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Growth, Survival, and Quality Components of 'Sangmok' Tea (*Camellia sinensis* (L.) O. Kuntze) Cultivated in Volcanic Ash and Non-Volcanic Ash Soils on Jeju Island, Korea

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Abstract

Tea (*Camellia sinensis* (L.) O. Kuntze) quality is shaped by soil, but comparisons among Jeju soil types are lacking. 'Sangmok' cuttings were grown for 33 months in three Jeju soils under identical greenhouse conditions—black volcanic ash soil (B-VAS), very dark-brown volcanic ash soil (VDB-VAS), and dark-brown non-volcanic ash soil (DB-NVAS)—and compared for survival, growth, and leaf amino acid and catechin profiles. Volcanic ash soils had more organic matter and nitrogen but less phosphorus and micronutrients than DB-NVAS. Survival (88.9%, 50.0%, and 55.6%; not statistically significant) and height increase (410.9%, 302.2%, and 116.1%) in B-VAS, VDB-VAS, and DB-NVAS were numerically greatest in B-VAS. The final DB-NVAS height-increase value reflects a single surviving plant and should be interpreted with caution. Total amino acids and theanine were 2.6- to 3.6-fold higher in volcanic ash soils than in DB-NVAS, whereas epigallocatechin (EGC) and epicatechin (EC) were higher in DB-NVAS, giving catechin quality index (CQI) values of 3.83, 3.13, and 2.20 and amino acid/catechin (A/C) ratios of 0.31, 0.28, and 0.10. In this pilot planting, survival was numerically highest in B-VAS, and the volcanic ash soils showed greater growth and higher amino acid levels in the pooled shoot samples, whereas the non-volcanic ash soil showed higher catechin accumulation despite weaker growth; these soil-type-level patterns are testable hypotheses for soil-type-informed 'Sangmok' cultivation that require confirmation in replicated trials.

Keywords: *Camellia sinensis* (L.) O. Kuntze; catechins; theanine; Jeju Island; nitrogen availability; amino acid/catechin ratio

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Academic Editors: Lingfei Ji, Yiyang Yang, Jianyun Ruan and Maria Roulia

Received: 7 September 2026
Revised: 8 October 2026
Accepted: 13 October 2026
Published: 15 October 2026

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1. Introduction

Tea (*Camellia sinensis* (L.) O. Kuntze) is among the most widely consumed beverage crops in the world, and the diverse metabolites present in its leaves determine not only its sensory characteristics but also its functional value. Among these, free amino acids—particularly theanine—contribute umami and sweet taste, whereas catechins, the principal polyphenols of tea, are responsible for astringency and are associated with antioxidant, anti-inflammatory, and cardiovascular health-promoting activities [1–3]. Tea quality is therefore commonly evaluated not only from total amino acid and catechin contents but also from composite indices such as the amino acid/catechin ratio (A/C ratio) and the catechin quality index (CQI), which reflect the balance between these two metabolite classes [4–7].

Tea quality is shaped both by cultivar-specific genetic factors and by the cultivation environment, with soil properties exerting a particularly strong influence. Soil pH, organic matter content, and the availability of nitrogen and mineral nutrients affect not only vegetative growth but also nitrogen metabolism and the accumulation of secondary metabolites in tea leaves [8,9]. In general, greater nitrogen availability promotes the accumulation of free amino acids, especially theanine, while often suppressing catechin biosynthesis, reflecting a metabolic trade-off between nitrogen-based and carbon-based metabolism [6,7,10–14].

Tea cultivation in Korea is concentrated in Jeollanam-do, Gyeongsangnam-do, and Jeju Special Self-Governing Province. Jeju Island, formed by volcanic activity, is characterized by a mosaic of soil types, including black volcanic ash soil, very dark-brown volcanic ash soil, and dark-brown non-volcanic ash soil, which differ markedly in organic matter content, total nitrogen, available phosphorus, and mineral element composition [15,16]. Because phosphate-fixing allophane and other short-range-order minerals dominate the clay fraction of Jeju volcanic ash soils, these soils typically show high organic matter and nitrogen retention but low phosphorus availability, in contrast to the non-volcanic ash soils derived from basalt weathering [15,17]. Differences in the chemical properties of these soil types have previously been shown to affect the growth and quality components of other crops cultivated on Jeju Island, such as garlic [16,18], but comparable data for tea are lacking.

Although the physicochemical properties of Jeju soils have been characterized, few studies have cultivated a single tea cultivar under identical management across these different soil types and comprehensively compared growth characteristics together with total amino acids, theanine, catechins, caffeine, and quality indices (A/C ratio, CQI). Moreover, the relationship between soil nutrient status and tea quality components in this environment has not been systematically analyzed.

Therefore, this study cultivated ‘Sangmok’, a nationally released standard Korean tea cultivar, under identical conditions in black volcanic ash soil, very dark-brown volcanic ash soil, and dark-brown non-volcanic ash soil on Jeju Island, and compared growth characteristics and the free amino acid, catechin, and caffeine contents of the shoots among soil types. Ultimately, this study aims to elucidate how distinct volcanic and non-volcanic soil environments shape the primary and secondary metabolic balance of tea shoots, thereby generating testable hypotheses for soil-type-informed cultivation and site selection in regional tea production. To this end, the physicochemical profiles of the three soil types were also compared descriptively alongside the tea quality-component results, with the broader aim of informing future, more rigorously replicated studies on soil-type-suitable cultivation on Jeju Island.

2. Materials and Methods

2.1. Plant Material and Cultivation Conditions

The plant material used in this study was the nationally released standard Korean tea cultivar ‘Sangmok’ (*Camellia sinensis* (L.) O. Kuntze; IT No. IT290950), cultivated in an unheated double-span greenhouse at the Research Institute of Climate Change and Agriculture (RICCA; 33°28′9.5″ N, 126°30′58.3″ E), Jeju, Republic of Korea. For each soil type—black volcanic ash soil (B-VAS), very dark-brown volcanic ash soil (VDB-VAS), and dark-brown non-volcanic ash soil (DB-NVAS)—three independent replicate beds were prepared to a depth of 50–70 cm, giving nine experimental beds in total. The nine beds were constructed at fixed positions within the greenhouse and were not randomized with respect to soil type; bed position and associated microenvironmental factors (e.g., light, drainage, and temperature) may therefore be partly confounded with soil type in this long-term experiment. Two-year-old rooted cuttings were transplanted into each bed in 2022 at a planting distance of 100 × 100 cm, with a total of 9 plants in B-VAS (three beds of three

plants each), 10 in VDB-VAS (three beds of three to four plants each), and 9 in DB-NVAS (three beds of three plants each). Plants were drip-irrigated three times per week (1 h per irrigation) in spring and autumn, daily (1 h) in summer, and twice per week (30 min) in winter; no fertilizer or other soil amendment was applied during the experimental period. The planting distance (100 × 100 cm) was chosen to prevent canopy overlap as plants matured, following standard spacing practice for young tea plants at this research station; pre-transplant physical soil properties (e.g., bulk density, drainage) were not characterized, and irrigation followed the fixed schedule above rather than being adjusted to soil moisture, which was not measured at any time during the experiment; because volcanic and non-volcanic ash soils differ in water-holding capacity, the fixed schedule may have produced different soil water regimes among soil types that could not be quantified. The slightly larger number of plants established in VDB-VAS (10 vs. 9) reflected the fixed dimensions of the available replicate beds for this soil type rather than a deliberate experimental choice. Survival was monitored for all transplanted plants in each soil type (9 in B-VAS, 10 in VDB-VAS, and 9 in DB-NVAS), with individual plant identity but not bed identity retained in the survival and growth records, whereas five individually tagged plants per soil type were monitored throughout the experiment for growth. Tagging was performed at random among the transplanted individuals in each soil type at the time of transplanting (2022), before any mortality had occurred, to avoid survivorship bias in the growth dataset. Tea shoot sampling for the free amino acid, catechin, and caffeine analyses followed a different, soil-type-level design because of survival losses, as described in Section 2.4.

2.2. Survival, Growth, and Leaf Number Measurements

Plant survival was recorded for all transplanted plants in each soil type and expressed as the percentage of plants alive at the end of the observation period (May 2025) relative to the number originally transplanted. Plant height was recorded for the tagged plants in each soil type at 13 time points from transplanting (August 2022) to December 2024, and total leaf number per plant was recorded at four time points from August 2022 to February 2023; at each survey date, both traits were expressed for each surviving plant as a percentage of the soil-type group mean value at the initial survey date (August 2022, defined as 100%), and the soil-type-level mean and SD of these individual-plant percentages were then calculated at each time point, excluding plants that had died by that date.

2.3. Soil Chemical Analysis

One composite soil sample was collected from the surface layer (0–20 cm) of each of the three replicate beds per soil type (i.e., three independent bed-level samples per soil type) before transplanting, air-dried, and passed through a 2 mm sieve prior to analysis. All soil chemical properties were determined according to the standard soil analysis methods of the Rural Development Administration [19]. Soil pH and electrical conductivity (EC) were measured in a 1:5 (w/v) soil–distilled water suspension after shaking for 30 min, using a pH meter (Five Easy Plus FP20, Mettler Toledo, Greifensee, Switzerland) and an EC meter (InoLab Cond Level 1, WTW, Weilheim, Germany), respectively. Organic matter (OM) content was determined by the Tyurin wet-oxidation method. Total nitrogen (TN) was determined by the Kjeldahl method following sample digestion with a Kjeltec digestion catalyst (Kjeltec Se 3.5; 3.5 g K_2SO_4 + 3.5 mg Se) and sulfuric acid using a Kjeltec digestion and distillation system (Kjeltec Auto 2400/2460, FOSS Tecator AB, Höganäs, Sweden). Available phosphorus (P_2O_5) was extracted by the Lancaster method, appropriate for the phosphate-fixing andic soils of Jeju Island, and determined colorimetrically. Exchangeable cations (K, Ca, Mg, Na) were extracted with 1 N ammonium acetate (pH 7.0), and micronutrients (Fe, Mn, Zn, Cu) were extracted with 0.1 N HCl; both were quantified by

inductively coupled plasma optical emission spectrometry (ICP-OES; Integra XL, GBC Scientific Equipment Pty Ltd., Melbourne, VIC, Australia).

2.4. Tea Sample Preparation

During the first-flush harvest period (13–18 April 2025), shoots at the same developmental stage (one bud and three leaves) were collected from all surviving plants within each soil type; because shoot developmental progress differed among plants, the harvest date was determined individually for each plant once its shoots reached this target stage, with all sampling completed within this six-day window. Because plant survival differed markedly among soil types, and the leaf biomass available on individual beds—particularly in VDB-VAS (50.0% survival) and DB-NVAS (55.6% survival)—was insufficient to prepare separate bed-level composite samples, shoots from all surviving plants within a soil type were pooled into a single composite sample per soil type rather than three independent bed-level composite samples. Each composite sample was freeze-dried, ground into a homogeneous powder, stored at −70 °C, and analyzed in triplicate (technical replicates) for free amino acids, catechins, and caffeine.

2.5. Free Amino Acid Analysis

Free amino acids were extracted and analyzed following the standard operating protocol of our laboratory, adapted from the manufacturer's application method for the ion-exchange amino acid analyzer [20]. Tea powder (0.5 g) was extracted with 10 mL distilled water at 95 °C for 15 min with vortex-mixing at 5 min intervals, then centrifuged at 6000 rpm for 10 min. The supernatant (0.5 mL) was deproteinized with an equal volume of 5% trichloroacetic acid, vortexed, and centrifuged at 10,000 rpm for 10 min. The resulting supernatant was diluted 10-fold with 0.02 N HCl and filtered through a 0.2 μm nylon syringe filter. Free amino acids were analyzed with a high-speed amino acid analyzer (LA8080, Hitachi High-Tech Science Corp., Tokyo, Japan) fitted with a Hitachi custom ion-exchange resin column (4.6 mm i.d. × 60 mm), using protein hydrolysate analysis buffers (PH-1, PH-2, PH-3, PH-4, and PJ-RG; Kanto Chemical Co., Tokyo, Japan) as the mobile phase at a flow rate of 0.35 mL/min. Detection wavelengths were 440 nm for theanine and 570 nm for the other free amino acids. Amino acid contents are expressed on a dry-weight basis (mg·g^{-1} DW), and total amino acid content was calculated as the sum of all detected free amino acids, including theanine. Free amino acids, including theanine, were quantified against authentic amino acid standards (Sigma-Aldrich Corp., St. Louis, MO, USA) using a single-point external calibration for each analyte, following standard practice for this ion-exchange amino acid analyzer; formal detection and quantification limits could not be determined for this single-point calibration and are not reported. Instrument precision, assessed as the percent relative standard deviation (%RSD) of peak area across three technical replicate injections of each soil-type composite sample, was 0.8–1.2% for total amino acids and theanine specifically, and ranged from 0.7% to 39.0% (mean 4.9%) across all 12–15 individually quantified amino acids; the higher values were confined to a small number of trace-level amino acids present at very low peak areas (e.g., phosphoserine, α-aminoadipic acid). Differences in these trace-level amino acids are therefore not interpreted. Because formal LOD/LOQ values were not established, "N.D." in the free amino acid data (Section 3.3) denotes that no peak was observed above the instrument's integration threshold; it does not indicate a concentration below a validated quantification limit, and trace-level values should be regarded as approximate.

2.6. Catechin and Caffeine Analysis

Tea powder (0.02 g) was extracted with 1 mL methanol by vortex-mixing followed by ultrasonic extraction for 25 min, then centrifuged at 13,000 rpm for 10 min, and the

supernatant was filtered through a 0.2 μm nylon syringe filter. Catechins and caffeine were analyzed by HPLC based on ISO 14502-2 [21], with modifications to the extraction and chromatographic conditions as described here, using an Agilent 1200 system (Agilent Technologies, Santa Clara, CA, USA) equipped with a diode array detector (DAD) and a Symmetry C18 column (4.6 × 150 mm, 5 μm; Waters Corp., Milford, MA, USA). The mobile phase consisted of 1% formic acid in distilled water (A) and 1% formic acid in acetonitrile (B), under the following gradient: 0–2 min, 98% A/2% B; 2–8 min, 98–75% A/2–25% B; 8–13.5 min, 75–70% A/25–30% B; 13.5–15 min, 70% A/30% B; 15–15.1 min, 70–40% A/30–60% B; 15.1–18 min, 40% A/60% B, at a flow rate of 1.5 mL/min with a 2 μL injection volume. Standards for (−)-epigallocatechin gallate (EGCG), (−)-epigallocatechin (EGC), (−)-epicatechin gallate (ECG), (−)-epicatechin (EC), (+)-catechin, and caffeine were purchased from Sigma-Aldrich Corp. (St. Louis, MO, USA). Calibration curves for all seven analytes (the six above plus gallic acid) were constructed using three-point external standards at 2, 20, and 200 ppm; coefficients of determination (R^2) exceeded 0.9999 for every analyte. Limits of detection and quantification, estimated from the standard error of the calibration curve as 3.3σ/S and 10σ/S, respectively, ranged from 0.0005 to 0.0087 ppm and 0.0015 to 0.0263 ppm across analytes; these values refer to solution concentrations in the injected extract and correspond to 0.025–0.435 $\mu g \cdot g^{-1}$ DW (LOD) and 0.075–1.315 $\mu g \cdot g^{-1}$ DW (LOQ) on a dry-weight basis, given the extraction ratio of 0.02 g tea powder per 1 mL solvent (conversion shown in Supplementary Table S2). Instrument precision (%RSD of peak area across three technical replicate injections of each soil-type composite sample) ranged from 1.5% to 13.1% (mean 3.9%); the highest value occurred for gallic acid, a minor trace compound not used as a primary quality index in this study. Each component is expressed on a dry-weight basis ($mg \cdot g^{-1}$ DW), and total catechin content (TC) was calculated as the sum of EGCG, EGC, ECG, EC, and catechin. The catechin quality index (CQI) was calculated as (EGCG + ECG) / EGC, and the amino acid/catechin (A/C) ratio was calculated as the ratio of total free amino acid content (Section 2.5) to total catechin content (TC) [4]. Gallic acid was also monitored as a potential marker of catechin hydrolysis but was not further analyzed here, as it fell outside the scope of this study.

2.7. Statistical Analysis

Results are expressed as the mean ± standard deviation, following the distinct replication schemes described for each dataset below. Because of the small number of plants per soil type, the survival analysis was treated as exploratory. Differences in survival rate among soil types were first assessed with a global Fisher–Freeman–Halton exact test on the 3 × 2 (soil type × alive/dead) contingency table, followed by pairwise Fisher's exact tests on the three 2 × 2 tables (B-VAS vs. VDB-VAS, B-VAS vs. DB-NVAS, and VDB-VAS vs. DB-NVAS), with *p*-values adjusted for multiplicity by the Holm method; these tests were computed in Python (ver. 3.13; SciPy ver.1.18). One-way analysis of variance (ANOVA) was performed on the soil chemical properties (Table 1) using SPSS software (ver. 18.0; SPSS Inc., Chicago, IL, USA), and means were separated by Duncan's multiple range test at $p < 0.05$. Soil chemical properties (Table 1) derive from three independent replicate beds per soil type, with one composite sample per bed, providing genuine biological replication at the bed level. The free amino acid, catechin, and caffeine data (Sections 3.3 and 3.4), by contrast, represent a single pooled composite sample per soil type analyzed in technical triplicate rather than independent biological replicates (Section 2.4), because survival losses left insufficient leaf biomass to prepare separate bed-level samples; these values are therefore presented descriptively (mean ± SD of technical replicates) without ANOVA, Duncan's multiple range test, or correlation analysis against soil physicochemical properties, because a single pooled sample per soil type and only three soil-type units cannot support a statis-

tically meaningful test of such associations. Separately, the survival and growth records (Section 3.2) were compiled at the level of individual plants without retaining bed identity, so potential clustering of plants within the same bed (e.g., shared microtopography or drainage) could not be explicitly modeled in Fisher's exact test or growth trend analysis; this is addressed further in the Discussion.

Table 1. Physicochemical properties of the three soil types used for cultivation of the tea cultivar 'Sangmok'.

Cu	Zn	Mn	Fe	Na	Mg	Ca	K	P_2O_5	TN	OM	EC	pH	Soil Type
(ppm)				(cmolc·kg^{-1})				(ppm)	(%)	(g·kg^{-1})	(dS·m^{-1})		
1.24 ± 0.03 b	2.33 ± 0.08 b	6.24 ± 0.09 b	64.10 ± 0.85 b	0.20 ± 0.01 b	0.45 ± 0.03 c	2.16 ± 0.09 b	0.37 ± 0.02 b	19.67 ± 0.35 c	0.61 ± 0.00 a	152.63 ± 0.64 a	0.06 ± 0.00	5.44 ± 0.01 b	B-VAS
1.11 ± 0.02 c	2.15 ± 0.04 b	5.75 ± 0.17 b	61.81 ± 1.01 b	0.23 ± 0.00 a	0.59 ± 0.00 b	2.18 ± 0.03 b	0.31 ± 0.00 c	40.70 ± 0.10 b	0.55 ± 0.00 b	152.53 ± 0.90 a	0.05 ± 0.00	5.49 ± 0.01 a	VDB-VAS
1.70 ± 0.06 a	12.58 ± 0.69 a	20.67 ± 1.40 a	73.64 ± 1.20 a	0.17 ± 0.00 c	1.62 ± 0.00 a	3.01 ± 0.01 a	0.65 ± 0.01 a	135.83 ± 2.16 a	0.16 ± 0.00 c	28.20 ± 0.20 b	0.05 ± 0.00	5.37 ± 0.01 c	DB-NVAS

Data are presented as mean ± SD (n = 3). Different letters within a column indicate significant differences by Duncan's multiple range test ($p < 0.05$). B-VAS, black volcanic ash soil; VDB-VAS, very dark-brown volcanic ash soil; DB-NVAS, dark-brown non-volcanic ash soil; OM, organic matter; TN, total nitrogen.

2.8. Use of Generative AI Tools

During the preparation of this manuscript, the authors used Claude (Claude Opus 5.5; Anthropic, San Francisco, CA, USA) for English language editing of the text, for verification of statistical calculations (the survival exact tests in Section 2.7), and for generating the plotting code used to draw Figure 1 from the authors' raw data. The authors reviewed, verified, and edited all AI-assisted output and take full responsibility for the content of this publication.

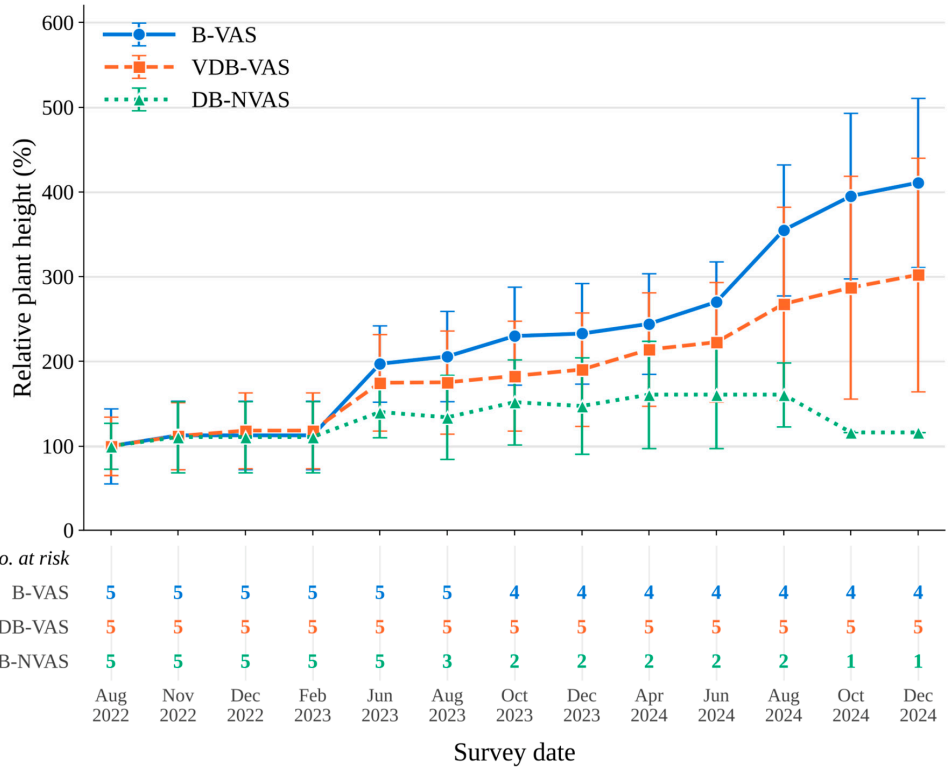


Figure 1. Change in relative plant height (%, individual plant height as a percentage of the soil-type baseline mean height at transplanting) of the tea cultivar 'Sangmok' grown in three soil types on Jeju Island, from transplanting (August 2022) to December 2024. Error bars indicate SD; the number of plants contributing at each survey date (No. at risk) is shown beneath the plot for each soil type (B-VAS, n = 4–5; VDB-VAS, n = 5; DB-NVAS, n = 1–5, decreasing over time as plants died). SD is not shown for the final two DB-NVAS time points, at which only one plant remained.

3. Results

3.1. Soil Physicochemical Properties

The physicochemical properties of the three soil types differed significantly (Table 1). Soil pH ranged narrowly from 5.37 to 5.49 but differed significantly among soils, with VDB-VAS > B-VAS > DB-NVAS. OM was more than five-fold higher and TN was more than three-fold higher in the two volcanic ash soils (B-VAS and VDB-VAS) than in DB-NVAS, whereas available P_2O_5 was 3.3- to 6.9-fold higher in DB-NVAS than in the volcanic ash soils. Exchangeable Ca and Mg and the micronutrients Fe, Mn, Zn, and Cu were also higher in DB-NVAS than in the volcanic ash soils, most markedly for Mn (3.3- to 3.6-fold higher) and Zn (5.4- to 5.9-fold higher). Exchangeable K and Na also differed significantly among soils but showed no consistent volcanic-ash-versus-DB-NVAS pattern, with the highest K in DB-NVAS (0.65 cmolc·kg^{-1}) and the highest Na in VDB-VAS (0.23 cmolc·kg^{-1}).

3.2. Survival and Growth Characteristics

Survival and vegetative growth of 'Sangmok' varied numerically among soil types (Table 2); as detailed below, survival differences were not statistically significant, and the growth comparison should be read as a descriptive observation from this pilot planting rather than a confirmed soil-type effect. Survival rate, assessed in May 2025 (33 months after transplanting), was highest in B-VAS (88.9%; 8 of 9 plants), intermediate in DB-NVAS (55.6%; 5 of 9 plants), and lowest in VDB-VAS (50.0%; 5 of 10 plants); plant death was concentrated in the second and third years of cultivation (Table S3). Despite this numerical range, the difference in survival rate among soil types was not statistically significant (global Fisher–Freeman–Halton exact test, $p = 0.222$; Holm-adjusted pairwise Fisher's exact tests, $p = 0.423$–1.000), likely reflecting the limited statistical power afforded by the small number of plants per treatment (n = 9–10).

Table 2. Survival rate of the tea cultivar 'Sangmok' by soil type, assessed 33 months after transplanting (May 2025).

Survival Rate (%)	Plants Surviving	Plants Transplanted	Soil Type
88.9	8	9	B-VAS
50.0	5	10	VDB-VAS
55.6	5	9	DB-NVAS

Baseline plant height and leaf number, recorded at transplanting (August 2022) for the five tagged plants per soil type, did not differ significantly among soil types (one-way ANOVA; height: $F(2, 12) = 2.19$, $p = 0.155$; leaf number: $F(2, 12) = 1.39$, $p = 0.286$), although DB-NVAS plants were numerically the smallest at this initial time point (mean height 11.2 cm vs. 17.4–18.6 cm in the volcanic ash soils; mean leaf number 9.4 vs. 14.2–15.6), a pre-existing trend to bear in mind when interpreting the group-mean-normalized growth trajectories below. With only five plants per soil type, however, this non-significant result does not establish that the starting material was equivalent among soil types. Cuttings were assigned to soil types from a common propagation batch without size-matching at transplanting, so this baseline imbalance was not experimentally controlled for and should be considered a limitation of the present design rather than a deliberate contrast; future trials should use size-matched transplants at establishment. Among surviving plants, the rate of increase in plant height diverged progressively among soil types (Figure 1). All three soil types showed broadly similar, modest height gains during the first six months (approximately 110–118% of initial height by February 2023), after which growth in the volcanic ash soils accelerated markedly relative to DB-NVAS. By the final survey (December

2024), plant height had increased to 410.9% of the initial value in B-VAS and 302.2% in VDB-VAS, but only to 116.1% in DB-NVAS. DB-NVAS height increase plateaued at approximately 160% of initial height between April and August 2024 and then declined sharply to 116.1% by October–December 2024; because only one DB-NVAS plant remained alive at these last two time points (Figure 1), this apparent decline reflects the trajectory of a single surviving individual rather than a population-level trend and should be interpreted with caution. Leaf number followed a similar trend during the shared early monitoring window (Table 3): by February 2023, total leaf number per plant had increased to 165.4% and 166.2% of the initial count in B-VAS and VDB-VAS, respectively, versus 127.7% in DB-NVAS.

Table 3. Leaf number increase (% of the soil-type initial mean) of the tea cultivar 'Sangmok' by soil type, from transplanting (August 2022) to February 2023.

Feb 2023	Dec 22	Oct 22	Aug 2022 (Baseline)	Soil Type
165.4 ± 61.0	147.4 ± 63.0	141.0 ± 61.3	100.0 ± 48.5	B-VAS
166.2 ± 80.8	157.7 ± 77.4	149.3 ± 67.6	100.0 ± 44.9	VDB-VAS
127.7 ± 57.3	123.4 ± 59.0	125.5 ± 56.0	100.0 ± 42.3	DB-NVAS

Data are presented as mean ± SD (n = 5 plants per soil type at each date); for each plant, leaf number at each date is expressed as a percentage of the soil-type group mean leaf number at the initial survey date (August 2022 transplanting; Section 2.2). Values are descriptive and were not formally significance-tested (Section 2.7).

3.3. Free Amino Acid Contents

The pooled shoot samples from the three soil types showed different total free amino acid and theanine contents (Table 4); as for all quality-component data, these are descriptive values from a single pooled composite sample per soil type (Section 2.7). Total amino acids were highest in B-VAS (39.63 mg·g^{-1} DW), followed by VDB-VAS (38.49 mg·g^{-1} DW), and were 2.6- to 2.7-fold lower in DB-NVAS (14.54 mg·g^{-1} DW). Theanine, the predominant free amino acid, followed a similar decreasing trend from B-VAS to VDB-VAS to DB-NVAS (26.38, 25.43, and 7.40 mg·g^{-1} DW, respectively; 3.4- to 3.6-fold higher in the volcanic ash soils than in DB-NVAS), accounting for approximately 67% of total amino acids in the volcanic ash soils versus 51% in DB-NVAS. Most other amino acids, including aspartate, threonine, serine, glutamate, alanine, and ornithine, were likewise higher in the volcanic ash soils than in DB-NVAS, whereas arginine was not detected in the DB-NVAS pooled sample. Trace-level amino acids (e.g., phosphoserine and α-aminoadipic acid) showed high technical variability and are not interpreted further (Section 2.5).

Table 4. Free amino acid contents (mg·g^{-1} DW) of 'Sangmok' tea shoots grown in three soil types.

DB -NVAS	VDB-VAS	B-VAS	Component
14.54 ± 0.12	38.49 ± 0.40	39.63 ± 0.14	Total free amino acids
7.40 ± 0.11	25.43 ± 0.19	26.38 ± 0.10	Theanine
0.18 ± 0.01	0.12 ± 0.00	0.16 ± 0.06	Phosphoserine
1.48 ± 0.01	2.30 ± 0.02	2.43 ± 0.03	Aspartate
0.26 ± 0.00	0.29 ± 0.01	0.32 ± 0.00	Threonine
0.83 ± 0.01	0.97 ± 0.02	1.08 ± 0.00	Serine
3.18 ± 0.10	4.85 ± 0.03	5.24 ± 0.03	Glutamate
0.15 ± 0.13	N.D.	N.D.	α-Aminoadipic acid
0.09 ± 0.01	0.08 ± 0.00	0.08 ± 0.01	Glycine
0.31 ± 0.01	0.44 ± 0.00	0.47 ± 0.01	Alanine
0.16 ± 0.01	0.17 ± 0.01	0.20 ± 0.02	α-Aminobutyric acid
0.08 ± 0.07	0.13 ± 0.01	0.12 ± 0.01	Valine
0.12 ± 0.00	0.17 ± 0.00	0.16 ± 0.00	γ-Aminobutyric acid

Table 4. *Cont.*

DB -NVAS	VDB-VAS	B-VAS	Component
0.30 ± 0.01	1.17 ± 0.06	1.26 ± 0.03	Ornithine
N.D.	2.31 ± 0.02	1.73 ± 0.01	Arginine

Data are presented as mean ± SD of three technical (analytical) replicates measured from a single pooled composite sample per soil type (Section 2.4); differences among soil types are descriptive and were not formally significance-tested (Section 2.7). N.D., not detected (no peak above the instrument integration threshold; formal LOD/LOQ were not determined, see Section 2.5). Lysine, detected at trace level in only one VDB-VAS technical replicate (0.17 mg·g^{-1} DW), is not listed separately but is included in total free amino acids. For analytes not detected in one of the three replicates, that replicate was entered as zero when calculating the mean ± SD. B-VAS, black volcanic ash soil; VDB-VAS, very dark-brown volcanic ash soil; DB-NVAS, dark-brown non-volcanic ash soil.

3.4. Catechin and Caffeine Contents

The catechin and caffeine data in Table 5 are descriptive values from a single pooled composite sample per soil type analyzed in technical triplicate and were not significance-tested (Section 2.7). Total catechin (TC) content was numerically lower in B-VAS (128.46 ± 0.91 mg·g^{-1} DW) than in DB-NVAS (139.40 ± 4.42 mg·g^{-1} DW), with VDB-VAS intermediate (136.35 ± 7.36 mg·g^{-1} DW; Table 5). EGCG, the dominant catechin, was broadly similar among soil types (68–73 mg·g^{-1} DW). Exact EGCG values were 70.16 ± 0.34, 73.10 ± 4.10, and 68.34 ± 2.15 mg·g^{-1} DW in B-VAS, VDB-VAS, and DB-NVAS, respectively. In contrast, EGC and EC—the di-hydroxylated, non-galloylated catechins—increased from B-VAS to VDB-VAS to DB-NVAS (EGC: 24.21 ± 0.67, 30.20 ± 1.67, and 39.33 ± 1.28 mg·g^{-1} DW; EC: 9.06 ± 0.05, 9.92 ± 0.44, and 11.89 ± 0.37 mg·g^{-1} DW). Conversely, ECG, catechin (monomer), and the catechin quality index (CQI) were highest in B-VAS and lowest in DB-NVAS (e.g., CQI: 3.83 ± 0.10, 3.13 ± 0.01, and 2.20 ± 0.01 in B-VAS, VDB-VAS, and DB-NVAS, respectively). Exact ECG and catechin (monomer) values were, respectively, 22.47 ± 0.09, 21.30 ± 1.07, and 18.04 ± 0.61 mg·g^{-1} DW (ECG) and 2.56 ± 0.01, 1.83 ± 0.10, and 1.80 ± 0.04 mg·g^{-1} DW (catechin) in B-VAS, VDB-VAS, and DB-NVAS. Caffeine content was highest in VDB-VAS (29.51 ± 1.08 mg·g^{-1} DW) and similar between B-VAS and DB-NVAS (26.99 ± 0.13 and 26.41 ± 0.80 mg·g^{-1} DW). The amino acid/catechin (A/C) ratio, which combines the amino acid results in Section 3.3 with total catechins, was markedly higher in the two volcanic ash soils (0.309 ± 0.001 and 0.283 ± 0.017 in B-VAS and VDB-VAS) than in DB-NVAS (0.104 ± 0.003).

Table 5. Catechin components, caffeine content, and quality indices of 'Sangmok' tea shoots grown in three soil types. Data are presented as mean ± SD of three technical (analytical) replicates measured from a single pooled composite sample per soil type (Section 2.4); differences among soil types are descriptive and were not formally significance-tested (Section 2.7). CQI, catechin quality index; A/C ratio, amino acid/catechin ratio.

DB -NVAS	VDB-VAS	B-VAS	Component (mg·g^{-1} DW Unless Noted)
68.34 ± 2.15	73.10 ± 4.10	70.16 ± 0.34	EGCG
39.33 ± 1.28	30.20 ± 1.67	24.21 ± 0.67	EGC
18.04 ± 0.61	21.30 ± 1.07	22.47 ± 0.09	ECG
11.89 ± 0.37	9.92 ± 0.44	9.06 ± 0.05	EC
1.80 ± 0.04	1.83 ± 0.10	2.56 ± 0.01	Catechin
139.40 ± 4.42	136.35 ± 7.36	128.46 ± 0.91	Total catechins (TC)
26.41 ± 0.80	29.51 ± 1.08	26.99 ± 0.13	Caffeine
2.20 ± 0.01	3.13 ± 0.01	3.83 ± 0.10	CQI
0.104 ± 0.003	0.283 ± 0.017	0.309 ± 0.001	A/C ratio

3.5. Soil Property Profile Across Soil Types

Table 1 summarizes the physicochemical profile of the three soil types. The two volcanic ash soils (B-VAS and VDB-VAS) shared a broadly similar profile of high organic matter and total nitrogen and low available phosphorus and micronutrients, whereas DB-NVAS showed the opposite profile (low organic matter and total nitrogen, high available phosphorus and micronutrients). Because the tea quality-component data in this study represent a single pooled composite sample per soil type rather than independent biological replicates (Section 2.4), and because only three soil-type units are available, we do not report a formal correlation or association analysis between soil properties and tea quality components in this manuscript. Any relationship between specific soil properties and tea quality traits suggested by this soil-type-level contrast should be regarded as a hypothesis to be tested in a future study with bed-resolved, replicated sampling, and is not treated as established by the present data.

4. Discussion

The two volcanic ash soils examined in this study (B-VAS and VDB-VAS) contained markedly more organic matter and total nitrogen but less available phosphorus and fewer micronutrients than the non-volcanic ash soil (DB-NVAS), consistent with previous reports that the allophanic clay fraction of Jeju volcanic ash soils retains organic matter and nitrogen while strongly fixing phosphate [15,17]. A comparable soil-type contrast was reported for garlic cultivated on Jeju Island, in which volcanic ash soils likewise showed higher organic matter and nitrogen but lower phosphorus availability than non-volcanic ash soil, with corresponding differences in crop growth and mineral composition [16,18]. The present results extend this pattern to tea, showing that a similar soil-type contrast is associated with the primary and secondary metabolite balance of 'Sangmok' shoots observed in this pilot planting.

The markedly higher total amino acid and theanine values in the volcanic-ash pooled samples are consistent with the well-documented role of nitrogen availability in promoting amino acid accumulation, and theanine biosynthesis in particular, in tea plants [6,7,9,11,13,14]. Nitrogen fertilization studies have similarly shown that increased nitrogen supply raises free amino acid and theanine contents in tea shoots, generally at the expense of catechin accumulation [6–8,10]. The inverse pattern between nitrogen/organic matter status and catechin-related traits observed across the pooled samples is consistent with the carbon–nitrogen balance hypothesis, which proposes that under nitrogen-rich conditions, carbon skeletons and photosynthate are preferentially allocated toward amino acid and protein synthesis, whereas under nitrogen-limited conditions relatively more carbon is available for phenylpropanoid-derived secondary metabolites such as catechins [12]. DB-NVAS also had higher available P_2O_5 and micronutrient concentrations (Fe, Mn, Zn, Cu; Table 1) alongside higher EGC and EC and lower CQI values (Table 5); this soil-type-level pattern is broadly consistent with reports that adequate leaf micronutrient status, including Zn, is associated with enhanced polyphenol accumulation in tea [8,22], although the present data cannot establish a causal or statistically supported relationship between any specific nutrient and catechin accumulation.

Given the limited number of plants per treatment (n = 9–10), the survival comparison in this study is best regarded as a pilot-scale, long-term field observation over 33 months rather than a definitive statistical test; the numerical pattern within this planting (88.9% in B-VAS versus 50.0–55.6% in the other soils) nonetheless provides a hypothesis-generating basis for larger-scale, multi-site trials. Notably, growth and survival did not track the same soil-type gradient as catechin accumulation: B-VAS combined the highest survival (88.9%) and the greatest height and leaf-number gains with the highest amino acid and theanine

contents, whereas DB-NVAS—despite its higher catechin, EGC, and EC content but lower CQI—showed markedly lower survival than B-VAS (55.6% vs. 88.9%, though still above VDB-VAS's 50.0%, the lowest of the three soils) and growth that plateaued and then declined after little more than a year in the field, the apparent late decline likely confounded by the loss of all but one plant by late 2024 (Section 3.2). B-VAS and VDB-VAS were nevertheless chemically similar to each other in most respects (Table 1)—including organic matter, total nitrogen, and most exchangeable cations and micronutrients, with VDB-VAS if anything having higher available P_2O_5—so this nearly two-fold difference in survival between two soils of the same broad volcanic-ash category is unlikely to be explained by the measured soil chemistry alone; unmeasured physical soil properties (e.g., drainage, bulk density, or soil structure) or bed-level stochastic effects not captured by this chemical characterization more plausibly contributed to it. Notably, the five-plant growth-monitoring subsample also diverged sharply from the overall soil-type survival pattern reported in Table 2: in VDB-VAS, all five tagged plants remained alive throughout the growth-monitoring period, implying that the plants that died were entirely among the untagged individuals, whereas in DB-NVAS only one of the five tagged plants survived to the final growth survey (December 2024), implying that most of the survivors recorded in Table 2 were untagged individuals. With only five tagged plants per soil type, these opposite-direction divergences most plausibly reflect chance variation, potentially compounded by the within-bed clustering discussed above, but they mean that the growth trajectories in Figure 1 should be read as describing this particular five-plant subsample rather than the full transplanted population. Because DB-NVAS also had the lowest OM (28.2 $g \cdot kg^{-1}$ versus >150 $g \cdot kg^{-1}$ in the volcanic ash soils), the poor establishment and growth of 'Sangmok' in this soil are more plausibly explained by insufficient organic matter and associated water- and nutrient-holding capacity for a young, transplanted tea plant than by any single mineral element, although this study cannot separate the contribution of OM from that of other correlated soil properties. This raises the untested hypothesis that organic-matter amendment could improve stand establishment of DB-NVAS despite its favorable catechin-accumulation profile; confirming this, and any resulting cultivation recommendation, would require a replicated trial that manipulates organic matter directly rather than the descriptive, single-planting comparison presented here.

It should also be noted that the absence of fertilization was maintained for 33 months rather than a short-term trial; over this period, progressive depletion of readily available nutrients and inter-annual variation in the greenhouse microenvironment (e.g., differences in indoor temperature, light, or ventilation associated with the fixed position and structure of the beds within the unheated greenhouse across 2022–2024, rather than open-field weather, since the plants were grown under cover and drip-irrigated) may have contributed additively to the soil-type differences observed, and these factors could not be statistically separated from the intrinsic soil-type effect in the present unreplicated-year design.

A related methodological point concerns the level of replication underlying the different analyses. Soil chemical properties (Table 1) are based on three independent replicate beds per soil type, providing genuine, bed-level biological replication and supporting the ANOVA and Duncan's multiple range test results reported for these traits. By contrast, the tea quality-component data (Tables 4 and 5) represent a single pooled composite sample per soil type—because survival losses left insufficient leaf biomass on individual beds to prepare separate bed-level samples (Section 2.4)—analyzed in technical triplicate rather than independent biological replicates; these values are therefore presented descriptively, without correlation or other inferential analysis against soil physicochemical properties (Section 3.5). The survival and growth records (Table 2, Figure 1), meanwhile, were compiled at the level of individual plants pooled across the three replicate beds per soil type

without retaining bed identity in the dataset, so any systematic differences among beds within a soil type (e.g., in microtopography, drainage, or local shading) could not be separated from the soil-type effect for these specific traits. Taken together, only the soil chemical properties in this study are based on a fully replicated, bed-level design; the tea quality-component and field performance data should both be interpreted with appropriate caution until confirmed in future trials with bed-resolved sampling and mixed-model analyses.

This composite-sampling approach was adopted deliberately rather than as an incidental shortcut: with survival already reduced to 50–56% in two of the three soil types by the first-flush harvest, retaining bed identity would have required destructively sampling individual beds down to only one or two surviving plants each, which we judged more likely to introduce additional, uncontrolled variation than to yield meaningful bed-level statistics. We therefore regard the present dataset as an exploratory, descriptive directional pattern—one consistent with the carbon–nitrogen balance framework discussed above—rather than a quantitatively confirmed effect. The priority for follow-up work is accordingly not to repeat this exploratory comparison but to test it under a design capable of supporting formal statistical inference, for example by increasing initial planting density per bed to buffer against mortality, or by sampling shoots earlier in stand establishment before substantial losses accumulate, so that bed-level composite samples and true biological replication of the quality-component data can be maintained even under realistic field attrition.

Taken together, these descriptive, soil-type-level patterns raise the hypothesis that the volcanic ash soils widely distributed on Jeju Island are comparatively favorable for growing ‘Sangmok’ tea with high amino acid and theanine content—desirable for umami-rich green tea and matcha—whereas the non-volcanic ash soil showed higher catechin accumulation and potentially greater astringency and functional properties, alongside weaker growth under the conditions tested here; because these patterns derive from a single pooled composite sample per soil type and from survival/growth records pooled across beds, they should be treated as hypotheses for confirmation in a replicated trial rather than as established soil-type effects. Stated as testable hypotheses rather than management recommendations, these patterns suggest that the suitability of a planting site for ‘Sangmok’ depends on soil type and the intended end product, that organic matter amendment improves tea establishment in non-volcanic ash soil, and that nitrogen and phosphorus fertilization modifies the amino acid/catechin balance within a given soil type. These could be tested in future replicated trials, potentially in conjunction with soil-biological approaches such as leguminous intercropping, which has been shown to enhance theanine accumulation via rhizosphere microecological effects [23].

5. Conclusions

Cultivation of the tea cultivar ‘Sangmok’ in three physicochemically distinct soil types on Jeju Island over 33 months showed descriptive plant-level differences in survival and growth: volcanic ash soils, characterized by high organic matter and total nitrogen but low available phosphorus and micronutrients, showed greater growth (410.9% height increase and, by February 2023, 165.4% leaf number increase in B-VAS) together with markedly higher total free amino acid and theanine contents than a non-volcanic ash soil with the opposite soil nutrient profile and weaker growth (116.1% height increase) under the conditions tested here, whereas survival was numerically highest in B-VAS (88.9% vs. 50.0–55.6% in the other soils) but did not differ significantly among soil types. This final DB-NVAS growth value is based on a single surviving plant at that time point and should be interpreted with due caution. The soil-type-level contrast in nutrient profile (Table 1) paralleled the observed differences in amino acid and catechin accumulation

(Sections 3.3 and 3.4); because tea quality components were measured from a single pooled composite sample per soil type and bed identity was not retained for survival and growth, these associations should be regarded as hypothesis-generating observations from this pilot planting rather than confirmed soil-type effects. These findings suggest that, of the soils examined, the volcanic ash soils widely distributed on Jeju Island may be better suited to 'Sangmok' cultivation, and provide testable hypotheses for soil-type-informed cultivation strategies—including organic matter amendment of non-volcanic ash soil—to target specific growth and quality profiles in Korean tea production. However, because survival and growth records in this study were pooled at the individual plant level across replicate beds, these field performance trends should be regarded as preliminary and require confirmation in fully replicated, multi-site trials incorporating bed-level mixed-model analyses.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/horticulturae12101279/s1: Table S1: Soil chemical properties and tea quality-related components of 'Sangmok' tea shoots by soil type and replicate index, underlying Table 1, Table 4, and Table 5 of the manuscript; Table S2: Method validation data for the free amino acid, theanine, catechin, and caffeine analyses of 'Sangmok' tea shoots (Sections 2.5 and 2.6 of the manuscript); Table S3: Individual-plant height (cm) of 'Sangmok' tea by soil type and plant ID at each survey date, underlying Figure 1 of the manuscript. "Dead" marks the survey date at or after which a given plant was recorded dead; the first "Dead" entry for each plant is the survey date of first-recorded mortality, and no further height values were recorded for that plant. Soil type abbreviations: B-VAS, black volcanic ash soil; VDB-VAS, very dark-brown volcanic ash soil; DB-NVAS, dark-brown non-volcanic ash soil.

Author Contributions: Conceptualization, S.J.K.; methodology, S.J.K.; investigation, Y.-S.K., H.R.H., D.-G.M., B.-H.K.; formal analysis, Y.-S.K., H.R.H., D.-G.M., B.-H.K.; writing—original draft preparation, Y.-S.K.; writing—review and editing, S.J.K.; supervision, S.J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Rural Development Administration (RDA), Republic of Korea, grant number PJ013861 ('Selection and breeding of cold-hardy tea plant genetic resources').

Institutional Review Board Statement: Not applicable. This study did not involve humans or animals.

Informed Consent Statement: Not applicable. This study did not involve human participants.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Acknowledgments: During the preparation of this manuscript, the authors used Claude (Claude Opus 5.5; Anthropic, San Francisco, CA, USA) for the purposes of English language editing, verification of statistical calculations, and generating the plotting code for Figure 1. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The sponsors had no role in the design, execution, interpretation, or writing of the study.

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