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Research Article

Polyphenols and Antioxidant Activity of *Thunbergia laurifolia* Infused Tea under Drying Conditions

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Thunbergia laurifolia leaf is used in Thai herbal medicine to moderate alcohol, food poisoning, and other health-related diseases mainly due to its overwhelming phytochemical compounds which exert several biological functions such as antioxidant, and anti-inflammatory properties, among others. This study investigated the potential effects of hot air-drying conditions (TL-D80°C, TL-D90°C, and TL-D100°C) of *T. laurifolia* tea leaves on phenolic compounds, total flavonoid content (TFC), total phenolic content (TPC), and antioxidant activities (AOA) of the infused teas. The results show that an increase in drying temperature significantly ($p < 0.05$) improved TPC (709.7 ± 1.36–744.8 ± 5.79 mg GAE/) and TFC (198.98 ± 7.59–207.16 ± 4.10 mg RE/L) of infused teas. TL-D80°C (69.9 ± 0.95%) and TL-D90°C (69.3 ± 0.7%) infused teas showed significantly ($p < 0.05$) higher DPPH inhibitory effect compared to TL-D100°C. Treatment had no effects ($p > 0.05$) on $ABTS^{\cdot+}$ scavenging activity. The phenolic compounds detected in infused teas were rosmarinic acid, caffeic acid, gallic acid, catechin, rutin, and quercetin. Regarding, the cumulative phenolic compounds TL-D100°C infused teas were significantly higher ($p < 0.05$) compared to TL-D90°C and TL-D80°C. The results suggest that drying conditions (i.e., TL-D100°C within 30 min) could be used to achieve appropriate moisture content of *T. laurifolia* tea leaves without compromising the phytochemical compositions and antioxidant potentials of the resulting infused teas.

1. Introduction

Tea is a non-alcoholic beverage consumed globally after water and beer [1]. Tea can be produced from different types of plant leaves and is mostly classified as herbal tea and non-herbal tea [2]. Non-herbal teas are processed from the leaves of *Camellia sinensis* (Family Theaceae) and categorized as Oolong, black, and green teas based on the degree of leaf fermentation [3]. Herbal teas on the other hand are processed from the various part of the plant (i.e., leaves, flowers, and roots) owing to their health benefits [1, 4, 5]. *Thunbergia laurifolia* is overwhelmed with phytochemical compounds thus various parts may potentially be processed into herbal tea. Collectively, the constituents extracted from leaves or root biomass contain secondary metabolites, also referred to as phytochemicals, which contain a variety of natural products including phenolic compounds and flavonoids [4].

T. laurifolia is a local Thai plant popularly known as "Rang Jued". Previous reports showed that *T. laurifolia* leaves possessed phytochemical constituents (i.e., apigenin, caffeic acid, catechin, rosmarinic acid, rutin, and quercetin) [6, 7] thus exerts several biological functions such as antioxidant, anti-inflammatory, detoxification, and anticancer potentials [8]. Various parts (leaves, stems, etc.) of *T. laurifolia* have been incorporated into Thai herbal medicine as herbal tea to curb alcohol, food poisoning, and other ailments [9]. The recent surge in large-scale processing of the *T. laurifolia* plant (leaves, stems, etc.) into herbal teas and capsules in several Thai herbal industries may be attributed to the beneficial health effects that stem from its polyphenols [10]. The phytochemical constituents of *T. laurifolia* leaf may be influenced by several tea processing factors such as leaf

drying, withering, and fermentation. However, the current study focused on drying because it is the last step in tea processing.

Traditionally, hot-air drying is a widely used method of dehydrating leaves and other food products due to its cost-effectiveness [11]. Generally, drying improves shelf-life and quality stability by reducing moisture content, thus, inhibiting microbial growth and other biochemical reactions which can alter the organoleptic properties of tea [12]. Likewise, high drying temperatures (>100°C) with extended duration may deteriorate heat-sensitive phenolic compounds [5, 13], thus decreasing the antioxidant and other biological effects of tea [14].

Therefore, this study evaluated the effect of hot air-drying conditions on phenolic compounds and the antioxidant activities of *T. laurifolia*-infused teas.

2. Materials and Methods

2.1. Chemical and Reagents. Sodium carbonate crystal (Na_2CO_3, 105.99 g/mol), sodium acetate (CH_3COONa, 82.03 g/mol), and aluminum chloride ($AlCl_3$, 241.43 g/mol) were sourced from Ajax Finechem (Albany, Auckland, New Zealand). Methanol (MeOH, 99.8% purity) reagent was purchased from Honeywell Burdick and Johnson (Cheoyong-ro, Nam-gu, Ulsan, South Korea). Gallic acid, rutin, 2,2′-Azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS, 548.68 g/mol), Folin-Ciocalteu reagent, and 2,2-diphenyl-1-picrylhydrazyl (DPPH, 394.32 g/mol) were obtained from Sigma–Aldrich (St Louis, Mo, USA). All chemicals used were of analytical grades.

2.2. Plant Material. Disease-free fresh *T. laurifolia* leaves were obtained from Kasetsart University, Bangkok, Thailand. The leaves were harvested in consultation with the Kasetsart University Botanical Garden to identify the right specie. The leaves were instantly transported in clean ziplock polypropylene clear bags (Thai Modern Industries Co., Ltd., Bangkok, Thailand) to the laboratory, washed with distilled water, dried, and processed into tea samples.

2.3. Tea Processing and Hot Air-Drying Conditions. The fresh *T. laurifolia* leaves were processed into tea powder using an orthodox black tea processing method with minor modifications [15]. The leaves were withered at 30 ± 2°C (12 h), hand-rolled (25 min), and allowed to ferment at 25 ± 2°C for 60 min. The fermented leaves (50 g) were evenly spread on a rectangular tray (21″ length × 16″ width × 0.75″ height) and placed in a hot-air oven (Memmert model 100–800, Schwabach, Germany). Drying temperatures of 80°C (TL-D80°C), 90°C (TL-D90°C), and 100°C (TL-D100°C)) were used with oven fan speed set at 100%. The samples were dried for 30 min in triplicate experiments. The dried tea leaves were milled into tea powder using a laboratory blender (Tefal Blendforce, China), sieved via 425 μm mesh, and stored in ziplock bags at -20°C until further analyses.

2.4. Moisture Content Analysis. The moisture contents (% w/w) of fresh *T. laurifolia* leaves and tea powder were determined according to a previously reported procedure [16]. Approximately, samples (3 g) were measured into pre-dried weighed moisture can and placed in a hot-air oven (Memmert model 100–800, Schwabach, Germany) at 105°C for 3 h. The cans with samples were cool to 25 ± 2°C in a desiccator for 30 min. The experiments were repeated in triplicate. The moisture content (% w/w) was calculated using the following formula:

$$\text{Moisture content}\,(\%\, w/w) = \frac{M_x - M_f}{M_x} \times 100, \quad (1)$$

where M_x is the initial weight of the sample before drying and M_f is the final weight of the sample after drying.

2.5. Tea Infusion Procedure. T. laurifolia teas were brewed following the ISO 3013:2019 procedure [17]. The tea powder (2 g) of each drying treatment was suspended in separate hot (90°C) deionized water (300 mL) in a beaker for 30 min with continuous stirring (150 rpm) using an overhead stirrer (IKA RW 20, Vietnam). Infused teas were filtered through a Whatman No. 4 filter paper (model 1004-090, pore size 20–25 μm, 90 mm (Cole-Parmer, Vernon Hills, USA) and stored in 250 mL amber bottled (Duran Group GmbH, Wertheim/Main, Germany) at −20°C for further analyses. This experiment was repeated in triplicate.

2.6. Physiochemical and Phytochemical Analysis

2.6.1. pH. The pH of infused teas in triplicate analyses was determined using a digital pH meter (Mettler ToledoTM, UK).

2.6.2. Total Phenolic Content (TPC). The total phenolic content of infused teas was measured based on the modified Folin–Ciocalteu method [18]. Briefly, 200 μL of standard (gallic acid) or infused teas were transferred into respective test tubes (10 mL). A volume of 1.4 mL Folin–Ciocalteu (10-fold dilution) was added, vortexed, and incubated for 5 min in a dark cabinet at 25 ± 2°C. Sodium carbonate (7.5% (w/v)) was added (1.8 mL), vortexed, and incubated for an hour in dark cabinet at 25 ± 2°C. The absorbance was determined using an ultraviolet-visible (UV-Vis) spectrophotometer (Shimadzu UV-1800, Tokyo, Japan) at a wavelength of 725 nm against distilled water. The TPC was calculated from the gallic acid standard curve ($y = 0.0059x + 0.0618$, $R^2 = 0.9918$ (Figure S1*)* and expressed as milligram gallic acid equivalent (GAE) per liter of tea (mg GAE/L).

2.6.3. Total Flavonoid Content (TFC). The total flavonoid content of infused teas was measured based on the modified aluminum chloride colorimetry method [19, 20]. Briefly, infused teas (0.5 mL) 2.5% (w/v) $AlCl_3$ (0.4 mL), 10% (w/v) CH_3COONa (0.5 mL), and 30% (v/v) MeOH (4 mL) were pipetted into test tubes and thoroughly mixed. The mixtures were allowed to stand for 15 min in a dark cabinet at 25 ± 2°C. The absorbance was measured at 430 nm using a UV-Vis spectrophotometer (Shimadzu UV-1800, Tokyo, Japan). The TFC was calculated from the rutin calibration

curve ($y = 0.0028x + 0.0679$, $R^2 = 0.9966$) and expressed as milligram rutin equivalent per liter of tea (mg RE/L) (Figure S2).

2.7. Antioxidant Activities (AOA)

2.7.1. DPPH Radical Scavenging Activity. The DPPH radical scavenging activity of infused teas was measured according to the previously described method [18, 20]. An aliquot (0.1 mL) of infused teas was mixed with 2.9 mL methanolic DPPH solution (60 μM) in assay tubes. The control samples were prepared similarly without infused teas. The tubes were incubated in a dark cabinet for an hour at 25 ± 2°C and absorbance was measured at 517 nm wavelength using a UV-Vis spectrophotometer (Shimadzu UV-1800, Tokyo, Japan) against methanol. DPPH-radical scavenging activity of infused teas was calculated using the following formula:

$$\text{Inhibition percentage} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100. \quad (2)$$

2.7.2. $ABTS^{\cdot+}$ Radical Scavening Activity. $ABTS^{\cdot+}$ antioxidant activity of infused teas was measured by the ABTS assay as previously described [18]. Briefly, $ABTS^{\cdot+}$ (7 μM) was mixed with 2.45 mM potassium persulfate in a 10 mL volumetric flask and incubated in a dark cabinet for 16 h at 25 ± 2°C. The mixture was diluted with distilled water to obtain an absorbance of ~0.700 ± 0.02 at 734 nm. The infused teas (0.1 mL) were mixed with $ABTS^{\cdot+}$ solution (2.9 mL) in separate assay tubes. The control samples were prepared similarly without infused tea. The mixture was vortexed and incubated in a dark cabinet at 25 ± 2°C for 20 min. The absorbance was measured with a UV-Vis spectrophotometer (Shimadzu UV-1800, Tokyo, Japan) at 734 nm against distilled water as blank. $ABTS^{\cdot+}$-radical scavenging activity of infused teas was calculated using the following equation:

$$\text{Inhibition percentage} = \frac{\text{Absorbance of control} - \text{Absorbance of sample}}{\text{Absorbance of control}} \times 100. \quad (3)$$

2.8. Analysis of Individual Phenolic Compounds. The individual phenolic compounds of the infused teas were measured using high-performance liquid chromatography (Shimazu, Tokyo, Japan) with a UV-Vis detector (SPD–20A Prominence, Shimazu, Tokyo, Japan) [18]. The mobile phase of the gradient elution system consisted of 2% v/v) acetic acid (solvent A) and 100% (v/v) acetonitrile (solvent B) at a flow rate of 0.8 mL/min for 90 min (Table S1) with 20 μL injection volume. The column temperature was set at 35°C. The standard solutions or infused teas were filtered via a 0.20-μm nylon filter and manually injected. Separation of phenolic compounds was conducted using a 250 mm × 4.6 mm × 5 μm Luna C_{18} column (Phenomenex, Torrance, USA). Methanolic solution of rosmarinic acid, caffeic acid, gallic acid, quercetin, catechin, and rutin at a concentration of 0.01–0.08 mM was used to generate calibration curves. The phenolic compounds were detected at 280 nm (gallic acid, quercetin, and catechin) and 320 nm (rosmarinic acid, caffeic acid, and rutin). The concentrations of phenolic compounds (μM/mL) were calculated from the calibration curves.

2.9. Statistical Analysis. The data obtained were reported as mean ± standard deviation of triplicate measurements using Minitab 18 (Minitab, LLC, PA, USA). Turkey test was used for comparisons of the treatment means ($p < 0.05$).

3. Results and Discussion

3.1. Moisture Content. The moisture content of fresh *T. laurifolia* leaves on a wet basis was 84.18 ± 0.76% (Figure 1). The dried samples had moisture content that ranged between 5.6 ± 0.19%–9.7 ± 0.33%. The increase in temperature during drying significantly ($p < 0.05$) influenced the moisture content of the processed leaves. *T. laurifolia* leaves dried at TL-D80°C had ($p < 0.05$) higher moisture content (9.7 ± 0.33% (w/w)) compared to TL-D90°C (6.2 ± 0.19% (w/w)) and TL-D100°C (5.6 ± 0.19% (w/w)) samples. The stability of tea phytochemical compounds during storage was influenced by the moisture content [15]. In addition, drying preserved the phytochemical constituents of tea leaves [14]. Previous report showed that high moisture content supported microbial growth and triggered the deterioration of tea phytochemicals [21]. Wang et al. [22] reported that a decrease in moisture content tea and enhanced tea aroma. Others have demonstrated that high drying temperatures (>100°C) with extended periods hardened and burnt tea leaves, thus degrading phytochemical composition due to extremely low moisture content [15]. The moisture content of tea leaves dried at TL-D90°C and TL-D100°C (Figure 1) were consistent with the recommended moisture content of herbal teas (>8% w/w) [23]. The current results demonstrate that drying *T. laurifolia* leaves at TL-D90°C and TL-D100°C for 30 min were effective to achieve appropriate moisture content.

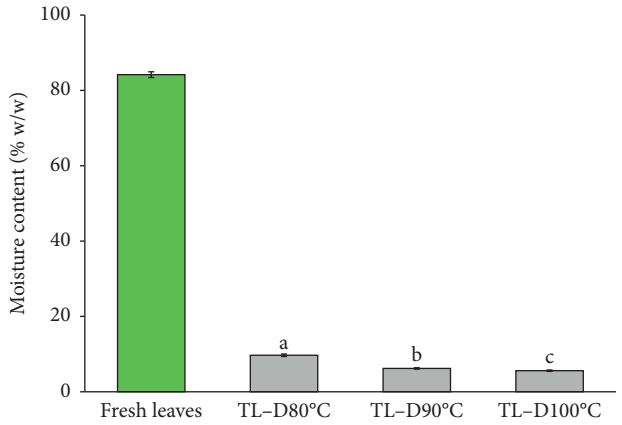

Figure 1: Moisture of fresh and dried *T. laurifolia* tea leaves. Data expressed are mean ± standard deviation of triplicate measurements. Bars with distinct letters differ significantly at $p < 0.05$ using Tukey's mean comparison test.

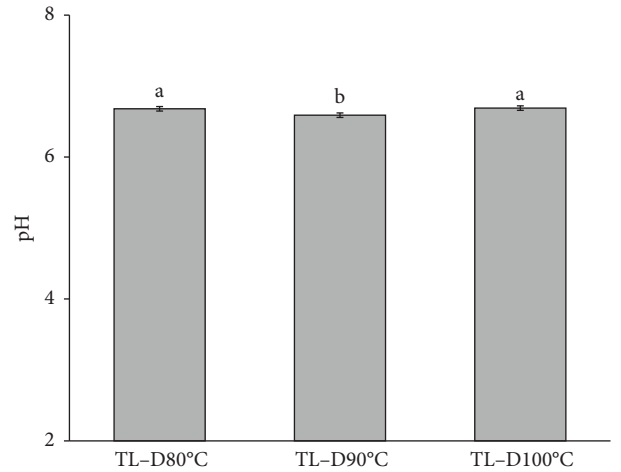

Figure 2: pH of *T. laurifolia*-infused teas. Data expressed as mean ($n = 3$) ± standard deviation. Bars with distinct letters indicate statistical difference ($p < 0.05$) from Tukey's multiple comparison tests of means.

3.2. pH. The pH of teas brewed ranged between 6.59 ± 0.01–6.69 ± 0.01 (Figure 2). TL-D100°C and TL-D80°C had significantly ($p < 0.05$) higher pH values compared to TL-D90°C although, a very minimal difference in pH value (0.1 pH unit) was observed among treatments. The present results were consistent with previously reported pH of herbal teas [24].

3.3. Bioactive Compounds. Folin-Ciolcateu (F-C) assay has been extensively used to evaluate the total phenolic content (TPC) of plant-based products (i.e., tea) because of its ability to react with phenols [25]. However, the F-C assay is influenced by plant pigments (i.e., chlorophyll) due to their solubility in ethanol, methanol, and other organic solvents. Distilled water was used to brew the teas which isnot readily soluble compared to the organic solvents thus, reduces the possibility of extracting chlorophyll consequently not reacting with TPC measurements [26]. Drying had a significant effect ($p < 0.05$) on the concentration of bioactive compositions of infused tea (Figures 3(a) and 3(b)). The concentration of TPC ranged between 709.7 ± 1.36–744.8 ± 5.79 mg GAE/L. Specifically, TL-D100°C (744.8 ± 5.79 mg GAE/L) and TL-D90°C (744.00 ± 12.99 mg GAE/L) had significantly ($p < 0.05$) higher TPC compared to the TL-D80 (709.7 ± 1.36 mg GAE/L). The results were similar to previous findings where lemon myrtle leaves dried at 90°C for 75 min showed higher TPC than 70°C and 50°C [27]. The TPC of *T. laurifolia* aqueous leaf extract was 22.18 ± 1.269 mg GAE/g [28], and 24.33 ± 0.57 mg GAE/g [29].

The TFC of infused teas ranged between 198.98 ± 7.59–207.16 ± 4.10 mg RE/L. TL–D100°C (207.16 ± 4.10 mg RE/L) showed significantly higher TFC compared to TL–D90°C (200.6 ± 1.23 mg RE/L) and TL–D80°C (198.98 ± 7.59 mg RE/L). Green tea leaves dried at 100°C had higher TFC (38.18 mg Quercetin/g dry weight) compared to 80°C (25.62 mg Quercetin/g dry weight) [11]. Thinh et al, reported that *T. laurifolia* dried leaves (45°C for 3 days) extract with water had TFC of 1.33 ± 0.03 mg QE/g CE [30].

Tea polyphenols are sensitive and decompose at higher drying temperatures thus decreased the concentration [31, 32]. Also, low drying temperatures with a lengthy drying period can degrade tea polyphenols. Oven-dried (50°C with 5 h) *T. laurifolia* leaves showed a 78.6% decrease in TPC due to enzymatic degradation of polyphenols by oxidative enzymes such as polyphenol oxidase and peroxidase at low drying temperature with extended period [33]. Others have demonstrated that rapid drying at high temperatures with short duration deactivated oxidative enzymes, thus preserved phytochemicals [14, 34]. Phenolic compounds (i.e., flavonoids) are abundant plant phytochemicals that exert health-promoting factors (i.e., antimicrobial, antioxidant, anticarcinogenic, antimutagenicity, anti-inflammatory activities) on human beings [4, 35]. The health-promoting effects of plant phytochemicals have resulted in their use as food supplements or ingredients for designing functional foods [36].

The increased levels of TPC and TFC in TL-D100°C may be attributed to the rapid disruption of cellular structures of *T. laurifolia* leaves coupled with the inactivation of oxidative enzymes which improved polyphenol content [31].

3.4. Antioxidant Activities (AOA). The DPPH scavenging activity of infused teas ranged between 64.8 ± 0.75–69.9 ± 0.95% (Figure 4(a)). TL-D80°C (69.9 ± 0.95%) and TL-D90°C (69.3 ± 0.7%) infused teas showed significantly ($p < 0.05$) higher inhibitory effect compared to TL-D100°C. Interestingly, TL-D100°C infused tea had higher TPC and TFC (Figures 3(a) and 3(b)) compared to TL-D80°C and TL-D90°C but showed lower DPPH activity which may be attributed to the difference in antioxidant properties of leaves due to treatment. The $ABTS^{\cdot+}$ scavenging activity of infused teas ranged between 71.0 ± 2.75–73.1 ± 1.13% (Figure 4(b)) with no treatment effects ($p > 0.05$) which may be due to the synergistic and antagonistic effects among phenolics and other constituents.

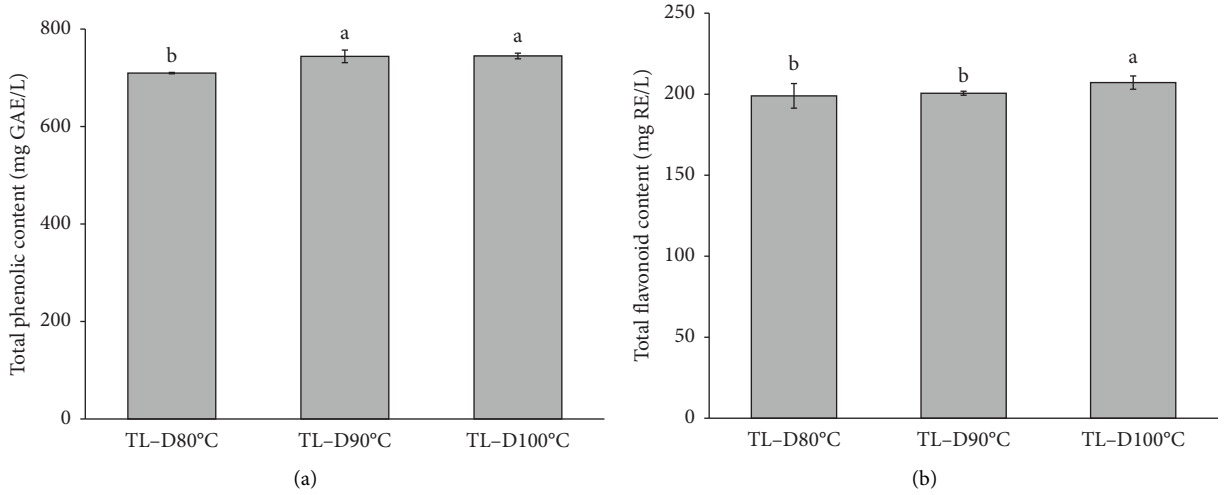

Figure 3: Total phenolic content (a) and total flavonoid content (b) of *T. laurifolia*-infused teas. Data expressed are mean ($n = 3$) ± standard deviation of triplicate measurements. Bars with distinct letters differ significantly at $p < 0.05$ using Tukey's mean comparison test.

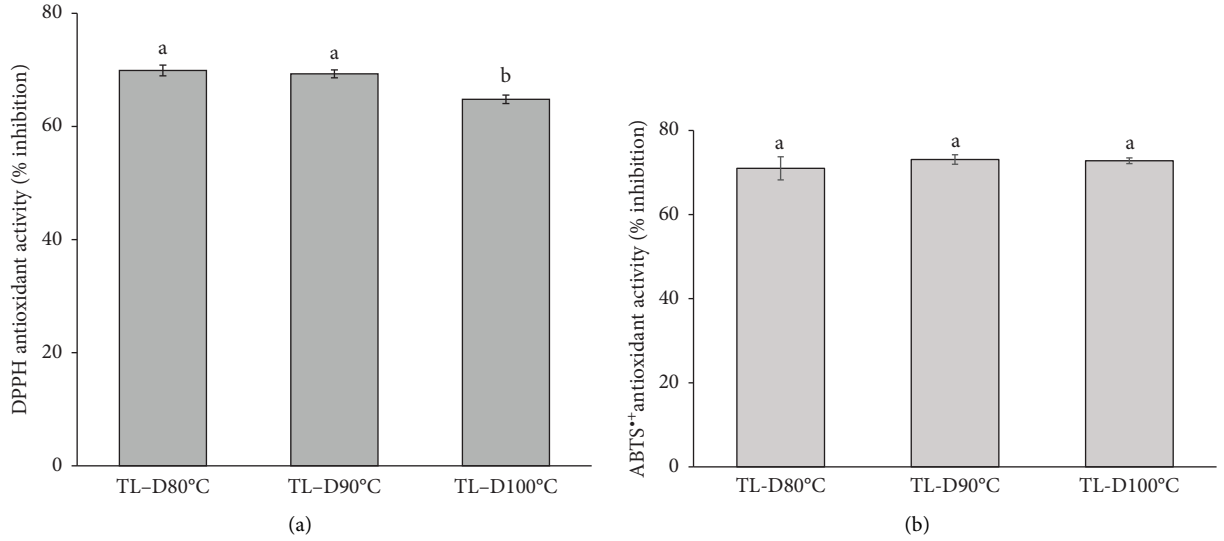

Figure 4: DPPH-scavenging (a) and $ABTS^{\cdot+}$scavenging activity (b) of *T. laurifolia* infused teas. Data expressed are mean ± standard deviation of triplicate measurements. Bars with distinct letters differ significantly at $p < 0.05$ using Tukey's mean comparison test.

The inhibition capacity of DPPH radical was lower compared to $ABTS^{\cdot+}$ scavenging assay which is consistent with previous findings [32, 37]. The difference observed could be ascribed to the variations in antioxidant assays and mechanistic actions of the antioxidant compound present in infused teas. ABTS + assay has high sensitivity and rapid reaction kinetics with phenolics thus affecting higher detection of AOA compared to DPPH assay [37]. Tea brewed from *Hibiscus cannabinus* leaves oven-dried at 80°C showed a higher DPPH radical scavenging activity (90.14%-91.65%) compared to leaves dried at 120°C (81.66%–90.04%) [38]. Furthermore, *Hibiscus sabdariffa* leaves oven-dried at 80°C and 100°C had higher DPPH radical scavenging activity compared to leaves dried at 60°C and 120°C [39]. Similarly, lemon myrtle leaves oven-dried at 90°C (75 min) showed higher $ABTS^{\cdot+}$ and DPPH AOA (1615.48 ± 24.98 and 963.56 ± 53.18 mM TE/g dry weight, respectively) than 70°C (105 min) and 50°C (314 min) [27], which implies that increasing drying temperature with short drying period preserves the bioactivity of phytochemicals than low drying temperature with extended drying time. Furthermore, *Acanthus ilicifolius* L. leaves oven-dried at 80°C and 100°C influenced the DPPH (503.82 ± 42.36 and 457.09 ± 35.67 mg TE/g dry weight, respectively) and $ABTS^{\cdot+}$ (954.99 ± 26.97 and 543.66 ± 29.28 mg TE/g dry weight, respectively) radical scavenging activity compared to leaves dried at 120°C and 140°C [40]. These findings confirm that *T. laurifolia* leaves have potent extractable polyphenolic compounds which exerts several biological effects such as antioxidant, anti-inflammatory, and anticancer [8, 9]. Thus, the concentration of bioactive compounds in *T. laurifolia* influenced the AOA due to the drying conditions. Therefore, drying conditions

Table 1: Concentration of individual phenolic compounds.

Phenolic compounds (μmol/mL)	Drying temperature		
	80°C	90°C	100°C
Rosmarinic acid	1149.1 ± 131.1^{b}	1157.3 ± 87.4^{b}	1670.8 ± 53.6^{a}
Caffeic acid	112.4 ± 16.0^{c}	130.0 ± 2.33^{b}	157.1 ± 2.01^{a}
Gallic acid	32.0 ± 2.76^{b}	18.9 ± 2.83^{c}	50.8 ± 0.96^{a}
Quercetin	30.90 ± 0.14^{c}	43.90 ± 2.99^{b}	92.3 ± 0.99^{a}
Catechin	16.0 ± 1.28^{b}	27.5 ± 0.70^{a}	13.6 ± 2.05^{b}
Rutin	33.0 ± 1.10^{b}	27.4 ± 4.17^{c}	40.9 ± 1.12^{a}
Cumulative phenolic compounds	1373.4 ± 33.0^{b}	1405.0 ± 7.14^{b}	2025.5 ± 9.19^{a}

Data expressed are mean ± standard deviation of triplicate measurements. Distinct letter in the same row shows significant differences ($p < 0.05$) using Tukey's mean comparison test.

Table 2: Pearson's correlation between phytochemical compounds and antioxidant activity of infused teas.

Variables R (R^2)	TPC	TFC	$ABTS^{\cdot+}$	DPPH
TFC	0.668 (0.4464)			
$ABTS^{\cdot+}$	0.994* (0.9874)	0.747 (0.1173)		
DPPH	−0.606 (0.3676)	−0.997* (0.9936)	−0.692 (0.4785)	
Rosmarinic acid	0.529 (0.2797)	0.985* (0.9699)	0.621 (0.3854)	−0.996* (0.9912)
Caffeic acid	0.811 (0.657)	0.977* (0.9551)	0.871 (0.7589)	−0.957* (0.9162)
Gallic acid	0.122 (0.150)	0.82 (0.6728)	0.233 (0.543)	−0.863 (0.7456)
Quercetin	0.679 (0.1605)	1.00* (0.9998)	0.757 (0.5727)	−0.996* (0.9811)
Catechin	0.335 (0.1121)	−0.477 (0.2279)	0.227 (0.515)	0.546 (0.2985)
Rutin	0.118 (0.139)	0.818 (0.6684)	0.228 (0.522)	−0.861 (0.7415)
CPC	0.553 (0.3063)	0.989* (0.9791)	0.643 (0.4141)	−0.998* (0.9954)

Pearson's correlation coefficient (R); coefficient of determination (R^2). The data in parentheses indicates the R^2 value. *Significance correlation at 95% confidence level ($p < 0.05$).

(TL-D90°C and TL-D100°C for 30 min) were appropriate to preserve the natural antioxidant compounds of infused teas.

3.5. Composition of Phenolic Compounds. Table 1 shows the effect of drying conditions on the concentration of individual phenolic compounds. Rosmarinic (RA) and caffeic acids (CA) were the dominant phenolic compounds detected the *T. laurifolia* infused teas with concentrations between 1149.1 ± 131.1–$1670.8 \pm 53.6\,\mu$mol/mL and 112.4 ± 16.0–$157.1 \pm 2.01\,\mu$mol/mL, respectively. In addition, the concentration of RA and CA increased with an increase in drying temperatures. Specifically, TL-D100°C showed significantly ($p < 0.05$) higher concentrations of CA and RA compared to TL-D90°C and TL-D80°C. Treatment had a significant effect ($p < 0.05$) on the concentration of gallic acid (GA). TL = D100°C had a significantly ($p < 0.05$) higher concentration of GA compared to TL-D80°C and TL-D90°C. Quercetin (QN) and rutin (RN) were the abundant flavonoid compounds detected in the infused teas with concentrations ranging from 30.90 ± 0.14–$92.3 \pm 0.99\,\mu$mol/mL and 27.4 ± 4.17–$40.9 \pm 1.12\,\mu$mol/mL, respectively. TL-D100°C infused teas exhibited statistically ($p < 0.05$) higher concentrations of QN and RN compared to TL-D80°C and TL-D90°C. Also, TL-D90°C teas had significantly ($p < 0.05$) higher catechin (CN) concentration than TL-D80°C and TL-D100°C.

In addition, treatment had a significant effect ($p < 0.05$) on the cumulative phenolic compounds (CPC) of *T. laurifolia*-infused teas with concentrations ranging between 1373.4 ± 33.0–$2025.5 \pm 9.19\,\mu$mol/mL (Table 1). TL-D100°C infused teas had significantly ($p < 0.05$) higher CPC followed by TL-D90°C and TL-D80°C been the lowest.

Previous studies detected CA, RA, QN, RN, and CN in *T. laurifolia* extract [7, 41] which corresponded with the the current study.

Report showed that drying temperature (88°C) influenced the concentration of phenolic compounds by deactivating oxidative enzymes [42]. Also, elevated drying temperatures with shorter durations degraded cell structures thus increased the leaching of phenolic constituents into infused teas [31]. Temperature above 74°C increased extraction by ~37% of the total phenolics of dried citrus pomace [43]. Among the treatments investigated, TL-D100°C for 30 min was suitable condition to retain the appropriate concentration of TPC, TFC, and total phenolic compounds with potent AOA. Nonetheless, the efficacy of drying conditions is relatively dependent on the compound of interest.

3.6. Correlation of Phytochemical Compounds and Antioxidant Activities. Table 2 shows the correlation between phytochemical compounds and the AOA of *T. laurifolia*-infused teas. There was a significant positive correlation between TPC and $ABTS^{\cdot+}$ ($R = 0.994$) whereas TPC correlated negatively with DPPH ($R = -0.606$) which is associated with the effect of different drying temperatures on TPC, thus increasing drying temperature was linked with an increase in

TPC but did not lead to high AOA via DPPH assay but vice versa as observed with $ABST^{\cdot+}$ assay, which might be associated with derived compounds formed at drying at higher temperatures (100°C) for 30 min and are less reactive inmethanolic DPPH solution relative to $ABTS^{\cdot+}$solution. Hence, a positive correlation was observed between TFC and $ABTS^{\cdot+}$ ($R = 0.747$) whilst TFC showed a significant negative correlation with DPPH ($R = -0.997$) $ABTS^{\cdot+}$.

RA showed a strong positive correlation with TFC ($R = 0.985$) compared to TPC ($R = 0.529$). In addition, RA correlated positively and negatively with ABTS and DPPH, respectively. Likewise, CA showed a strong positive correlation with TPC ($R = 0.811$) and TFC ($R = 0.985$). GA showed a strong positive and weak correlation with TFC ($R = 0.82$) and TPC ($R = 0.122$), respectively.

$ABTS^{\cdot+}$ and DPPH showed a positive and negative correlation with CA, respectively. GA positively correlated with ABTS whilst negatively aligned with DPPH. Additionally, CN showed a weak positive ($R = 0.335$) and negative ($R = -0.477$) correlation with TPC and TFC. There was a significant positive correlation between QN and TFC ($R = 1.00$). Also, a positive correlation was observed between QN and TPC ($R = 0.679$). The relationship between RN and TFC was strongly correlated ($R = 0.818$) compared to RN and TPC ($R = 0.118$). CN ($R = 0.227$) and RN ($R = 0.288$) showed a weak positive correlation with $ABTS^{\cdot+}$. In contrast, CN showed a moderate correlation with DPPH whilst RN showed a strong negative correlation with DPPH ($R = -0.861$). The relationship between DPPH and $ABTS^{\cdot+}$ was negatively correlated ($R = -0.692$). The correlations observed in the current study were similar to previous reports [44, 45]. CPC correlated positively and negatively with $ABTS^{\cdot+}$ and DPPH, respectively.

4. Conclusion

Considering the increase in consumption of *T. laurifolia* leaves in the form of herbal teas and capsules in recent times, it is imperative to use the best drying conditions that preserve the bioactive compounds. Among the drying conditions screened, TL-D100°C for 30 min preserved the appropriate moisture content of *T. laurifolia* tea leaves without degrading the phytochemical constituents and antioxidant potentials of the resulting infused teas. These results revealed that drying conditions significantly ($p < 0.05$) influenced the concentration of bioactive compounds in the infused teas.

Data Availability

The data supporting the findings of the current study are included in the article.

Conflicts of Interest

The authors confirm no potential conflicts of interest for this publication.

Authors' Contributions

J. A. E. and U. W. performed conceptualization; J. A. E. and H. G. designed the experiment; J. A. E, P. A. curated the data and performed the analysis; J. A. E. wrote the original manuscript draft; P. A., H. G., and U. W. reviewed and edited the manuscript; U. W. supervised the study; U. W. acquired funding. All authors have read and consented to the published version of the manuscript.

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Supplementary Materials

Supplementary Figure 1. Gallic acid standard curve. *Supplementary Figure 2.* Rutin standard curve. *Supplementary Table 1.* HPLC gradient elution program. (*Supplementary Materials*)

References

[1] J.-y. Wan, Y. Long, Y.-l. Zhang et al., "A novel technology to reduce astringency of tea polyphenols extract and its mechanism," *Chinese Herbal Medicines*, vol. 13, no. 3, pp. 421–429, 2021.

[2] I. R. D. Anjarsari, "Indonesia tea catechin: prospect and benefit," *Kultivasi*, vol. 15, no. 2, pp. 99–106, 2016.

[3] H. Jiang, M. Zhang, D. Wang et al., "Analytical strategy coupled to chemometrics to differentiate *Camellia sinensis* tea types based on phenolic composition, alkaloids, and amino acids," *Journal of Food Science*, vol. 85, no. 10, pp. 3253–3263, 2020.

[4] M. Soleimani, A. Arzani, V. Arzani, and T. H. Roberts, "Phenolic compounds and antimicrobial properties of mint and thyme," *Journal of Herbal Medicine*, vol. 36, Article ID 100604, 2022.

[5] A. Snoussi, I. Essaidi, H. Ben Haj Koubaier et al., "Drying methodology effect on the phenolic content, antioxidant activity of *Myrtus communis* L. leaves ethanol extracts and soybean oil oxidative stability," *BMC chemistry*, vol. 15, no. 1, pp. 31–11, 2021.

[6] M. Junsi and S. Siripongvutikorn, "*Thunbergia laurifolia,* a traditional herbal tea of Thailand: botanical, chemical composition, biological properties and processing influence," *International Food Research Journal*, vol. 23, no. 3, p. 923, 2016.

[7] N. Ruangpayungsak, P. Sithisarn, P. Rojsanga, and R. Technologies, "High performance liquid chromatography fingerprinting and chemometric analysis of antioxidant quality of *Thunbergia laurifolia* leaves," *Journal of Liquid Chromatography & Related Technologies*, vol. 41, no. 11, pp. 713–721, 2018.

[8] M. Junsi, S. Siripongvutikorn, C. T. Yupanqui, and W. Usawakesmanee, "Phenolic and flavonoid compounds in aqueous extracts of *Thunbergia laurifolia* leaves and their effect on the toxicity of the carbamate insecticide methomyl to murine macrophage cells," *Functional Foods in Health and Disease*, vol. 7, no. 7, pp. 529–544, 2017.

[9] A. Rocejanasaroj, T. Tencomnao, and W. Sangkitikomol, "*Thunbergia laurifolia* extract minimizes the adverse effects of toxicants by regulating P-glycoprotein activity, CYP450, and lipid metabolism gene expression in HepG2 cells," *Genetics and Molecular Research*, vol. 13, no. 1, pp. 205–219, 2014.

[10] E. W. C. Chan, S. Y. Eng, Y. P. Tan, Z. C. Wong, P. Y. Lye, and L. N. Tan, "Antioxidant and sensory properties of Thai herbal teas with emphasis on *Thunbergia laurifolia* Lindl," *Chiang Mai Journal of Science*, vol. 39, no. 4, pp. 599–609, 2012.

[11] S. Roshanak, M. Rahimmalek, and S. A. H. Goli, "Evaluation of seven different drying treatments in respect to total flavonoid, phenolic, vitamin C content, chlorophyll, antioxidant activity and color of green tea (*Camellia sinensis or C. assamica*) leaves," *Journal of Food Science & Technology*, vol. 53, no. 1, pp. 721–729, 2016.

[12] M. Rahimmalek and S. A. H. Goli, "Evaluation of six drying treatments with respect to essential oil yield, composition and color characteristics of *Thymys daenensis* subsp. daenensis. Celak leaves," *Industrial Crops and Products*, vol. 42, pp. 613–619, 2013.

[13] K. Kulwinder and A. Singh, "Drying kinetics and quality characteristics of beetroot slices under hot air followed by microwave finish drying," *African Journal of Agricultural Research*, vol. 9, no. 12, pp. 1036–1044, 2014.

[14] A. S. Roslan, A. Ismail, Y. Ando, and A. Azlan, "Effect of drying methods and parameters on the antioxidant properties of tea (*Camellia sinensis*) leaves," *Food Production, Processing and Nutrition*, vol. 2, no. 1, pp. 8–11, 2020.

[15] K. Teshome, A. Debela, and W. Garedew, "Effect of drying temperature and duration on biochemical composition and quality of black tea (*Camellia sinensis* L.) O. Kuntze at Wush Wush, South Western Ethiopia," *Asian Journal of Plant Sciences*, vol. 12, no. 6-8, pp. 235–240, 2013.

[16] W. Horwitz, *Official Methods of Analysis of AOAC International. Volume I, Agricultural Chemicals, Contaminants*William Horwitz, Gaithersburg (Maryland), 1997.

[17] Iso 3103:1980, *Standardization IOf Tea-preparation of Liquor for Use in Sensory Tests*, ISO, Geneva, Switzerland, 1980.

[18] H. Gonu, C. Wanapu, and U. Withayagiat, "The correlation of free and bound phenolic acid with antioxidant activity accelerated by germination period and temperature," *Journal of the American Society of Brewing Chemists*, vol. 80, no. 3, pp. 305–315, 2021.

[19] A. Hosu, V.-M. Cristea, and C. Cimpoiu, "Analysis of total phenolic, flavonoids, anthocyanins and tannins content in Romanian red wines: prediction of antioxidant activities and classification of wines using artificial neural networks," *Food Chemistry*, vol. 150, pp. 113–118, 2014.

[20] J. A. Essiedu, P. Adadi, and E. G. Kovaleva, "Production and characterization of beer supplemented with *Hibiscus sabdariffa* (Malvaceae)," *Food Frontiers*, vol. 3, no. 2, pp. 328–338, 2021.

[21] Z. Zhao, L. Chen, G. Chen, W. Xie, and J. Peng, "An approach for in-line control of moisture content during green tea processing," *IEEE Access*, vol. 8, pp. 59701–59714, 2020.

[22] Y. Wang, P.-C. Zheng, P.-P. Liu et al., "Novel insight into the role of withering process in characteristic flavor formation of teas using transcriptome analysis and metabolite profiling," *Food Chemistry*, vol. 272, pp. 313–322, 2019.

[23] T. Ministry of Public Health, "(Unofficial) notification of the ministry of public health (No. 196) B.E. 2543," *Published in the Government Gazette*, vol. 118, 2000.

[24] S. Akyuz and A. Yarat, "The pH and neutralisable acidity of the most-consumed Turkish fruit and herbal teas," *Journal of Oral Health and Dental Management in the Black Sea Countries*, vol. 9, no. 2, pp. 75–78, 2010.

[25] C. Andrés-Lacueva, A. Medina-Remon, R. Llorach, M. Urpi-Sarda, N. Khan, G. Chiva-Blanch et al., "Phenolic compounds: chemistry and occurrence in fruits and vegetables. Fruit and vegetable phytochemicals: chemistry," *Nutritional Value and Stability*, vol. 1, pp. 53–56, 2010.

[26] M. El-Hamidi, F. A. Zaher, and S. M. El-Shami, "Interaction of oilseed pigments and phospholipids in the determination of total phenolic compounds using the Folin-Ciocalteu reagent," *International Journal of PharmTech Research*, vol. 9, pp. 207–214, 2016.

[27] M. Saifullah, R. McCullum, A. McCluskey, and Q. Vuong, "Effects of different drying methods on extractable phenolic compounds and antioxidant properties from lemon myrtle dried leaves," *Heliyon*, vol. 5, no. 12, Article ID e03044, 2019.

[28] W. Pukumpuang, N. Thongwai, and Y. Tragoolpua, "Total phenolic contents, antibacterial and antioxidant activities of some Thai medicinal plant extracts," *Journal of Medicinal Plants Research*, vol. 6, no. 36, pp. 4953–4960, 2012.

[29] R. Oonsivilai, M. G. Ferruzzi, and S. Ningsanond, "Antioxidant activity and cytotoxicity of Rang chuet (*Thunbergia laurifolia* lindl.) extracts," *Asian Journal of Food and Agro-Industry*, vol. 1, no. 2, pp. 116–128, 2008.

[30] N. H. Thinh, P. Wichittrakarn, C. Laosinwattana, and M. Teerarak, "Total polyphenol content and antioxidant activity of the extracts from *Thunbergia laurifolia* Lindl. leaves," *International Journal of Agricultural Technology*, vol. 13, pp. 1325–1332, 2017.

[31] F. J. Esparza-Martínez, R. Miranda-López, and S. H. Guzman-Maldonado, "Effect of air-drying temperature on extractable and non-extractable phenolics and antioxidant capacity of lime wastes," *Industrial Crops and Products*, vol. 84, pp. 1–6, 2016.

[32] Q. V. Vuong, H. N. T. Pham, and C. Negus, "From herbal teabag to infusion—impact of brewing on polyphenols and antioxidant capacity," *Beverages*, vol. 8, no. 4, p. 81, 2022.

[33] E. Chan and Y. Y. Lim, "Antioxidant activity of *Thunbergia laurifolia* tea," *Journal of Tropical Forest Science*, pp. 130–136, 2006.

[34] J. Samoticha, A. Wojdyło, and K. Lech, "The influence of different the drying methods on chemical composition and antioxidant activity in chokeberries," *LWT - Food Science and Technology*, vol. 66, pp. 484–489, 2016.

[35] R. Kiani, A. Arzani, and S. A. M. Mirmohammady Maibody, "Polyphenols, flavonoids, and antioxidant activity involved in salt tolerance in wheat, *Aegilops cylindrica* and their amphidiploids," *Frontiers of Plant Science*, vol. 12, Article ID 646221, 2021.

[36] M. I. Choudhary, S. Maher, A. Begum et al., "Characterization and antiglycation activity of phenolic constituents from *Viscum album* (European Mistletoe)," *Chemical and Pharmaceutical Bulletin*, vol. 58, no. 7, pp. 980–982, 2010.

[37] K. J. Lee, Y. C. Oh, W. K. Cho, and J. Y. Ma, "Antioxidant and anti-inflammatory activity determination of one hundred kinds of pure chemical compounds using offline and online screening HPLC assay," *Evidence-based Complementary and*

Alternative Medicine, vol. 2015, Article ID 165457, 13 pages, 2015.

[38] Y. T. Haw, Y. Y. Sim, and K. L. Nyam, "Effect of steam blanching and high temperature drying on the physicochemical properties, antioxidant activities and consumer acceptability of *Hibiscus cannabinus* leaves tea," *Journal of Food Science & Technology*, vol. 57, no. 12, pp. 4588–4598, 2020.

[39] Q. V. Nguyen and H. V. Chuyen, "Processing of herbal tea from roselle (*Hibiscus sabdariffa* L.): effects of drying temperature and brewing conditions on total soluble solid, phenolic content, antioxidant capacity and sensory quality," *Beverages*, vol. 6, no. 1, p. 2, 2020.

[40] O. Bualuang, D. I. Onwude, and S. Prangsri-aroon, "The effect of various drying strategies on the greenness, chlorophyll, bioactive compounds, antioxidant activity, and anti-tyrosinase of dried *Acanthus ilicifolius* L. leaves," *International Food Research Journal*, vol. 29, no. 2, pp. 416–432, 2022.

[41] W. Chaiyana, S. Chansakaow, N. Intasai et al., "Chemical constituents, antioxidant, anti-MMPs, and anti-hyaluronidase activities of *Thunbergia laurifolia* Lindl. leaf extracts for skin aging and skin damage prevention," *Molecules*, vol. 25, no. 8, p. 1923, 2020.

[42] V. Dewanto, X. Wu, K. K. Adom, and R. H. Liu, "Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity," *Journal of Agricultural and Food Chemistry*, vol. 50, no. 10, pp. 3010–3014, 2002.

[43] C. Delgado-Nieblas, J. Zazueta-Morales, J. Ahumada-Aguilar et al., "Optimization of an air-drying process to obtain a dehydrated naranjita (*Citrus mitis* B.) pomace product with high bioactive compounds and antioxidant capacity," *Journal of Food Process Engineering*, vol. 40, no. 1, Article ID e12338, 2017.

[44] Y. Hong, Z. Wang, C. J. Barrow, F. R. Dunshea, and H. A. R. Suleria, "High-throughput screening and characterization of phenolic compounds in stone fruits waste by lc-esi-qtof-ms/ms and their potential antioxidant activities," *Antioxidants*, vol. 10, no. 2, p. 234, 2021.

[45] X. Xu, J. Yang, Z. Ning, and X. Zhang, "Lentinula edodes-derived polysaccharide rejuvenates mice in terms of immune responses and gut microbiota," *Food & Function*, vol. 6, no. 8, pp. 2653–2663, 2015.