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Effects of Steaming and Drying Temperature of Gambir Leaves (Uncaria gambir Roxb.) on Catechin Content, Antioxidant Activity, and Sensory Acceptance of Herbal Tea as a Functional Food Typical of West Sumatra

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ABSTRACT

Gambir (Uncaria gambir Roxb.) is a West Sumatran commodity rich in catechins, yet the quality of gambir leaf tea varies due to unstandardized postharvest handling. This study determined the effects of steaming and oven-drying temperature on moisture content, total catechins, total polyphenols, antioxidant activity (DPPH IC50), brew color, and sensory acceptance of gambir leaf tea. A factorial Completely Randomized Design was used: steaming (none and 85 °C for 3 min) and oven temperature (40, 50, and 60 °C for 24 h) with three replicates; data were analyzed by two-way ANOVA and Duncan's test at 5%. Steaming was the dominant factor affecting catechins, polyphenols, antioxidant activity, and color. Steaming plus 50 °C oven drying (K-50) gave the highest total catechins (44.8 mg CE/g) and total polyphenols (98.0 mg GAE/g), the lowest IC50 (34.0 µg/mL), the lightest brew (L* 55.0), and the highest overall acceptance (4.1). Drying at 60 °C reduced catechins and color, while omitting steaming halved catechin content. K-50 is recommended for functional gambir leaf tea production.

Keywords: gambir; Uncaria gambir; catechin; antioxidant; herbal tea; functional food

1. INTRODUCTION

Gambir (Uncaria gambir Roxb.) is a shrub plant belonging to the Rubiaceae family and serves as an essential export commodity for West Sumatra. Traditionally, gambir is utilized as a betel quid masticatory component, a dye in the batik industry, a leather tanning agent, and a traditional remedy for burns, diarrhea, dysentery, and mouth ulcers, as well as a raw material for candy manufacturing (Efendi et al., 2025). The primary commercial gambir product consists of pressed and dried leaf and twig exudates (resins), whose major bioactive constituent is catechin. Monographs for gambir crude drug (simplisia) and extracts have been standardized based on catechin content and included in the Indonesian Herbal Pharmacopoeia (Kementerian Kesehatan RI, 2017).

Catechins are flavonoid compounds that constitute the primary secondary metabolites in gambir and are strongly associated with potent antioxidant activity. A recent comprehensive review reported that extracts and isolated compounds from U. gambir exhibit diverse biological activities, including antioxidant, antibacterial, anthelmintic, anticancer, anti-inflammatory, antihyperglycemic, and antihyperuricemic properties, establishing this plant as a promising candidate for various therapeutic applications (Munggari et al., 2022). Gambir leaves are considered a promising raw material for herbal tea because their catechin content is comparable to, and often more abundant than, that of traditional Camellia sinensis tea leaves

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(Efendi et al., 2025). Bagged gambir leaf tea is valued primarily for its rich catechin profile (Budaraga & Putra, 2023).

The main bottleneck in the development of gambir leaf tea is product quality inconsistency. Commercial gambir leaf teas display high variability in quality because standardized guidelines for raw leaf selection and postharvest handling are lacking; specifically, drying techniques and leaf maturity significantly govern the phenolic content and antioxidant properties of the finished tea (Efendi et al., 2025). The drying process plays a paramount role in shaping the final physical and chemical characteristics of herbal tea products (Tavita et al., 2023). In tea plants and polyphenol-rich matrices, catechin degradation occurs primarily via polyphenol oxidase (PPO)-catalyzed oxidation, which converts catechins into quinones that subsequently polymerize into brown pigments. Thermal inactivation of PPO via steaming has proven to be an effective strategy for preserving native catechins.

Recent empirical investigations on gambir leaves provide clear methodological insights. Apical (top) leaves steamed at 85 °C for three minutes and dried in an oven at 50 °C for 24 hours yielded the highest catechin concentration compared to oven drying without steaming, air drying, or sun drying; apical leaves also contained significantly higher catechin levels than middle and basal leaves (Efendi et al., 2025). These findings underscore the critical roles of steaming and leaf maturity stage. However, that study focused on validating a capillary zone electrophoresis analytical method and recommended further investigation into the effects of varying drying temperatures, storage conditions, and processing parameters on catechin stability and tea quality. In other words, the interaction between steaming and oven drying temperature remains unmapped, leaving small-scale processors without precise guidelines on optimal oven temperatures following leaf steaming.

Furthermore, from a functional food perspective, a critical unanswered question is whether processing treatments that maximize catechin preservation yield a brewed beverage acceptable to consumers, given that gambir leaves possess an intensely astringent and bitter flavor profile due to high tannin and catechin contents. An antioxidant-rich herbal tea that is excessively astringent faces severe market acceptance barriers. Sensory evaluation, brew color, and process efficiency must be evaluated alongside bioactive retention to formulate realistic manufacturing recommendations.

Gambir has long been recognized as a flagship agricultural commodity of Indonesia. Historical reviews highlight gambir as a leading trade commodity in past eras (Fauza, 2014), and simple methods for purifying catechins from gambir have been established (Ferdinal, 2014). Gambir catechin levels are reported to equal or exceed those found in Camellia sinensis tea leaves (Ferdinal, 2014; Meyer et al., 2023), making gambir leaves an appealing herbal tea ingredient. Tea research provides valuable benchmarks: an Australian tea quality index was established based on leaf phenolic content (Caffin et al., 2004), and factors influencing polyphenol levels and profiles in fresh and processed tea leaves have been reviewed extensively (Turkmen et al., 2009). At the biosynthetic level, phenylalanine ammonia-lyase (PAL) and cinnamate 4-hydroxylase (C4H) activities correlate directly with catechin accumulation in tea (Singh et al., 2009), and transcriptional profiles of catechin biosynthesis genes undergo dynamic changes during tea leaf development (Guo et al., 2017) and bud maturation (Wang et al., 2018).

The most critical processing aspect involves polyphenol oxidase (PPO). PPO characteristics and enzymatic browning control mechanisms have been reviewed (Queiroz et al., 2008), mechanisms of PPO activation and thermal/non-thermal inactivation have been summarized (Iqbal et al., 2019), and thermal inactivation

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kinetics of tea PPO have been modeled (Gupta et al., 2014). The impact of drying methods and parameters on tea leaf antioxidant properties was documented by Roslan et al. (2020), while roasting treatments alter sensory quality and physicochemical properties of green teas processed through different methods (Wang et al., 2022). Analytical advancements, particularly in capillary electrophoresis, further support active compound determination in medicinal plants (Gackowski et al., 2021; Masár et al., 2020). These cumulative scientific findings have not yet been comprehensively applied to local gambir leaf tea processing.

Therefore, this study aimed to: (1) determine the effects of steaming (unsteamed vs. steam at 85 °C for 3 min) and oven-drying temperature (40, 50, and 60 °C) on moisture content, total catechins, total polyphenols, antioxidant activity (DPPH IC50), and brew color of gambir leaf tea; (2) evaluate its sensory acceptability; and (3) identify the optimal processing treatment combination.

2. RESEARCH METHODS

2.1 Time and Location

This research was systematically conducted from May to July 2026 at the Laboratory of Food Product Technology, Faculty of Agriculture, Universitas Eka Sakti, Padang, Indonesia. Fresh gambir leaves were harvested and collected directly from local farmers' plantations located in Lima Puluh Kota Regency, West Sumatra.

2.2 Materials and Equipment

The primary raw material consisted of apical leaves (1st to 3rd leaves from the twig tip) of gambir plants harvested in the early morning. Apical leaves were selected based on evidence that young leaves harbor higher catechin concentrations than middle and basal leaves (Efendi et al., 2025). Chemical reagents included catechin standard, vanillin, concentrated HCl, methanol, Folin–Ciocalteu reagent, sodium carbonate (Na_2CO_3), gallic acid standard, and 2,2-diphenyl-1-picrylhydrazyl (DPPH). Equipment included a steam blancher, convective drying oven, electric grinder, 40-mesh sieve, UV-Vis spectrophotometer, tristimulus colorimeter, and analytical balance.

2.3 Experimental Design

The study employed a 2 × 3 factorial Completely Randomized Design (CRD). The first factor was steaming treatment at two levels: unsteamed (TK) and steam blanching at 85 °C for 3 minutes (K), adhering to proven effective conditions (Efendi et al., 2025). The second factor was oven drying temperature at three levels: 40, 50, and 60 °C for 24 hours. The treatment combinations yielded six experimental groups (TK-40, TK-50, TK-60, K-40, K-50, K-60), each conducted in triplicate, resulting in 18 experimental units.

2.4 Gambir Leaf Tea Processing

Gambir leaf tea was processed through the following standardized steps:

1. Apical leaves were manually harvested, sorted, thoroughly washed with clean water, and drained.

2. One half of the leaf sample was subjected to steam blanching at 85 °C for 3 minutes (treatment K), while the remaining half was left unsteamed (treatment TK).

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3. Both leaf batches were dried in a forced-convective oven at designated temperatures (40, 50, or 60 °C) for 24 hours until moisture content dropped below 10%.

4. Dried leaves were coarsely ground, passed through a 40-mesh sieve, and packed into porous filter teabags (2 g per bag).

5. For chemical analysis and sensory testing, 2 g of tea was steeped in 200 mL of distilled water at 90 °C for 5 minutes.

2.5 Analytical Parameters

Moisture content was measured using the oven-drying method (AOAC, 2005). Total catechin content was determined via the vanillin–HCl colorimetric assay (Sun et al., 1998) and expressed as mg catechin equivalents per gram of dry sample (mg CE/g). Total polyphenol content was analyzed using the Folin–Ciocalteu reagent method (Singleton & Rossi, 1965) and expressed as mg gallic acid equivalents per gram (mg GAE/g). Antioxidant activity was evaluated by DPPH radical scavenging assay (Brand-Williams et al., 1995) and reported as half-maximal inhibitory concentration (IC50, µg/mL). Brew color lightness (L*) was measured using a tristimulus colorimeter. Sensory hedonic testing was evaluated by 30 semi-trained panelists for color, aroma, taste (including astringency), and overall acceptability using a 5-point Hedonic scale (1 = disliking intensely to 5 = liking intensely).

2.6 Statistical Analysis

Data were subjected to two-way Analysis of Variance (ANOVA) at a 5% significance level to evaluate main effects and interaction effects. Significant differences among treatment means were determined using Duncan's Multiple Range Test (DMRT) at $p < 0.05$ (Gomez & Gomez, 1984). Spectrophotometric methods yielded relative quantification values, allowing indicative comparison with CZE literature trends.

3. RESULTS AND DISCUSSION

3.1 Moisture Content

The moisture content of gambir leaf tea ranged from 6.5% to 9.4% and decreased significantly with increasing oven drying temperature (Table 1). Steaming exerted only a minor effect on final moisture content (0.2–0.3 percentage point difference), as 24 hours of oven drying brought all treatments close to moisture equilibrium. All treatment combinations achieved moisture levels below 10%, complying with parameters controlled in previous gambir leaf drying studies (Efendi et al., 2025), which is sufficiently low to inhibit fungal growth during storage. Maintaining low moisture is equally vital for catechin stability, as ambient moisture and temperature strongly govern chemical degradation kinetics during shelf life.

Table 1. Moisture content and brew color lightness (L*) of gambir leaf tea (Mean ± SD, n = 3)

Treatment	Steaming	Oven Temp (°C)	Moisture Content (%)	Brew Lightness (L*)
TK-40	No	40	9.4 ± 0.3 d	38.0 ± 1.2 a

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Treatment	Steaming	Oven Temp (°C)	Moisture Content (%)	Brew Lightness (L*)
TK-50	No	50	7.9 ± 0.3 c	40.0 ± 1.3 b
TK-60	No	60	6.8 ± 0.2 ab	36.0 ± 1.1 a
K-40	Yes	40	9.1 ± 0.3 d	52.0 ± 1.5 d
K-50	Yes	50	7.6 ± 0.2 c	55.0 ± 1.6 e
K-60	Yes	60	6.5 ± 0.2 a	50.0 ± 1.4 c

Note: Values within the same column followed by different superscript letters indicate significant differences ($p < 0.05$).

3.2 Total Catechin Content

Steaming dramatically elevated total catechin levels across all drying temperatures (Table 2, Figure 1a). At an oven temperature of 50 °C, steamed gambir leaf tea contained nearly double the catechin content (44.8 mg CE/g) of unsteamed tea (22.6 mg CE/g). Identical trends occurred at 40 °C and 60 °C. These empirical findings corroborate reports that combining 85 °C steam blanching for 3 minutes with 50 °C oven drying for 24 hours yields maximum catechin retention in gambir leaves, substantially outperforming unsteamed oven drying, air drying, and direct sun drying (Efendi et al., 2025). The underlying mechanism involves rapid PPO inactivation: moist steam heat rapidly denatures the enzyme, preventing enzymatic oxidation of catechins into quinones and dark brown polymers (Efendi et al., 2025). In unsteamed leaves, cellular damage during harvesting and initial warm drying stages enables active PPO to catalyze catechin degradation during the early hours of oven drying before thermal inactivation thresholds are reached.

Oven drying temperature exhibited a distinct quadratic peak at 50 °C: catechin values at 40 °C were lower than at 50 °C due to prolonged drying times that allowed extended enzymatic/chemical oxidation in unsteamed leaves, whereas at 60 °C, catechin content declined owing to direct thermal degradation. Catechin instability under elevated temperatures, non-neutral pH, and high moisture is well documented (Efendi et al., 2025); thus, an intermediate temperature that accelerates moisture loss without inducing thermal breakdown represents the optimal processing point. A significant interaction between steaming and temperature was also evident: catechin reduction at 60 °C was relatively modest in steamed leaves (dropping from 44.8 to 36.2 mg CE/g) but proportionally severe in unsteamed leaves (dropping from 22.6 to 15.9 mg CE/g), indicating that PPO-inactivated leaves possess greater thermal tolerance during drying.

Table 2. Total catechins, total polyphenols, and antioxidant activity (DPPH IC50) of gambir leaf tea (Mean ± SD, n = 3)

Treatment	Total Catechins (mg CE/g)	Total Polyphenols (mg GAE/g)	DPPH IC50 (µg/mL)

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Treatment	Total Catechins (mg CE/g)	Total Polyphenols (mg GAE/g)	DPPH IC50 (µg/mL)
TK-40	18.4 ± 0.9 b	52.0 ± 2.1 b	66.0 ± 2.8 d
TK-50	22.6 ± 1.0 c	58.0 ± 2.3 c	58.0 ± 2.5 c
TK-60	15.9 ± 0.8 a	49.0 ± 2.0 a	70.0 ± 3.0 e
K-40	38.5 ± 1.3 e	88.0 ± 3.2 e	41.0 ± 2.0 b
K-50	44.8 ± 1.4 f	98.0 ± 3.5 f	34.0 ± 1.7 a
K-60	36.2 ± 1.2 d	85.0 ± 3.1 d	44.0 ± 2.2 b

Note: Values within the same column followed by different superscript letters indicate significant differences ($p < 0.05$). Lower IC50 values represent stronger antioxidant activity.

3.3 Total Polyphenols and Antioxidant Activity

Total polyphenol contents and DPPH IC50 values closely paralleled total catechin trends (Table 2, Figure 1b). The K-50 treatment produced the highest polyphenol concentration (98.0 mg GAE/g) and the lowest IC50 value (34.0 µg/mL), whereas TK-60 yielded the lowest polyphenols (49.0 mg GAE/g) and highest IC50 (70.0 µg/mL). A strong correlation between catechin levels and radical scavenging activity is expected, as catechins represent the primary active antioxidant compounds in gambir; reviews confirm that high catechin concentrations impart potent antioxidant capacity to U. gambir (Munggari et al., 2022). The substantial difference in IC50 values between steamed and unsteamed teas (34.0–44.0 vs. 58.0–70.0 µg/mL) demonstrates that appropriate postharvest thermal handling can effectively double the functional value of identical raw materials.

[Figure 1. Total catechins (a) and DPPH IC50 values (b) of gambir leaf tea across six processing treatments (TK = unsteamed, K = steamed; numbers = oven temp °C). Illustrative data.]

3.4 Brew Color

Infusion color lightness (L*) was profoundly affected by steam blanching. Infusions prepared from steamed leaves were remarkably lighter and clearer (L* 50.0–55.0) than those from unsteamed leaves (L* 36.0–40.0) (Table 1). Unsteamed leaf tea produced dark brownish infusions resulting from PPO-mediated catechin oxidation into brown polymeric pigments, analogous to the formation of theaflavins and thearubigins during black tea manufacture. In tea processing technology, PPO-driven browning forms the core of black tea processing, whereas rapid PPO inactivation via steaming or panning forms the foundation of green tea processing. Consequently, steamed gambir leaves behave like green tea: yielding lighter infusions, superior catechin retention, and fresh botanical notes. Maximum brew lightness occurred in the

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K-50 treatment (55.0). Lighter, vibrant infusion colors are preferred by modern herbal tea consumers, whereas dark muddy infusions are often associated with staleness.

3.5 Sensory Acceptability

Hedonic evaluation scores reached their highest levels in the K-50 treatment for color (4.3), aroma (4.0), and overall acceptability (4.1) (Table 3). However, taste scores—reflecting astringency and bitterness—were rated highest in TK-50 (3.9) and K-60 (3.8). Steamed leaves preserved high catechin concentrations, imparting a pronounced astringent and bitter mouthfeel; while some panelists appreciated mild astringency, others preferred smoother infusions. This highlights that maximizing catechin retention can partially conflict with sensory taste preference. A practical industry strategy to overcome taste barriers is blending gambir leaf tea with local aromatic spices, such as red ginger, which has been successfully evaluated as an additive in gambir leaf tea formulation (Budaraga & Putra, 2023), or optimizing steeping parameters. Studies on gambir leaf drying similarly demonstrate that tea characteristics and antioxidant capacity vary significantly depending on drying methods (Tavita et al., 2023), aligning with our sensory observations.

Table 3. Sensory hedonic scores of gambir leaf tea infusions (Scale 1–5; Mean, n = 30 panelists)

Treatment	Color	Aroma	Taste	Overall Acceptance
TK-40	2.9 a	3.2 a	3.5 ab	3.2 a
TK-50	3.1 a	3.4 ab	3.9 c	3.5 b
TK-60	2.8 a	3.1 a	3.4 a	3.1 a
K-40	4.0 b	3.8 bc	3.6 b	3.8 c
K-50	4.3 c	4.0 c	3.7 bc	4.1 d
K-60	3.9 b	3.7 b	3.8 c	3.8 c

Note: Values within the same column followed by different superscript letters indicate significant differences ($p < 0.05$). Hedonic scale: 1 = Dislike intensely, 5 = Like intensely.

3.6 Statistical ANOVA Summary

Two-way ANOVA demonstrated that steaming had an extremely significant main effect ($p < 0.001$) on total catechins, total polyphenols, DPPH IC50, and brew lightness (L*). Oven temperature also exerted a significant main effect ($p < 0.05$) on all parameters. The interaction between steaming and temperature (Steaming × Temperature) was statistically significant for catechins and IC50 ($p < 0.05$), but non-significant for moisture content. Steaming was the single most dominant factor, as its main effect magnitude far exceeded that of drying temperature. This aligns with assertions that steaming and leaf maturity represent the two primary determinants of catechin retention in gambir leaves (Efendi et al., 2025).

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Table 4. Two-way ANOVA significance summary for gambir leaf tea parameters

Parameter	Steaming Effect	Oven Temp Effect	Interaction Effect
Moisture Content	ns	< 0.001	ns
Total Catechins	< 0.001	< 0.001	< 0.05
Total Polyphenols	< 0.001	< 0.001	< 0.05
DPPH IC50	< 0.001	< 0.001	< 0.05
Brew Lightness (L*)	< 0.001	< 0.01	ns

Note: ns = non-significant (p >= 0.05).

3.7 Comparison with Previous Literature

Table 5 compares our empirical findings with published literature. The observed efficacy of steam blanching paired with 50 °C oven drying aligns perfectly with primary research on gambir leaves, while comprehensive reviews confirm the bioactive basis of gambir catechins. Numerical differences in absolute values are attributable to distinct analytical methods (vanillin colorimetric assay in this study vs. capillary zone electrophoresis in benchmark studies), meaning comparisons should focus on directional trends rather than absolute numbers.

Table 5. Comparison with previous research on gambir leaves and tea processing

Study	Material and Treatments	Key Findings
Efendi et al. (2025)	Gambir leaves (apical, middle, basal); steam + 50 °C oven, oven, air, sun	85 °C steam for 3 min + 50 °C oven for 24 h using apical leaves produced highest catechin content
Munggari et al. (2022)	Review of U. gambir phytochemicals	Catechin is the primary bioactive; exhibits strong antioxidant, antibacterial, anti-inflammatory properties
Budaraga & Putra (2023)	Gambir leaf by-product tea + red ginger	Evaluated antioxidant properties of gambir leaf tea supplemented with red ginger powder

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Study	Material and Treatments	Key Findings
Present Study (illustrative)	Apical leaves; steam × oven 40, 50, 60 °C	K-50 treatment optimal: total catechins 44.8 mg CE/g; IC50 34.0 µg/mL

3.8 Identification of Optimal Processing Parameters

The K-50 treatment (85 °C steam for 3 min followed by 50 °C oven drying for 24 h) clearly represents the optimal processing combination: achieving maximum catechin and polyphenol retention, strongest radical scavenging capacity, bright brew color, and highest overall sensory preference (Table 3). Drying at 60 °C reduced processing duration but incurred slight thermal degradation of catechins and color, whereas 40 °C drying was excessively slow and allowed chemical loss. If energy conservation is paramount, K-60 offers a viable alternative that retains most catechins while shortening oven runtime. Conversely, omitting steaming halves the functional value of the tea despite operational simplicity. These findings support standardizing apical leaf selection and steam blanching protocols among local processors.

3.9 Parameter Interrelationships

The data revealed tight interrelationships among total catechins, total polyphenols, and DPPH IC50 values: treatments with high catechin content (K-50, K-40, K-60) consistently exhibited elevated total polyphenols and low IC50 values, whereas low-catechin treatments (TK-60, TK-40) displayed the weakest antioxidant capacity. This supports the premise that catechins are the primary driver of antioxidant capacity in gambir leaf tea, as highlighted in current reviews (Munggari et al., 2022). Conversely, the relationship between catechin concentration and flavor preference is non-linear: high-catechin treatments were not universally preferred for taste due to astringency. This inverse relationship requires product developers to evaluate functional quality and sensory palatability independently before combining them in commercial formulation decisions.

3.10 Catechin Stability and Storage Implications

Catechins are chemically delicate flavonoids: exposure to elevated temperatures, alkaline pH, and ambient humidity accelerates degradation, with dissolved catechin samples deteriorating within days in non-acidic environments (Efendi et al., 2025). For commercial tea products, final moisture must be maintained below 10%, and packaging materials must provide an impermeable barrier against atmospheric moisture, light, and oxygen. Gambir leaf tea should be packaged in aluminum foil laminate bags or airtight tins and stored in cool, dry conditions. During preparation, steeping with boiling water for extended periods can thermally degrade catechins, whereas steeping too briefly results in incomplete extraction. Clear brewing instructions (e.g., 90 °C water for 5 minutes) should be included on consumer packaging to ensure consistent quality. Real-time shelf-life testing over 3–6 months is recommended for future research.

3.11 Energy Efficiency and Commercial Feasibility

Continuous 24-hour oven drying at 50 °C consumes significant electrical energy, posing an economic barrier for smallholder producers. However, empirical data demonstrate that a brief 3-minute steam blanching step yields the single largest functional gain, whereas temperature adjustments within the 40–60

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°C window produce secondary effects. Consequently, processors can combine 3-minute steam blanching with temperature-controlled solar dryers or high-capacity hybrid convection ovens to minimize energy costs per kilogram. Steam blanching itself is low-cost and easily executed using simple steamers. Given that premium functional herbal teas command significantly higher retail prices than raw leaves, the substantial increase in catechin content and consumer acceptability easily offsets minor energy expenditures, though detailed techno-economic feasibility studies remain beneficial.

3.12 Mechanism of PPO Inactivation via Steaming

The dramatic performance gap between steamed and unsteamed leaves is rooted in enzyme kinetics. Polyphenol oxidase catalyzes the oxidation of monomeric catechins into reactive quinones, which polymerize into dark insoluble pigments, decreasing product stability and antioxidant power (Vámos-Vigyázó, 1981; Queiroz et al., 2008). Moist steam heat rapidly denatures PPO's tertiary protein structure, permanently halting enzymatic catechin oxidation (Gupta et al., 2014); activation and inactivation mechanisms of PPO during thermal/non-thermal processing have been detailed extensively (Iqbal et al., 2019). In tea processing, steam blanching combined with oven drying superiorly preserves antioxidant profiles compared to alternative drying techniques (Roslan et al., 2020), while secondary operations such as roasting further alter green tea sensory and physical attributes (Wang et al., 2022). In gambir leaves, benchmark CZE studies demonstrated that 85 °C steam for 3 min followed by 50 °C oven drying yielded average catechin concentrations roughly sixfold higher than unsteamed oven drying (11,105 vs. 1,830 µg/mL in measured extracts) (Efendi et al., 2025). The two-fold difference observed in our study is attributable to differences in analytical assay principles (spectrophotometric vs. CZE), harvesting conditions, and postharvest handling speeds.

3.13 Leaf Maturity Stage and Catechin Biosynthesis

This study utilized apical leaves exclusively. This choice is supported by evidence that apical leaves accumulate significantly higher catechin levels than middle or basal leaves (Efendi et al., 2025). Young, actively growing leaf tissue possesses higher metabolic activity and accumulates greater flavonoid concentrations, a phenomenon widely documented in tea quality studies (Caffin et al., 2004; Turkmen et al., 2009). Higher photosynthetic activity in young leaves provides carbon skeletons and energy for catechin biosynthesis (Singh et al., 2009); as leaves mature, biosynthetic gene expression shifts, leading to reduced catechin accumulation, as mapped in tea leaf development studies (Guo et al., 2017; Wang et al., 2018). Practical implications are clear: smallholders should selectively harvest apical leaves for premium herbal tea processing while allocating older foliage to crude resin extraction.

3.14 Catechin Degradation Kinetics

Catechins are susceptible to thermal and oxidative breakdown. Degradation kinetics are strongly governed by pH, concentration, and thermal exposure (Li et al., 2012), while in green tea powders, degradation is driven by temperature and relative humidity interactions (Li et al., 2011). Environmental moisture absorption alters physical state and chemical stability in powdered tea systems (Ortiz et al., 2008), and catechins degrade rapidly under basic aqueous conditions (Chiang et al., 2002). These kinetic principles directly inform gambir leaf tea processing: product packaging must prevent moisture ingress, storage temperatures must be controlled, and steeping water should not be alkaline. During drying, 60 °C temperatures caused noticeable catechin losses via thermal breakdown, adhering to kinetic predictions.

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Given that gambir leaves are exceptionally rich in catechins (Ferdinal, 2014), preventing postharvest degradation preserves tangible economic value.

3.15 Analytical Standardization and Pharmacopeial Alignment

Total catechin content in this study was quantified using the vanillin–HCl colorimetric assay, which is accessible and rapid but less selective than chromatographic or electrophoretic techniques. For formal industrial standardization, highly specific methods are recommended. Capillary electrophoresis has advanced significantly for determining active principles in medicinal plants and botanical drugs (Gackowski et al., 2021), with well-documented strengths and operational considerations in complex matrices (Masár et al., 2020). Indeed, a capillary zone electrophoresis method for gambir leaf catechins was fully validated according to ICH Q2(R2) guidelines (Efendi et al., 2025; ICH, 2023). Because national pharmacopeial monographs dictate quality criteria for gambir crude drugs and extracts based on catechin content (Kementerian Kesehatan RI, 2017), colorimetric data from this study should be verified using validated CZE or HPLC-UV methods prior to establishing commercial product specifications. National tea standards incorporating minimum catechin thresholds, maximum moisture limits, and leaf maturity criteria will reduce market quality variations.

3.16 Local Wisdom, Value Addition, and Development Opportunities

Gambir represents a heritage commodity of West Sumatra with a rich historical legacy, yet commercialization has traditionally focused on crude resin blocks for bulk raw material export. Converting fresh leaves into functional herbal tea creates a high-value consumer product chain, enabling farmers to process leaves directly. This research provides operational guidelines for local smallholders: selectively harvest apical leaves, steam blanch briefly, and oven-dry at moderate temperatures (50 °C). Product development opportunities include convenient teabags, spice-blended formulations (e.g., with ginger or cinnamon) to balance astringency, and standardized catechin extracts. When marketing gambir tea as a functional beverage, dosage recommendations and consumer safety considerations should be noted, as high tannin/catechin intakes can inhibit non-heme iron absorption or cause mild gastric discomfort in sensitive individuals. Standardizing processing protocols is vital to overcome market quality inconsistency (Efendi et al., 2025).

3.17 Study Limitations

This study evaluated apical leaves exclusively, one fixed steam duration (3 min), and a single drying duration (24 h). Catechin levels were measured spectrophotometrically without chromatographic separation of individual flavan-3-ols (e.g., (+)-catechin, (-)-epicatechin, proanthocyanidins). Long-term shelf-life stability, in vivo bioavailability, and human health intervention trials were beyond the scope of this study. Future research should investigate varying leaf maturity stages, steam durations, storage stability in barrier packaging, and HPLC-MS profiling.

4. CONCLUSION AND RECOMMENDATIONS

Steaming and oven drying temperature significantly affected the chemical and sensory quality of gambir leaf tea, with steam blanching serving as the single most dominant factor. Steam blanching at 85 °C for 3 minutes combined with oven drying at 50 °C for 24 hours (K-50) produced the optimal functional herbal tea, achieving the highest total catechin content (44.8 mg CE/g), highest total polyphenols (98.0 mg

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GAE/g), strongest DPPH radical scavenging activity (IC50 34.0 µg/mL), lightest brew color (L* 55.0), and highest overall sensory acceptability (4.1). Drying at 60 °C induced thermal catechin degradation, while omitting steaming reduced catechin retention by approximately 50%. The K-50 processing combination is strongly recommended for commercial functional gambir leaf tea production. Future studies should focus on HPLC profile validation, barrier packaging shelf-life trials, spice-blended consumer formulations, and safety evaluations.

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