generation (Debnath et al., 2021; Nille et al., 2021). At the same time, adopting sustainable packaging options (biodegradable and recyclable materials) fits with global market trends for environmentally friendly products and boosts Yunnan tea's international image. In China, circular agricultural economies (CAE) are being developed to recycle agricultural by-products (e.g., tea waste) to reduce waste and increase profit. This model focuses on resource efficiency along with creating new value chains; both of which are important for rural development and job creation (Bhattacharya et al., 2024). Export models are evolving to include low-carbon logistics, traceability systems, and alignment with international sustainability certifications to further differentiate themselves in the market and build consumer trust. These circular economy strategies not only reduce waste and resource inefficiencies, but also create a resilient, value-centric export system, that enables long-term sustainability and international competitiveness with the Yunnan tea industry in the changing global market (Varghese et al., 2023; Duarah et al., 2024).

Conclusion

The sustainability and resilience of Yunnan's tea industry are at a critical crossroads, influenced by deep-rooted cultural heritage, ecological fragility, and intensified market pressures from China's expanding tea inventory. Despite Yunnan's distinctive global status—anchored in Pu'er tea, ancient tea trees, and ethnic cultivation traditions—challenges such as overproduction, market saturation, and supply chain inefficiencies increasingly threaten socio-economic stability and ecological integrity. Smallholder farmers, the backbone of the sector, face vulnerability due to price volatility, constrained infrastructure, and rising certification costs, while inconsistent product quality and branding erode global competitiveness. Addressing these challenges demands a holistic strategy that synergizes traditional ecological knowledge with advanced agronomic practices, digital innovations (e.g., blockchain traceability, cold-chain logistics), and supportive policy frameworks emphasizing quality control, rural development, and market diversification. Preservation of cultural heritage—including terroir-specific varieties and ethnic tea customs—must be integrated with modernization efforts to enhance international market positioning. Tackling domestic inventory surpluses requires recalibrated supply-demand alignments through targeted exports and niche product development. Moreover, adopting climate-resilient agronomic systems, cooperative models, and digital commerce platforms can improve farmer livelihoods and environmental stewardship. The integration of cutting-edge technologies—such as AI-driven precision agriculture and genomics-based breeding—alongside circular economy approaches, will underpin low-carbon, resource-efficient production. Collectively, these multidimensional interventions offer a robust framework for repositioning Yunnan as a globally competitive, sustainable, and culturally vibrant tea economy, aligning with China's broader sustainable development goals and the imperatives of a climate-constrained global market.

REFERENCES

[1] Abashidze, G. (2023): Digital agriculture-technological means and possibilities of digital transformation of agriculture. – Economic Science for Rural Development 10: 13-19.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[2] Adams, A., Osei-Amponsah, C., Tetteh Jumpah, E. (2020): Analysing the determinants, constraints and opportunities of smallholder farmers access to input markets: evidence from northern Ghana. – Journal of Agribusiness and Rural Development 56: 133-143.
[3] Adewusi, A. O., Asuzu, O. F., Olorunsogo, T., Iwuanyanwu, C., Adaga, E., Daraojimba, D. O. (2024): AI in precision agriculture: a review of technologies for sustainable farming practices. – World Journal of Advanced Research and Reviews 21: 2276-2285.
[4] Agrawal, J., Arafat, M. Y. (2024): Transforming farming: a review of AI-powered UAV technologies in precision agriculture. – Drones (2504-446X) 8.
[5] Alidu, A. F., Man, N., Ramli, N. N., Haris, N. B.-M., & Alhassan, A. (2025): Enhancing adoption intensity: Exploring the nexus between climate information access and climate-smart adaptation practices among smallholder farmers in Ghana. – Journal of Global Innovations in Agricultural Sciences 13: 19–27.
[6] An, C. E. C. L. U., Pe, D. (2021): Cultural Landscape of Pu'er Tea Forest of Jingmai Mountain in Yunnan Province. – International Council on Monuments and Sites, Charenton-le-Pont.
[7] Arhin, I., Li, J., Mei, H., Amoah, M., Chen, X., Jeyaraj, A., Li, X., Liu, A. (2022): Looking into the future of organic tea production and sustainable farming: a systematic review. – International Journal of Agricultural Sustainability 20: 942-954.
[8] Assad, M., Ashaolu, T. J., Khalifa, I., Baky, M. H., Farag, M. A. (2023): Dissecting the role of microorganisms in tea production of different fermentation levels: a multifaceted review of their action mechanisms, quality attributes and future perspectives. – World Journal of Microbiology and Biotechnology 39: 265.
[9] Barhoi, P., Dayal, S. (2024): Adivasi women temporary workers in tea gardens and the Covid-19 pandemic. – Equality, Diversity and Inclusion: An International Journal 43: 211-229.
[10] Basa, R. (2024): AI in agriculture: revolutionizing precision farming and sustainable crop management. – International Journal of Scientific Research in Computer Science, Engineering and Information Technology 10: 535-543.
[11] Bera, R., Datta, A., Bose, S., Barik, A., Asthana, A., Seal, A. (2024): Sustainable tea initiatives with the adoption of Inhana Rational Farming Technology to address the principles of regenerative farming for crop sustainability and reduction of pesticide usage. – Advances in Research on Teaching 25: 140-166.
[12] Berna, I. E., Vijay, K., Jeyalakshmi, J., Samuel, P. (2024): How AI Contributes to Precision Agriculture. Artificial Intelligence for Precision Agriculture. – Auerbach Publications, Boca Raton, FL.
[13] Bhat, S. A., Huang, N.-F. (2021): Big data and ai revolution in precision agriculture: survey and challenges. – IEEE Access 9: 110209-110222.
[14] Bhattacharya, R., Ramrakhiani, L., Mukhopadhyay, A., Bhattacharjee, P. (2024): Application of tea leaves in the circular economy: a sustainable approach to remove synthetic dye from wastewater by alkali-activated spent tea leaves. – ChemRxiv. DOI:10.26434/chemrxiv-2024-xv5mf.
[15] Bhattacharyya, S., Bera, R., Seal, A. (2023): Tea quality and value-added marketing potential of safe and sustainable tea in Indian domestic market: consumers choice for conventional vis-a-vis sustainable tea. – International Journal of Plant & Soil Science 35: 410-424.
[16] Choudhury, N. D., Bhuyan, N., Narzari, R., Saikia, R., Seth, D., Saha, N., Kataki, R. (2021): Various Conversion Techniques for the Recovery of Value-Added Products from Tea Waste. – In: Bhat, R. (ed.) Valorization of Agri-Food Wastes and By-Products. Elsevier, Amsterdam, pp. 237-265.
[17] Cvejić, S., Jocić, S., Mitrović, B., Bekavac, G., Mirosavljević, M., Jeromela, A. M., Zorić, M., Radanović, A., Kondić-Špika, A., Miladinović, D. (2022): Innovative Approaches in the Breeding of Climate-Resilient Crops. – In: Benkeblia, N. (ed.) Climate Change and Agriculture: Perspectives, Sustainability and Resilience. Wiley, Hoboken, NJ, pp. 111-156.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[18] Dakir, A., Barramou, F., Alami, O. B. (2022): Opportunities for Artificial Intelligence in Precision Agriculture Using Satellite Remote Sensing. – In: Barramou, F. et al. (eds.) Geospatial Intelligence: Applications and Future Trends. Springer, Cham, pp. 107-117.
[19] Das, A., Mishra, R. (2020): An appraisal of constraints faced by tea (Camellia sinensis) value chain players during COVID-19 crisis. – SSRN Electronic Journal. DOI:10.2139/ssrn.3715266.
[20] Das, S., Karmakar, D. (2024): Lifestyle of women in tea garden community: a systematic literature review. – International Journal for Multidisciplinary Research. https://doi.org/10.36948/ijfmr.2024.v06i06.34321.
[21] Debnath, B., Haldar, D., Purkait, M. K. (2021): Potential and sustainable utilization of tea waste: a review on present status and future trends. – Journal of Environmental Chemical Engineering 9: 106179.
[22] Debnath, B., Purkait, M. K. (2023): Sustainable Utilization of Tea Waste. – In: Ramawat, K. G. et al. (eds.) Agricultural Waste: Environmental Impact, Useful Metabolites and Energy Production. – Springer, Singapore.
[23] Deguine, J.-P., Aubertot, J.-N., Flor, R. J., Lescourret, F., Wyckhuys, K. A., Ratnadass, A. (2021): Integrated pest management: good intentions, hard realities. A review. – Agronomy for Sustainable Development 41: 38.
[24] Devos, R. J. B., De Araújo Barth, C., Dettmer, A., Bertolin, T. E., Colla, L. M. (2021): Pu-erh tea: fermentative process as a potentialized of sensory aspects and bioactive profile–a review. – Research, Society and Development 10: e3510816999-e3510816999.
[25] Dodd, O., Liao, S. (2025): The role of inventory in firm resilience to the Covid-19 pandemic. – European Financial Management 31: 786-818.
[26] Dou, Z., Ji, M., Wang, M., Li, H. (2021): RETRACTED ARTICLE: Empirical analysis of Pu'er tea price bubble measurement based on GSADF method. – Acta Agriculturae Scandinavica, Section B—Soil & Plant Science 71: 81-90.
[27] Duarah, P., Haldar, D., Singhania, R. R., Dong, C.-D., Patel, A. K., Purkait, M. K. (2024): Sustainable management of tea wastes: resource recovery and conversion techniques. – Critical Reviews in Biotechnology 44: 255-274.
[28] Duc, N. M., Nhuan, N. H., Huong, T. T. T., Hai, N. M., Vien, T. D. (2024): Revolutionising agriculture and rural economy through digital transformation: bridging theory with practice. – The VMOST Journal of Social Sciences and Humanities 66: 20-29.
[29] Fahad, A. (2023): Modern techniques in integrated pest management to achieve sustainable agricultural development. – International Journal of Family Studies, Food Science and Nutrition Health 4: 1-14.
[30] Fan, Y., Pujeeb, N., Phanthabutr, S. (2024): The culture of Pu'er tea in Yunan: development of cultural awareness in term of Puer's culture in China. – Journal of Arts Management 8: 39-52.
[31] Fan, Z., Liu, K. (2022): The promotion effect of the belt and road initiative on China's tea export trade. – Journal of Sociology and Ethnology 32: 1-8.
[32] Fang, Y.-S., Fang, L.-C. (2022): A review of Chinese e-commerce research: 2001–2020. – IEEE Access 10: 49015-49027.
[33] Fernando, W. M., Thibbotuwawa, A., Ratnayake, R. C., Perera, H. N. (2024): Unveiling waste patterns in tea smallholder producer supply chains: a case study from a developing economy. – 2024 Joint International Conference on Digital Arts, Media and Technology with ECTI Northern Section Conference on Electrical, Electronics, Computer and Telecommunications Engineering (ECTI DAMT & NCON), IEEE, pp. 365-370.
[34] Guan, J. (2022): The Tea Industry in Modern China and Public Demand for Tea. – In: Nobayashi, A. (ed.) Making Food in Local and Global Contexts: Anthropological Perspectives. – Springer, Singapore.
[35] Guo, Y., Li, S. (2024): A policy analysis of China's sustainable rural revitalization: integrating environmental, social and economic dimensions. – Frontiers in Environmental Science 12: 1436869.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[36] Han, F., Mao, X., Yu, X., Yang, L. (2024): Government environmental protection subsidies and corporate green innovation: evidence from Chinese microenterprises. – Journal of Innovation & Knowledge 9: 100458.
[37] Han, X. (2023): Reconstruction of ethnicity and production of Pu'er tea in post-Mao China: a case study of Bulang ethnic group in Mangjing Village, Yunnan Province. – Asian Ethnicity 24: 344-368.
[38] Hao, F., Zang, Y., Fan, B., Zhang, Y. (2023): Environmental regulation promotes green development in China: from the perspective of technological innovation. – Frontiers in Energy Research 11: 1209650.
[39] Hasddin, U., Ulyasniati, Mukaddas, J., Marjani, Mirad, Kan, M., Ega, A.-A., & Afa, M. (2025): Sustainable agriculture: The role of biostimulants in enhancing crop growth and resilience. – Journal of Global Innovations in Agricultural Sciences 13: 561–573.
[40] He, Z. (2021): Analysis of the agricultural E-Commerce in Rural China. – Proceedings of the 2021 12th International Conference on E-Education, E-Business, E-Management, and E-Learning, pp. 360-363.
[41] Heid, B., Mínguez, R., Minondo, A. (2021): Is competition from China so special? – The World Economy 44: 64-88.
[42] Hoque, A., Padhiary, M. (2024): Automation and AI in precision agriculture: innovations for enhanced crop management and sustainability. – Asian J. Res. Comput. Sci 17: 95-109.
[43] Idris, A. L., Fan, X., Muhammad, M. H., Guo, Y., Guan, X., Huang, T. (2020): Ecologically controlling insect and mite pests of tea plants with microbial pesticides: a review. – Archives of Microbiology 202: 1275-1284.
[44] Jagadeesh, M., Vinay, H., Pavithra, V., Abhishek, G. (2024): India's tea export potential: stirring up global trade opportunities. – Journal of Experimental Agriculture International 46.
[45] Jeyalakshmi, J., Vijay, K., Berna, I. E., Sowmia, K. (2025): AI in Optimisation of Agricultural Output in Precision Agriculture. – Raj, P. et al. (eds.) Artificial Intelligence for Precision Agriculture. Auerbach Publications, Boca Raton, FL.
[46] Jumi, T., Borah, S., Das, M. D. (2021): Problems faced by women tea plantation workers in performing their duties. – Age 18: 45.
[47] Koshariya, A. K. (2022): Climate-resilient crops: breeding strategies for extreme weather conditions. – Plant Science Archives. https://doi.org/10.51470/PSA.2022.7.2.01.
[48] Li, C. (2024): Enshi Yulu tea cultural and creative product design based on AHP hierarchical analysis method. – Proceedings of the 2024 International Conference on Computer and Multimedia Technology, pp. 212-216.
[49] Li, H., Yang, S., Yan, J., Gao, W., Cui, J., Chen, Y. (2024a): From conventional to organic agriculture: influencing factors and reasons for tea farmers' adoption of organic farming in Pu'er City. – Sustainability 16: 10035.
[50] Li, T., Lu, C., Wei, Y., Zhang, J., Shao, A., Li, L., Wang, Y., Ning, J. (2024b): Chemical imaging for determining the distributions of quality components during the piling fermentation of Pu-erh tea. – Food Control 158: 110234.
[51] Li, W., Zhang, Q., Fan, Y., Cheng, Z., Lu, X., Luo, B., Long, C. (2023): Traditional management of ancient Pu'er teagardens in Jingmai Mountains in Yunnan of China, a designated Globally Important Agricultural Heritage Systems site. – Journal of Ethnobiology and Ethnomedicine 19: 26.
[52] Li, Y. (2023): TWG Tea Company v. Pudong Intellectual Property Office (administrative punishment on infringement of geographical indications and registered trademarks). – In: Wu, H. et al. (eds.) Annotated Landmark International Intellectual Property Cases in China, 2021-2022. L'Erma di Bretschneider Srl, Rome, pp. 225-241.
[53] Liu, H., Fan, J., Zhou, K. (2018): An Empirical study on spatial–temporal dynamics and influencing factors of tea production in China. – Sustainability 10: 3037.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[54] Lv, H., Feng, X., Song, H., Ma, S., Hao, Z., Hu, H., Yang, Y., Pan, Y., Zhou, S., Fan, F. (2023): Tea storage: A not thoroughly recognized and precisely designed process. – Trends in Food Science & Technology 140: 104172.
[55] Ma, C., Ma, B., Zhou, B., Xu, L., Hu, Z., Li, X., Chen, X. (2024): Pile-fermentation mechanism of ripened Pu-erh tea: omics approach, chemical variation and microbial effect. – Trends in Food Science & Technology 146: 104379.
[56] Ma, Z. (2024): Making tea, making ethnic minority women: women's labor, ethnicized femininity, and the Pu'er tea business in contemporary China. – Food, Culture & Society 1-17.
[57] Mutea, F. M., Kibera, F. N., Kinoti, M. W., Njeru, W. G. (2024): Fairtrade practices and performance of certified small tea producer organizations in Kenya. – European Journal of Business and Management Research 9: 209-218.
[58] Nille, O. S., Patil, A. S., Waghmare, R. D., Naik, V. M., Gunjal, D. B., Kolekar, G. B., Gore, A. H. (2021): Valorization of Tea Waste for Multifaceted Applications: A Step Toward Green and Sustainable Development. – In: Bhat, R. (eds.) Valorization of Agri-Food Wastes and By-Products. – Elsevier, Amsterdam.
[59] Nurhayati, A., Madjid, R., Yusuf, H., & Hatani, L. (2025): Innovations in agricultural e-commerce: Analyzing purchase decisions and the role of consumer credibility. – Journal of Global Innovations in Agricultural Sciences 13: 607–616.
[60] Omer, A. A., Zhang, C.-H., Liu, J., Shan, Z.-G. (2025): Comprehensive review of mapping climate change impacts on tea cultivation: bibliometric and content analysis of trends, influences, adaptation strategies, and future directions. – Frontiers in Plant Science 15: 1542793.
[61] Pan, Z., Zheng, X. (2023): Price volatility transmission of perishable agricultural products: evidence from China. – Economic Research—Ekonomska Istraživanja 36.
[62] Prabhu, K. R., Kumar, A., Yumkhaibam, R. S., Janeja, H. S., Krishna, B., Talekar, N. (2023): A review on conventional and modern breeding approaches for developing climate resilient crop varieties. – Journal of Applied & Natural Science 15.
[63] Premalatha, V., Sunitha, R., Rajkishore, S. K., Manimekalai, R., Thamaraiselvi, S. P., Moorthy, S. P., Raveena, R., Ramesh, D. (2024): Insights of carbon footprint of tea through life cycle approach. – Plant Science Today 11: 5374.
[64] Qaim, M. (2020): Role of new plant breeding technologies for food security and sustainable agricultural development. – Applied Economic Perspectives and Policy 42: 129-150.
[65] Qiang, Z. (2024): Multi-ethnic Cultural Landscapes as Heritage: The Case of Jingmai Mountain Traditional Tea Forests, Pu'er City, Yunnan Province. – In: Holl, A. F. C. (ed.) Anthropological Explorations of Gender, Identity, and Economics. BP International, London.
[66] Qin, K., Zhou, L. (2024): Analysis of the high-quality development path of China's tea export. – PloS ONE 19: e0311629.
[67] Raj, A., Jhariya, M. K., Devi, A., Kerketta, A., Poonam (2023): Eco-Farming for Sustainability: Defending Our Way of Life Against Agrochemicals. – In: Ogwu, M. C. et al. (eds.) One Health Implications of Agrochemicals and their Sustainable Alternatives. Springer, Singapore.
[68] Ramakrishnan, M., Sudhama, V., Rajanna, L. (2023): A review on the genome-based approaches for the development of stress and climate resilient tea crops. – Plant Science Today. DOI: https://doi.org/10.14719/pst.1758.
[69] Roy, C., Naskar, S., Ghosh, S., Rahaman, P., Mahanta, S., Sarkar, N., Chaudhuri, R. K., Babu, A., Roy, S., Chakraborti, D. (2024): Sucking pest management in tea (Camellia sinensis (L.) Kuntze) cultivation: integrating conventional methods with bio-control strategies. – Crop Protection 106759.
[70] Ru, S. H. (2022): Conceptualizing China's tea history in the 19th century: incorporation into the capitalist world-economy. – Journal of Agrarian Change 22: 812-830.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[71] Santhosh, A. (2022): Geographical indications: a study on history, laws and socio-economic effects with a case study of Darjeeling tea. – Indian Journal of Integrated Research in Law 2(3).
[72] Seth, R., Maritim, T. K., Parmar, R., Sharma, R. K. (2021): Underpinning the molecular programming attributing heat stress associated thermotolerance in tea (Camellia sinensis (L.) O. Kuntze). – Horticulture Research 8.
[73] Sharma, S. (2023): Cultivating sustainable solutions: integrated pest management (ipm) for safer and greener agronomy. – Corporate Sustainable Management Journal 1: 103-108.
[74] Shekarian, E., Ijadi, B., Zare, A., Majava, J. (2022): Sustainable supply chain management: a comprehensive systematic review of industrial practices. – Sustainability 14: 7892.
[75] Sigley, G. (2021): Reimagining the 'Central Plains'(Zhongyuan) and 'Borderlands'(Bianjiang): the cultural heritage scholarship of the Ancient Tea Horse Road (Chamagudao) of Southwest China. – International Journal of Heritage Studies 27: 904-919.
[76] Subba, B., Mondal, S., Mandal, U. K., Tamang, L. (2024): Small-scale tea farming sustainability: a case study of Darjeeling hill region, India. – Farming System 2: 100080.
[77] Suroso, A. I., Abdullah, A., Haryono, A., Tandra, H. (2025): The potential of China's tea trade and how it affects China's economic growth. – The Journal of International Trade & Economic Development 34: 428-449.
[78] Tan, Y. (2022): Market analysis of new tea industry based on questionnaire survey. – BCP Business & Management 24:140-148. https://doi.org/10.54691/bcpbm.v24i.1455.
[79] Thomas, H. (2021): A 'Decent Cuppa': Worker power and consumer power in the Sri Lankan tea sector. – British Journal of Industrial Relations 59: 114-138.
[80] Tripathi, V. (2024): Analyzing the role of legal protection for trademarks and geographical indications in preserving cultural heritage and enhancing global trade. – Journal of Law and Intellectual Property Rights 1: 50-63.
[81] Varghese, S. A., Pulikkalparambil, H., Promhuad, K., Srisa, A., Laorenza, Y., Jarupan, L., Nampitch, T., Chonhenchob, V., Harnkarnsujarit, N. (2023): Renovation of agro-waste for sustainable food packaging: a review. – Polymers 15: 648.
[82] Wang, T., Li, R.-Y., Liu, K.-Y., Chen, Q.-Y., Bo, N.-G., Wang, Q., Xiao, Y.-Q., Sha, G., Chen, S.-Q., Lei, X. (2023): Changes in sensory characteristics, chemical composition and microbial succession during fermentation of ancient plants Pu-erh tea. – Food Chemistry: X 20: 101003.
[83] Wei, Y., Wen, Y., Huang, X., Ma, P., Wang, L., Pan, Y., Lv, Y., Wang, H., Zhang, L., Wang, K. (2024): The dawn of intelligent technologies in tea industry. – Trends in Food Science & Technology 144: 104337.
[84] Wong, C. Y., Elbegsaikhan, M. (2020): Geographical indications in development contexts: function, supply chain and pursuit of rural industrial development. – The Journal of World Intellectual Property 23: 712-735.
[85] Wong, S. W. K. (2022): Rebranding terroir: ethnoecology and tea agro-ecosystem management in response to increased market integration in southern Yunnan, China. – Landscape Architecture Frontiers 10(4): 84-95.
[86] Wu, B., Li, Z. (2022): Study on the factors influencing the price volatility of agricultural products in China. – Academic Journal of Business & Management 4: 67-73.
[87] Xia, Y., Guo, H., Xu, S., Pan, C. (2024): Environmental regulations and agricultural carbon emissions efficiency: evidence from rural China. – Heliyon 10.
[88] Xie, L., Nallaluthan, K. (2024): Integration and innovation: an overview of the development status and trends of Chinese tea e-commerce live streaming. – International Journal of Global Economics and Management 4: 121-126.
[89] Yang, H., Suntornvongsagul, K., Wang, J., Wang, Q., Zhang, W. (2024): Indigenous knowledge in the sustainable management of a biodiversity-based millennium-old tea forest in the highlands of Yunnan Province, southwestern China. – Biodiversity 25: 142-152.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary

[90] Yu, P., Chen, J., Sampat, M., Misuko, N. (2022): The Digital Transformation of Rural Agricultural Business Management: A Case Study of China. – In: Bilgaliyan, S. et al. (eds.) Empirical Research for Futuristic E-Commerce Systems: Foundations and Applications. IGI Global, Hershey, PA.
[91] Yu, Z., Jiao, W., Min, Q. (2024): Carbon footprints of tea production in smallholder plantations: A case study of Fenghuang Dancong tea in China. – Ecological Indicators 158: 111305.
[92] Zhang, C., Ye, X., Zhang, H., Xie, J., Yang, X. (2023): Environmental footprint performance improvement of black tea using the life cycle assessment approach. – Journal of Cleaner Production 430: 139574.
[93] Zhiyang, L. (2020): Tibetan tea road: trade and transport of Sichuan frontier tea from the early Qing Dynasty to the Republican China Period (1700-1950). – International Journal of Business Anthropology 10: 66-81.
[94] Zhou, C., Afla, M. R. M. (2024): Cultural landscape design and protection of Lifang Village, Shuangbai County, Yunnan, China, in the context of rural revitalization. – Journal of Chinese Architecture and Urbanism 6: 2891.
[95] Zhou, W., Arcot, Y., Medina, R. F., Bernal, J., Cisneros-Zevallos, L., Akbulut, M. E. (2024): Integrated pest management: an update on the sustainability approach to crop protection. – ACS Omega 9: 41130-41147.
[96] Zhu, J., Chen, C., You, L. (2022): Engaging smallholders in flower agribusiness for inclusive rural development: the case of Yunnan, China. – Sustainability 14: 2614.
[97] Zhu, Y., He, L., Hu, W., Li, J. (2024): Research on the development status, problems and strategies of agricultural products e-commerce live streaming platform—taking "EAST BUY" as an example. – Academic Journal of Business & Management 6: 134-142.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2305_1005110073
© 2025, ALÖKI Kft., Budapest, Hungary