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RESEARCH ARTICLE

Cultivar-Specific Responses of *Curcuma Longa* L. to Soil Properties: A Multivariate Assessment of Phytochemical Profiles and Extraction Yield

Naronk Duangkaew[1], Tharakorn Maneerat[1,2,4], Plaipol Dedvisitsakul[1,3] and Kanchana Watla-iad[1,2,*]

[1]*School of Science, Mae Fah Luang University, Chiang Rai 57100, Thailand*
[2]*Center of Chemical Innovation for Sustainability, School of Science, Mae Fah Luang University, Chiang Rai 57100, Thailand*
[3]*Microbial Products and Innovation Research Unit, School of Science, Mae Fah Luang University, Chiang Rai 57100, Thailand*
[4]*Medicinal Plant Innovation Center, Mae Fah Luang University, Chiang Rai 57100, Thailand*

([*]Corresponding author's e-mail: kanchana.wat@mfu.ac.th)

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Abstract

Soil properties significantly impact turmeric (*Curcuma longa* L.) growth and quality. This study evaluated the response of two commercial cultivars, Trang 1 (T1) and Trang 84-2 (T84-2), to varying soil conditions across 24 sites in Chiang Rai, Thailand. Both cultivars successfully exceeded the Thai Herbal Pharmacopoeia (THP) standard for total curcuminoids ($\geq 5.0\%$ w/w). Cluster analysis categorized the soil profiles into three distinct groups: C1 (highest calcium, 2398 ± 749 mg/kg), C2 (highest phosphorus, 68.8 ± 72.0 mg/kg), and C3 (lowest pH, 4.72 ± 0.80). An independent t-test revealed that T1 produced significantly higher extraction yields, total curcuminoids, and bisdemethoxycurcumin (BDMC) than T84-2 ($p < 0.05$). Its quality parameters correlated positively with soil organic carbon (OC). Furthermore, T1 exhibited remarkable phenotypic stability across soil clusters (ANOVA $p > 0.05$), strongly governed by genetic background, as supported by high broad-sense heritability ($H^2 = 72.6\%$ for BDMC). Conversely, T84-2 maintained a narrower range of extraction yield but displayed greater sensitivity to nitrate, potassium, and excessive cations. These findings provide crucial insights into the distinct characteristics of turmeric cultivars, highlighting the necessity of cultivar-specific soil management, such as prioritizing organic amendments for T1 and preventing over-fertilization for T84-2, to optimize both extraction yield and medicinal quality.

Keywords: Trang 1 cultivar, Trang 84-2 cultivar, Bisdemethoxycurcumin, Chemometrics, Phenotypic stability

Introduction

Turmeric (*Curcuma longa* L.), widely cultivated in Southeast Asia, contains three majors bioactive curcuminoids: Curcumin (CUR), demethoxycurcumin (DMC), and bisdemethoxycurcumin (BDMC), which exhibit notable antioxidants, anti-inflammatory, and therapeutic properties [1-2]. Among these compounds, CUR is the most extensively studied and exhibits the highest superoxide anion-scavenging activity. However, its therapeutic application is limited by its instability under physiological conditions [3]. While BDMC is more stable for therapeutic application and is also the most active in modulating the MDR-1 gene in multidrug-resistant cervical carcinoma cells [4], inhibition of NF-κB signaling and the activation of the Nrf2/HO-1 pathway [5], effectively reducing chronic inflammation and oxidative stress associated with neurodegenerative diseases and osteoarthritis [5,6]. The Thai Herbal Pharmacopoeia (THP) has studied and recommended that dried turmeric should not contain less than 6.0% v/w of turmeric oil content and 5.0% w/w of total curcuminoid content calculated as CUR [7]. The

quality of turmeric, particularly its curcuminoid content, is a key factor for both culinary and medicinal uses.

In Thailand, turmeric cultivation is expanding due to growing demand for both local consumption and export. Chiang Rai, a northern province with its ideal soil and climate, has become an important area for turmeric cultivation [8]. The important factors for *Curcuma longa* L. growth and quality, like soil nutrients, environmental conditions, and altitude, significantly influence rhizome yield and curcumin content [9]. Dark-red soil, characterized by its relatively loose structure with the lowest apparent density (0.867 g cm^{-3}), an optimal pH level of 5.26, and specific nutrient combinations, has been associated with higher turmeric yield and curcumin content [10]. Balanced application of nitrogen, phosphorus, and potassium fertilizers enhances turmeric growth, yield, and curcumin content [11-13]. Although soil properties (organic carbon, pH, EC, and CEC) influence plant development and secondary metabolite biosynthesis, their specific impact on turmeric extraction yield and curcuminoid profiles in Chiang Rai remains uninvestigated. This study evaluated two officially Thai cultivars, Trang 1 (T1) and Trang 84-2 (T84-2), selected for exceeding the Thai Herbal Pharmacopoeia curcuminoid standards [14-15]. In southern Thailand, T1 yields ~2.23 tons/rai of fresh rhizomes, containing 10.62% curcuminoids, 7.99% essential oils, and 47% ar-turmerone; conversely, T84-2 yields ~2.59 tons/rai, with 11.4% curcuminoids, 7.78% essential oils, 47.6% ar-turmerone, and 23.38% alpha-turmerone [14]. Crucially, how these cultivars perform under Chiang Rai's specific soil conditions has not yet been examined. It was hypothesized that variations in specific soil properties would significantly influence these parameters and that the two cultivars would exhibit distinct adaptive performances under local conditions. Therefore, this study aimed to investigate the relationship between soil properties and the agronomic and phytochemical traits of turmeric cultivated in Chiang Rai, northern Thailand. The findings can guide farmers in optimizing soil management practices and selecting the most suitable cultivar between T1 and T84-2 for local cultivation. Ultimately, this study contributes to improving the quality of turmeric production, supporting both local consumption and export demand.

Materials and methods

Study sites and turmeric rhizome sample collection

The study sampled 24 commercial turmeric (*C. longa* L.) farms across Chiang Rai, Thailand, representing regional large-scale cultivation practices. Collection sites encompassed Mae Lao, Thoeng, Mae Fah Luang, Wiang Pa Pao, Mae Chan, Chiang Saen, and Mueang Chiang Rai districts (including Doi Hang, Tha Sut, and Mae Kao Tom sub-districts). Geographic and cultivar data are detailed in **Figure 1** and **Table 1**. Turmeric rhizome sampling was conducted in 2022 at 9 months post-planting. To ensure uniform physiological age, harvesting at each site was strictly synchronized with the 'dry matter accumulating period', which was visually identified by complete foliar senescence, specifically the drying and collapsing of leaves, following regional commercial harvest standards [16,17]. At each site, 5 - 10 healthy turmeric clumps were randomly collected and pooled into a single composite sample [18,19], yielding 24 samples (S1 - S24) processed according to Thai Herbal Pharmacopoeia standards [7]. These comprised two cultivars: Trang 1 (T1, n = 17) and Trang 84-2 (T84-2, n = 7). Their geographic distribution indicates cultivation across multiple districts, reflecting adaptability to regional environmental conditions (**Figure 1**).

Table 1 Geographical sampling locations and corresponding cultivars of the 24 turmeric rhizome samples collected in Chiang Rai province.

No. Sample	Location	Cultivar
S1 - S10	Pong Phrae, Mae Lao District	Trang 1
S11	Mueang Chiang Rai District	Trang 84-2
S12	Mae Chan District	Trang 84-2

No. Sample	Location	Cultivar
S13	Ngio, Thoeng District	Trang 84-2
S14-S15, S17-S18	Doi Hang, Mueang Chiang Rai District	Trang 1
S16, S19	Doi Hang, Mueang Chiang Rai District	Trang 84-2
S20	Tha Sut, Mueang Chiang Rai District	Trang 84-2
S21	Mae Salong Nai, Mae Fah Luang District	Trang 1
S22	Chedi Mai, Wiang Pa Pao District	Trang 84-2
S23	Chiang Saen District	Trang 1
S24	Mae Kao Tom, Muang Chiang Rai District	Trang 1

Turmeric rhizomes preparation and analysis

Turmeric rhizomes were identified by comparison with herbarium specimens at the Medicinal Plant Innovation Center, Mae Fah Luang University, Thailand. Fresh rhizomes were washed, machine-brushed, shade-dried overnight, sliced, and oven-dried at 55 °C for 6 h. Dried samples were then pulverized and sieved into powder. Turmeric quality parameters, including extraction yield and total curcuminoid content, were determined using a spectrophotometric method (CUR (Spectroscopic method)) adapted from the Thai Herbal Pharmacopoeia [7]. Curcumin (CUR), bisdemethoxycurcumin (BDMC), and demethoxycurcumin (DMC) were quantified via high-performance liquid chromatography (HPLC) adapted from Mudge *et al*. [19]. Total curcuminoids by HPLC were calculated as the total of CUR, BDMC, and DMC (total CUR).

HPLC analysis was performed using an Agilent 1260 Infinity II system equipped with a quaternary pump, a temperature-controlled column compartment, an autosampler, and a UV-visible diode array detector. Chromatographic separation utilized an InfinityLab Poroshell 120 EC-C18 column (4.6×150 mm, 4 µm). Reference standards included USP standards for Curcumin (Lot No.: R137E0, CAS# 1151855), Desmethoxycurcumin (CAS# 1173100), and Bisdesmethoxycurcumin (CAS# 1075305) from Merck (USA). Certified reference materials comprised NIST SRM 3299 (*Curcuma longa* L. Rhizome), NIST-3300 (*Curcuma longa* L. Rhizome Extract), and Curcumin DRE-C11780000.



Figure 1 Locations of the 24 turmeric farm sampling sites across multiple districts in Chiang Rai Province, Thailand.

Soil sampling and physicochemical analysis

At each site, triplicate soil samples from the turmeric planting site, as mentioned above, were randomly collected from three positions evenly distributed across the entire plot at a depth of 15 cm, following the standardized procedures described by Motsara [20]. The three subsamples from each site were thoroughly mixed to form a single composite sample per location for subsequent nutrient analysis. Composite soil samples were air-dried (≤ 35 °C, 30% - 60% relative humidity). Paired soil–rhizome samples were labeled

using a synchronized coding system (S1 - S24) to ensure precise data integration between soil properties and phytochemical profiles.

For soil physicochemical characterization, pH and electrical conductivity (EC) were determined using a potentiometric method and a 1:2 soil/water suspension, respectively [20]. Soil organic matter (SOM) was determined by the weight loss on ignition method. Subsequently, soil organic carbon (SOC) was calculated using the standard conversion factor (SOC = SOM×0.58) [20]. Available nitrogen, including nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) was extracted using Morgan's solution and measured spectrophotometrically at 470 nm [21]. Available phosphorus (P) was determined according to Bray's method [22]. Exchangeable cations (K, Ca, and Mg) and cation exchange capacity (CEC) were extracted with 1 N ammonium acetate (pH 7.0) and quantified via inductively coupled plasma mass spectrometry (ICP-MS) [23]. Total sulfur (S) was analyzed following wet digestion with nitric (HNO_3) and perchloric ($HClO_4$) acids, with absorbance measured at 420 nm. [24]. Finally, soil micronutrients (Fe, Zn, Cu, and Mn) were extracted using the DTPA method and measured by ICP-MS [20].

Statistical analysis

Statistical analyses were performed using MetaboAnalyst 6.0 (a web-based statistical analysis platform, Xia Lab, University of Alberta, Edmonton, Canada). An independent Student's t-test evaluated differences in extraction yield and curcuminoid profiles (CUR, DMC, BDMC, and total curcuminoids) between cultivars T1 and T84-2. Cultivar separation and driving parameters were visualized using Principal Component Analysis (PCA) and Partial Least Squares Discriminant Analysis (PLS-DA) with Variable Importance in Projection (VIP) scores. For soil data, Hierarchical Cluster Analysis (HCA) using complete clustering algorithm and squared Euclidean distance grouped sampling sites, with differences validated via one-way ANOVA ($p < 0.05$). Broad-sense heritability (H^2) was estimated by partitioning phenotypic variance into genotypic (Vg) and environmental (Ve) components derived from ANOVA. Cluster features were visualized using the K-means-based Feature Overview, and Pearson's correlation evaluated relationships between soil properties and curcuminoid parameters.

Results and discussion

Extraction yield and phytochemical profiles of turmeric cultivars

The analytical evaluation of twenty-four turmeric samples revealed significant phytochemical differences between the T1 (n = 17) and T84-2 (n = 7) cultivars (**Table 2**, **Figure 2**). Cultivar T1 exhibited a significantly superior performance compared to T84-2, characterized by a higher extraction yield (p = 0.0014), total curcuminoid content (12.82 ± 1.71% w/w vs. 11.10 ± 1.25 %w/w; p = 0.0131), and BDMC content (p = 0.001). Notably, the highest total curcuminoid level (17.23% w/w) was recorded in a T1 sample from the Doi Hang subdistrict (sample S18). To ensure data reliability, curcumin quantification was successfully cross-evaluated using both spectroscopic and HPLC methods. These findings demonstrate that cultivar T1 possesses a stronger intrinsic capacity for curcuminoid biosynthesis, making it a superior cultivar under the local environmental conditions. This genetic and environmental differentiation is further validated by the fact that all samples were analyzed at a standardized 9-month maturity stage, the peak period for stable curcuminoid deposition [16,17].

Table 2 Extraction yield and curcuminoid contents of T1 and T84-2 turmeric cultivars across twenty-four sampling sites in Chiang Rai, Thailand.

Sample	Turmeric parameter						
	Cultivar	Extraction Yield (%w/w)	CUR (Spectroscopic, %w/w)	CUR (HPLC, %w/w)	BDMC (HPLC, %w/w)	DMC (HPLC, %w/w)	Total Curcuminoids (HPLC, %w/w)
S1	T1	17.05 ± 1.0	7.18 ± 0.69	7.96 ± 0.10	2.85 ± 0.07	2.33 ± 0.03	13.1 ± 0.28
S2	T1	14.73 ± 0.57	6.33 ± 0.6	7.81 ± 0.05	2.71 ± 0.12	2.14 ± 0.05	12.1 ± 0.30

Sample	Turmeric parameter						
	Cultivar	Extraction Yield (%w/w)	CUR (Spectroscopic, %w/w)	CUR (HPLC, %w/w)	BDMC (HPLC, %w/w)	DMC (HPLC, %w/w)	Total Curcuminoids (HPLC, %w/w)
S3	T1	19.29 ± 0.2	9.23 ± 0.73	8.37 ± 0.22	4.04 ± 0.17	2.73 ± 0.08	15.14 ± 0.47
S4	T1	17.26 ± 0.19	6.73 ± 0.57	7.51 ± 0.07	3.07 ± 0.05	2.22 ± 0.02	12.83 ± 0.13
S5	T1	20.02 ± 0.69	9.06 ± 0.79	8.22 ± 0.11	4.02 ± 0.07	2.71 ± 0.05	14.95 ± 0.22
S6	T1	18.22 ± 0.5	9.6 ± 0.86	7.60 ± 0.43	3.91 ± 0.07	2.54 ± 0.13	14.05 ± 0.63
S7	T1	22.03 ± 0.59	10.21 ± 0.69	7.94 ± 0.08	3.90 ± 0.04	2.76 ± 0.37	14.35 ± 0.12
S8	T1	18.51 ± 0.16	9.98 ± 0.52	8.52 ± 0.11	3.50 ± 0.06	2.50 ± 0.03	14.51 ± 0.20
S9	T1	19.03 ± 0.36	9.81 ± 0.45	7.66±0.23	4.06 ± 0.18	2.54±0.09	14.26 ± 0.50
S10	T1	18.85 ± 0.47	10.03 ± 0.2	7.77 ± 0.01	3.86 ± 0.01	2.47 ± 0.01	14.10 ± 0.02
S11	T84-2	15.14 ± 0.36	7.35 ± 0.24	8.06 ± 0.01	1.70 ± 0.02	2.20 ± 0.00	11.96 ± 0.02
S12	T84-2	14.45 ± 0.37	13.3 ± 1.07	6.24 ± 0.08	1.82 ± 0.04	2.54 ± 0.05	10.60 ± 0.17
S13	T84-2	10.96 ± 0.08	5.26 ± 0.39	6.38 ± 0.05	1.70 ± 0.02	2.00 ± 0.01	10.08 ± 0.08
S14	T1	12.01 ± 0.12	3.81 ± 0.18	5.88 ± 0.23	1.26 ± 0.09	1.62 ± 0.07	8.76 ± 0.38
S15	T1	14.93 ± 0.64	6.68 ± 0.54	7.03 ± 0.12	1.16 ± 0.05	1.73 ± 0.03	9.93 ± 0.19
S16	T84-2	14.96 ± 0.22	8.06 ± 0.3	7.26 ± 0.13	2.20 ± 0.06	2.30 ± 0.05	11.76 ± 0.23
S17	T1	14.59 ± 0.65	8.19 ± 0.48	7.14 ± 0.15	2.59 ± 0.10	2.22 ± 0.05	11.95 ± 0.31
S18	T1	17.62 ± 0.20	17.23 ± 0.78	7.42 ± 0.03	4.44 ± 0.01	2.82 ± 0.01	14.68 ± 0.04
S19	T84-2	15.62 ± 0.28	9.78 ± 0.33	7.59 ± 0.15	2.49 ± 0.07	2.58 ± 0.07	12.65 ± 0.29
S20	T84-2	14.29 ± 0.38	13.69 ± 1.31	8.13 ± 0.10	2.06 ± 0.03	2.39 ± 0.04	12.58 ± 0.17
S21	T1	16.78 ± 0.47	9.21 ± 0.25	8.29 ± 0.08	3.06 ± 0.05	2.57 ± 0.03	13.91 ± 0.16
S22	T84-2	12.29 ± 0.33	5.85 ± 0.56	6.48 ± 0.10	1.85 ± 0.01	2.39 ± 0.04	10.7 ± 0.12
S23	T1	17.47 ± 0.07	10.51 ± 0.49	7.65 ± 0.05	3.77 ± 0.03	2.55 ± 0.02	13.97 ± 0.10
S24	T1	17.14 ± 0.43	12.56 ± 1.2	7.69 ± 0.07	3.38 ± 0.09	2.60 ± 0.03	13.66 ± 0.18
Mean±SD		**16.49±2.67**	**9.152±0.59**	**7.29±1.32**	**2.92±0.97**	**2.40±0.29**	**12.82±1.71**

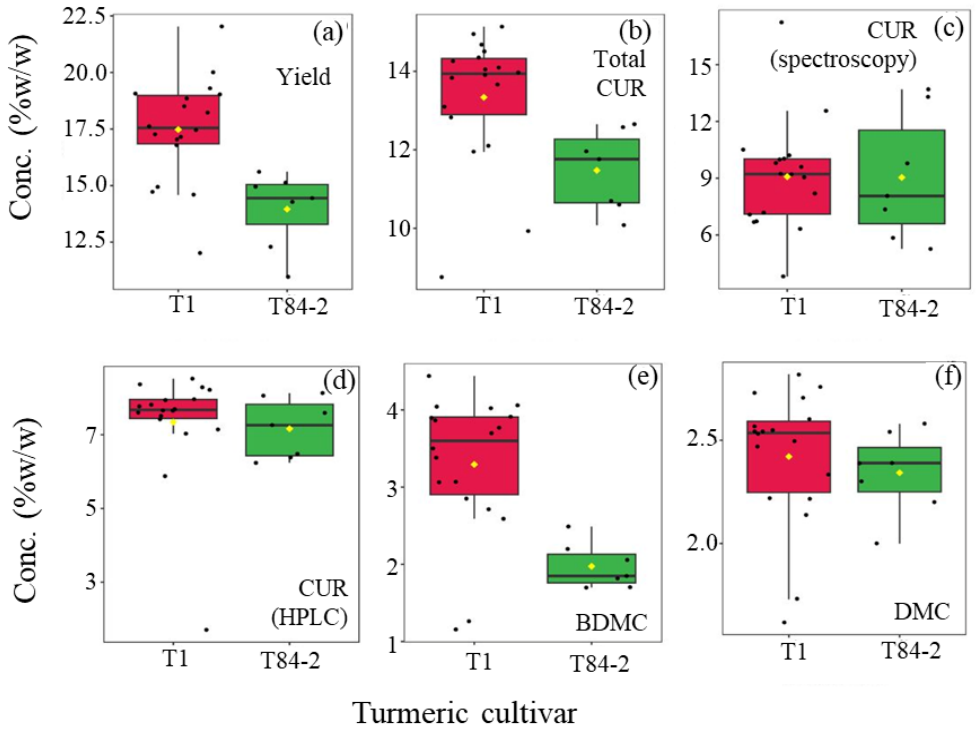


Figure 2 Box plots comparing the extraction yield and curcuminoid contents (% w/w) between turmeric cultivars T1 (red) and T84-2 (green): (a) extraction yield, (b) total curcuminoids, (c) curcumin (CUR) determined by spectroscopic method, (d) curcumin (CUR) determined by HPLC method, (e) BDMC, and (f) DMC. Yellow diamonds indicate the mean values, while black dots represent individual data points.

PCA of data in **Table 2** revealed distinct spatial separation between cultivars T1 (n = 17) and T84-2 (n = 7), with PC1, PC2 and PC3 explaining 71.1%, 25.0% and 2.6% of the total variance, respectively (**Figure 3(a)**). PLS-DA identified extraction yield, total curcuminoids, and BDMC as the top discriminating variables (VIP ≥ 0.5, **Figure 3(b)**). Notably, T1 exhibited significant BDMC enrichment, underscoring its chemical stability and pharmacological potential in modulating multi-drug resistance [4].

The observed variations can be attributed to inherent genotypic differences between the two cultivars. Previous studies demonstrate that cultivar background significantly influences curcuminoid production, and higher rhizome extraction yields do not necessarily correlate with greater curcuminoid content [25]. Interestingly, while BDMC and total curcuminoids differed significantly in our study, CUR and DMC levels remained consistent across both analytical methods, suggesting differential regulation within the curcuminoid biosynthetic pathway. Cultivar-specific genetic factors may selectively modulate the upstream synthesis or metabolic conversion rates of BDMC while maintaining a steady curcumin baseline. This hypothesis aligns with molecular evidence showing multiple curcumin synthase isoforms (CURS1, CURS2, and CURS3) in *Curcuma longa* with distinct substrate specificities for precursor molecules like feruloyl-CoA and *p*-coumaroyl-CoA [26]. Consequently, differential expression profiles of these *CURS* genes can dictate the stoichiometric accumulation of specific analogs, such as BDMC, without disrupting core curcumin synthesis [27]. Moreover, the pronounced fluctuation in T84-2's quality parameters indicates high environmental sensitivity. Because secondary metabolite genes are actively modulated by environmental variables, including soil composition, climate, and microenvironments [14,28], the variance in T84-2 likely stems from site-specific environmental differences, though the influence of a smaller sample size must be considered**.** This evident sensitivity warrants a detailed investigation into specific soil properties and their direct correlations with turmeric quality.

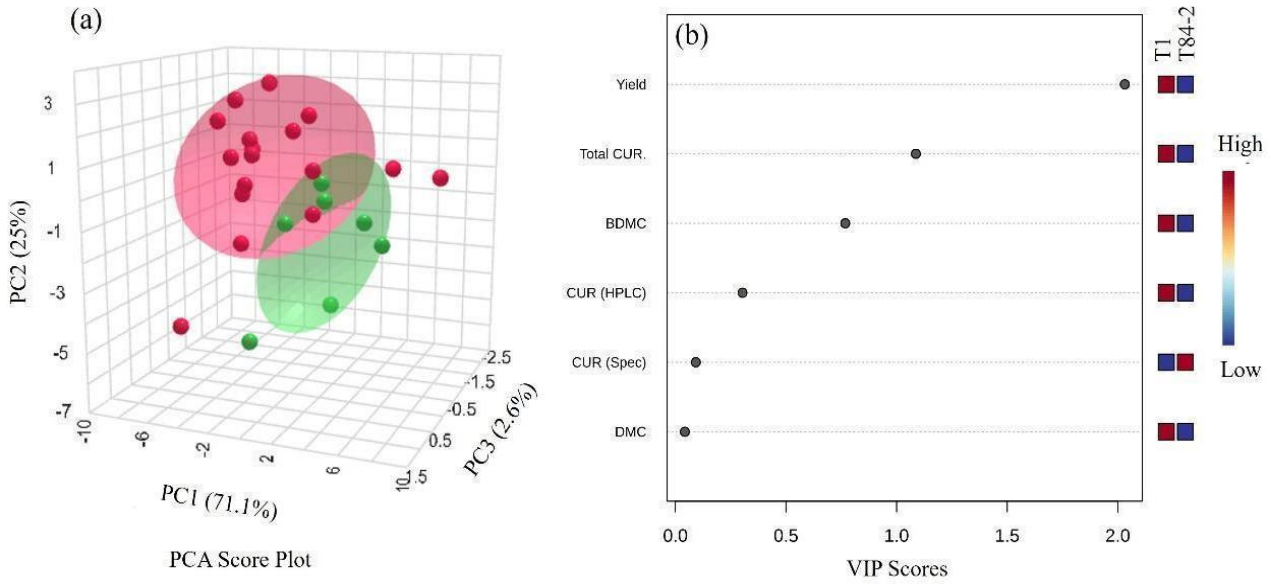


Figure 3 Differentiation of turmeric cultivars (T1 and T84-2). **(a)** 3D-PCA score plot displaying the clustering trends of the two cultivars based on PC1 (71.1%), PC2 (25%), and PC3 (2.6%). **(b)** VIP scores from PLS-DA identifying the key quality parameters of driving cultivar separation.

Soil physicochemical parameters and clustering analysis across sampling locations

Soil physicochemical profiles across the 24 sampling locations are detailed in **Table 3**. To identify geographical patterns among cultivation environments, hierarchical cluster analysis (HCA) using complete clustering algorithm and squared Euclidean distance was performed, generating a dendrogram (Figure 4(A)) that categorized the sites into three distinct clusters (C1, C2, and C3). This partition revealed a notable pattern associated with the cultivated varieties. Cluster 1 (C1, n = 6) is a mixed group containing the T1 cultivar (S6, S8, S17, S21) alongside two T84-2 samples (S11, S13). Cluster 2 (C2, n = 5) containing two T1 cultivar samples (S4, S18) and three T84-2 cultivar samples (S12, S20, S22), while Cluster 3 (C3, n = 13) containing eleven T1 samples (S1, S2, S3, S5, S7, S9, S10, S14, S15, S23, S24) and two T84-2 samples (S16, S19). To further characterize these distinct cultivation environments, a one-way analysis of variance (ANOVA) was conducted to evaluate significant differences in soil parameters among the three clusters (**Table 4**).

Table 3 Soil physicochemical parameters (mean ± SD) across the different sampling sites.

Sample	Soil physicochemical parameters															
	OC (%w/w)	pH	EC (µS/cm)	CEC (meq/ 100g)	NO_3 – N (mg/kg)	NH_4-N (mg/kg)	P (mg/kg)	K (mg/kg)	Na (mg/kg)	S (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Zn (ug/kg)	Cu (ug/kg)
S1	3.65 ± 0.02	3.89 ± 0.34	62.0 ± 20.3	25.0 ± 1.6	58.9 ± 3.7	46.1 ± 16.9	5.9 ± 0.1	45.2 ± 0.8	3.4 ± 0.3	4.1 ± 0.2	809 ± 13	114.3 ± 2.9	0.038 ± 0.017	124.7 ± 18.1	84.0 ± 5.0	2.24 ± 1.66
S2	2.05 ± 0.04	4.72 ± 0.86	25.6 ± 15.3	14.6 ± 0.5	0.0 ± 1.6	71.3 ± 3.2	2.9 ± 0.3	157.3 ± 183.2	3.4 ± 3.0	2.4 ± 0.4	1,246 ± 1055	165.0 ± 109.9	0.511 ± 0.076	105.1 ± 1.1	3.4 ± 3.4	1.42 ± 0.14
S3	2.74 ± 0.13	3.71 ± 0.32	14.5 ± 0.6	16.7 ± 0.3	22.1 ± 2.2	46.8 ± 2.7	9.0 ± 0.7	74.7 ± 3.7	ND	1.6 ± 0.4	299 ± 7	46.6 ± 2.6	0.092 ± 0.007	97.2 ± 19.0	0.1 ± 0.1	1.09 ± 1.05
S4	4.07 ± 0.05	6.35 ± 0.33	127.1 ± 18.1	23.7 ± 0.6	32.5 ± 0.7	92.6 ± 0.5	37.3 ± 0.6	498.3 ± 33.6	3.8 ± 6.6	3.9 ± 0.5	1,656 ± 53	320.9 ± 8.3	1.186 ± 0.157	81.3 ± 8.5	8.3 ± 3.0	1.27 ± 0.43
S5	5.45 ± 0.07	4.20 ± 0.21	13.9 ± 0.7	27.5 ± 0.5	12.0 ± 4.1	138.8 ± 20.5	1.5 ± 0.7	109.7 ± 6.4	1.4 ± 2.5	6.2 ± 0.4	441 ± 17	129.3 ± 7.2	0.326 ± 0.029	70.2 ± 9.2	2.7 ± 1.7	27.16 ± 1.35

Sample	Soil physicochemical parameters															
	OC (%w/w)	**pH**	**EC (µS/cm)**	**CEC (meq/ 100g)**	**NO_3 – N (mg/kg)**	**NH_4-N (mg/kg)**	**P (mg/kg)**	**K (mg/kg)**	**Na (mg/kg)**	**S (mg/kg)**	**Ca (mg/kg)**	**Mg (mg/kg)**	**Mn (mg/kg)**	**Fe (mg/kg)**	**Zn (ug/kg)**	**Cu (ug/kg)**
S6	4.34 ± 0.12	6.25 ± 0.05	143.5 ± 150.1	27.6 ± 1.3	43.8 ± 0.7	43.0 ± 20.9	18.6 ± 0.0	262.6 ± 202.7	4.8 ± 4.3	4.8 ± 0.8	1,734 ± 1314	214.4 ± 161.6	1.614 ± 0.412	42.5 ± 31.7	97.5 ± 59.0	6.21 ± 7.72
S7	3.98 ± 0.10	4.58 ± 0.20	21.8 ± 0.8	24.0 ± 1.5	25.6 ± 0.5	83.8 ± 8.5	3.6 ± 0.1	85.4 ± 6.7	3.3 ± 3.3	2.6 ± 1.2	744 ± 14	138.9 ± 11.2	0.329 ± 0.052	60.7 ± 7.2	5.9 ± 4.8	13.34 ± 7.12
S8	3.65 ± 0.59	6.12 ± 0.52	41.1 ± 12.4	23.0 ± 0.4	0.0 ± 0.2	52.3 ± 1.4	4.6 ± 0.1	101.1 ± 8.9	39.8 ± 40.5	5.2 ± 1.5	1,927 ± 52	220.7 ± 3.9	1.321 ± 0.050	60.9 ± 0.9	11.9 ± 2.4	1.16 ± 0.41
S9	3.62 ± 0.10	4.00 ± 0.23	25.6 ± 24.7	21.1 ± 1.6	66.1 ± 6.5	40.5 ± 0.7	1.5 ± 0.7	59.0 ± 4.0	5.1 ± 2.9	4.9 ± 1.3	89 ± 10	27.6 ± 2.8	0.105 ± 0.005	120.3 ± 3.5	1.4 ± 2.4	1.50 ± 0.40
S10	5.34 ± 0.10	4.70 ± 0.98	23.7 ± 5.9	23.9 ± 2.3	4.0 ± 1.1	60.0 ± 46.6	1.2 ± 0.5	44.8 ± 0.8	3.6 ± 0.8	2.4 ± 0.5	203 ± 2	56.5 ± 1	0.254 ± 0.014	63.0 ± 2.3	0.0 ± 0.0	2.40 ± 0.26
S11	2.36 ± 0.07	6.50 ± 0.21	171.8 ± 30.2	18.3 ± 0.2	95.3 ± 1.4	91.5 ± 19.2	15.2 ± 0.5	137.8 ± 22.5	4.2 ± 1.2	5.6 ± 0.3	2,238 ± 60	154.1 ± 23.2	0.791 ± 0.455	86.7 ± 33.8	18.9 ± 26.0	23.72 ± 0.00
S12	3.71 ± 0.06	5.99 ± 0.51	338.2 ± 257.1	19.7 ± 2.0	51.6 ± 5.7	86.5 ± 5.3	9.3 ± 0.9	344.7 ± 32.0	67.8 ± 5.8	4.3 ± 0.4	1,297 ± 21	320.4 ± 31.3	0.291 ± 0.027	120.7 ± 13.8	6.0 ± 3.0	0.00 ± 0.00
S13	2.65 ± 0.06	6.78 ± 0.24	539.2 ± 233.0	18.7 ± 0.8	45.7 ± 1.1	58.4 ± 13.5	82.0 ± 2.1	681.0 ± 35.1	82.4 ± 5.2	5.7 ± 1.6	2,649 ± 168	385.8 ± 29.2	1.414 ± 0.129	56.3 ± 4.2	36.0 ± 4.8	2.87 ± 0.57
S14	1.82 ± 0.01	5.94 ± 1.03	151.9 ± 226.0	15.0 ± 1.3	11.3 ± 1.3	84.7 ± 8.2	2.9 ± 0.2	43.4 ± 1.8	4.4 ± 6.1	2.6 ± 1.0	835 ± 20	111.9 ± 3.7	0.230 ± 0.036	109.6 ± 7.5	21.9 ± 13.3	0.28 ± 0.19
S15	1.67 ± 0.04	5.69 ± 0.28	50.2 ± 11.1	15.9 ± 2.7	4.3 ± 1.5	ND	2.2 ± 0.3	75.2 ± 30.5	3.3 ± 1.3	5.5 ± 1.1	1025 ± 46	129.6 ± 36.6	0.598 ± 0.028	104.7 ± 1.7	1.1 ± 2.0	0.00 ± 0.00
S16	2.20 ± 0.03	4.46 ± 0.03	28.1 ± 14.6	13.2 ± 1.0	0.0 ± 2.5	72.5 ± 9.4	5.1 ± 0.2	62.2 ± 0.2	1.5 ± 0.7	6.1 ± 0.8	520 ± 7	49.9 ± 0.5	0.819 ± 0.026	118.5 ± 6.6	0.7 ± 1.1	0.18 ± 0.00
S17	2.43 ± 0.05	6.75 ± 0.30	195.3 ± 119.5	18.8 ± 2.1	87.2 ± 0.6	16.5 ± 9.7	205.8 ± 2.5	163.3 ± 15.8	2.9 ± 1.0	8.3 ± 1.1	2,064 ± 86	233.1 ± 23.8	1.080 ± 0.229	83.3 ± 10.9	29.9 ± 11.5	1.77 ± 1.81
S18	2.76 ± 0.02	6.32 ± 0.01	132.6 ± 16.0	15.7 ± 1.8	16.1 ± 0.8	161.9 ± 17.0	34.6 ± 1.8	232.2 ± 33.7	12.1 ± 10.7	4.0 ± 0.0	1,301 ± 222	260.8 ± 33.3	1.012 ± 0.126	115.6 ± 6.6	0.2 ± 0.4	0.02 ± 0.00
S19	1.11 ± 0.03	5.57 ± 0.36	22.2 ± 4.1	9.5 ± 1.2	9.6 ± 0.9	9.2 ± 11.5	5.4 ± 0.6	42.6 ± 1.0	0.3 ± 0.6	3.7 ± 0.2	728 ± 15	136.7 ± 1.5	1.010 ± 0.074	56.9 ± 0.4	2.7 ± 2.2	4.06 ± 1.86
S20	3.48 ± 0.15	5.26 ± 0.38	54.8 ± 35.3	25.6 ± 0.6	5.4 ± 2.0	34.4 ± 1.4	142.6 ± 6.0	84.3 ± 2.3	0.7 ± 1.2	4.8 ± 0.1	1529 ± 38	120.5 ± 3.1	0.817 ± 0.047	87.1 ± 4.9	206.6 ± 13.5	2.40 ± 1.92
S21	2.59 ± 0.06	6.52 ± 0.24	134.1 ± 33.2	15.7 ± 0.9	71.7 ± 5.5	105.0 ± 16.2	7.8 ± 0.3	92.6 ± 4.7	9.1 ± 14.8	5.8 ± 1.7	2,971 ± 196	51.1 ± 2	0.585 ± 0.056	90.8 ± 3.1	8.8 ± 2.0	0.25 ± 0.08
S22	3.02 ± 0.10	6.42 ± 0.41	141.7 ± 56.8	16.6 ± 1.3	48.1 ± 2.3	72.3 ± 10.5	47.2 ± 1.0	217.2 ± 13.0	21.1 ± 5.2	4.5 ± 0.6	1,394 ± 29	276.1 ± 7.5	0.697 ± 0.047	100.7 ± 15.4	71.5 ± 36.1	1.08 ± 0.00
S23	1.47 ± 0.02	4.81 ± 0.32	19.3 ± 0.6	10.8 ± 9.0	79.2 ± 12.4	71.5 ± 71.8	5.9 ± 0.3	100.2 ± 4.7	10.9 ± 2.8	5.7 ± 0.3	598 ± 21	138.3 ± 6.4	0.268 ± 0.013	85.1 ± 2.0	0.0 ± 0.0	0.87 ± 0.61
S24	3.70 ± 0.16	4.08 ± 0.02	20.4 ± 1.2	16.9 ± 0.3	65.1 ± 5.8	41.0 ± 3.3	5.7 ± 1.0	40.1 ± 11.6	10.3 ± 5.9	7.2 ± 0.6	358 ± 245	52.7 ± 41	0.191 ± 0.003	108.7 ± 17.4	2.9 ± 2.0	0.49 ± 0.04
Mean ± SD	3.08 ± 1.13	5.40 ± 1.02	104.1 ± 122.3	19.1 ± 5.1	35.6 ± 30.7	28.5 ± 37.6	27.4 ± 49.9	137.5 ± 16.3	12.5 ± 8.3	4.7 ± 1.6	1,721 ± 11	79.3 ± 98.7	0.390 ± 0.460	120.1 ± 24.1	30.8 ± 47.4	4.54 ± 7.19

Note: ND = Not Detected.

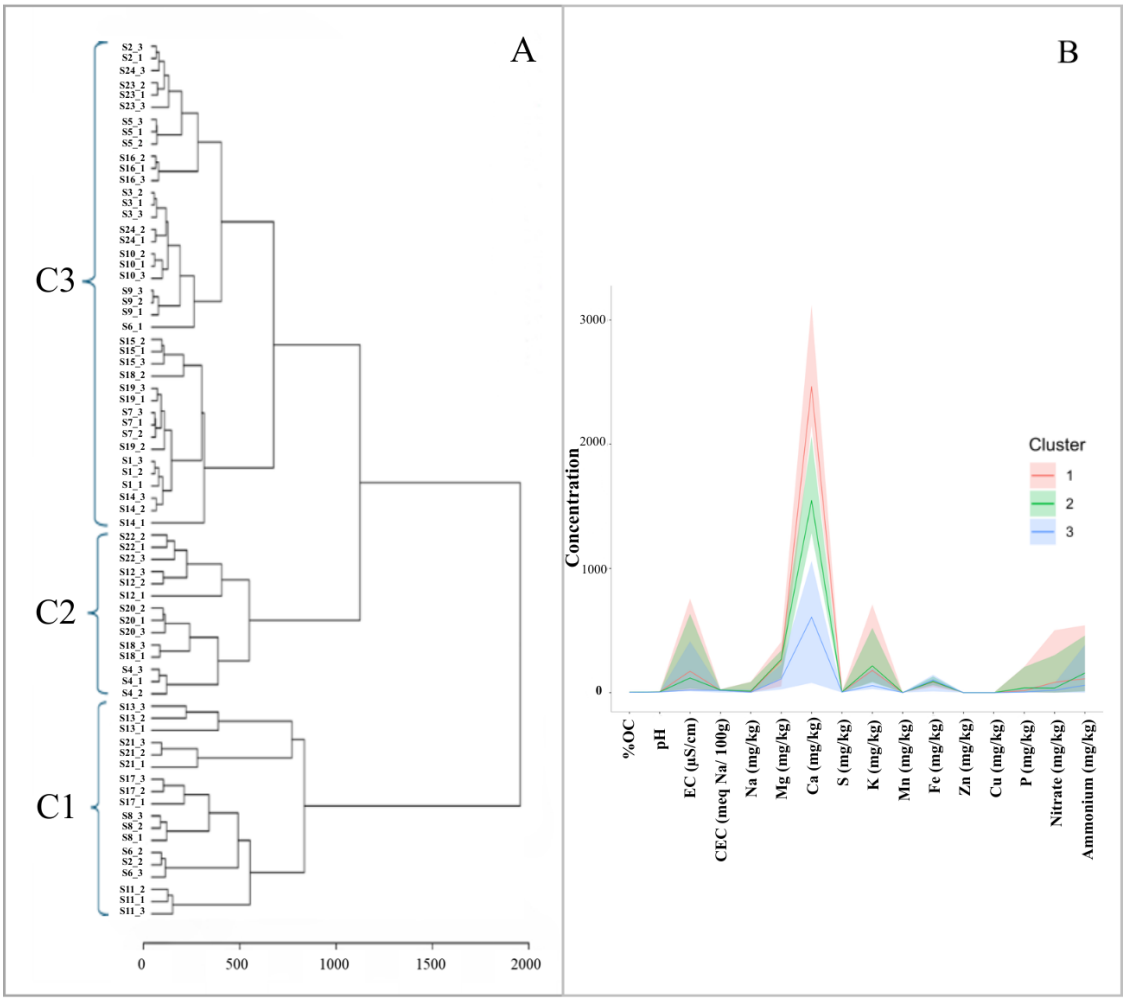


Figure 4 Classification and physicochemical profiles of the cultivation soils: (A) dendrogram from hierarchical cluster analysis (Complete clustering algorithm and squared Euclidean distance) grouping the 24 soil samples; (B) feature overview profile showing the mean concentrations (solid lines) and variance (shaded areas) of soil parameters across the defined clusters.

Table 4 Analysis of variance (ANOVA) of soil physicochemical parameters among the three soil clusters.

	Soil cluster			***p*-value**			
Name	**C1**	**C2**	**C3**	**C1vsC2vsC3**	**C1vsC2**	**C1vsC3**	**C2vsC3**
%OC	2.88 ± 0.71	3.16 ± 0.64	2.86 ± 1.30	> 0.05	0.385	0.403	0.239
pH	6.51 ± 0.260	6.17 ± 0.55	4.72 ± 0.794	< 0.001 *	0.023 *	< 0.001 *	< 0.001 *
EC (µS/cm)	247 ± 214	147 ± 132	38.7 ± 66.2	< 0.001 *	0.104	< 0.001 *	< 0.001 *
CEC (meq Na/100 g)	20.1 ± 4.74	20.4 ± 3.74	18.1 ± 6.30	> 0.05	0.927	0.214	0.086
NO_3 - N (mg/kg)	205 ± 180	94.5 ± 106	27.5 ± 27.5	< 0.001 *	0.036 *	< 0.001 *	0.021 *
NH_4 - N (mg/kg)	225 ± 176	184 ± 152	87.6 ± 93.5	0.001 *	0.600	0.009 *	0.006 *
P (mg/kg)	30.9 ± 31.1	68.8 ± 72.0	3.64 ± 1.84	< 0.001 *	0.184	< 0.001 *	< 0.001 *

	Soil cluster			*p*-value			
Name	**C1**	**C2**	**C3**	**C1vsC2vsC3**	**C1vsC2**	**C1vsC3**	**C2vsC3**
K (mg/kg)	293 ± 258	234 ± 140	72.1 ± 56.5	< 0.001 *	0.956	< 0.001 *	< 0.001 *
S (mg/kg)	5.46 ± 1.14	5.01 ± 1.59	4.44 ± 1.76	> 0.05	0.112	0.066	0.227
Na (mg/kg)	25.1 ± 35.3	21.2 ± 27.1	4.24 ± 4.09	0.001 *	0.955	0.124	0.021 *
Mg (mg/kg)	201 ± 145	250 ± 67.7	104 ± 52.8	< 0.001 *	0.289	0.054	< 0.001 *
Ca (mg/kg)	2398 ± 749	1595 ± 299	633 ± 415	< 0.001 *	< 0.001 *	< 0.001 *	< 0.001 *
Fe (mg/kg)	69.1 ± 29.1	92.8 ± 21.5	94.0 ± 25.6	0.009 *	0.012 *	0.011 *	0.876
Mn (mg/kg)	1.10 ± 0.519	0.915 ± 0.344	0.389 ± 0.286	< 0.001 *	0.224	< 0.001 *	< 0.001 *
Zn (mg/kg)	0.040 ± 0.045	0.048 ± 0.071	0.012 ± 0.024	0.010 *	0.600	0.001 *	0.002 *
Cu (mg/kg)	0.004 ± 0.007	0.001 ± 0.001	0.004 ± 0.008	> 0.05	0.147	0.924	0.048 *

Note: * = significantly different at *p-value* = 0.05.

Distinctive soil physicochemical profiles among clusters

Soil parameters varied significantly across clusters, primarily driven by calcium (Ca) ($p = 5.09\times10^{-19}$). Cluster 1 showed near-neutral pH (6.51 ± 0.260), the highest EC (247 ± 214 µS/cm), the highest Ca (2398 ± 749 mg/kg) and significantly elevated nitrate (NO_3 - N), ammonium (NH_4 - N), and potassium (K), suggesting intensive fertilization or active mineralization [29]. These elevated macronutrient levels likely reflect agricultural management, such as chemical fertilizers or organic manuring, alongside natural soil variations. This localized nutrient enrichment suggests that field practices shaped the chemical profile of Cluster 1, potentially influencing the environmental sensitivity of cultivar T84-2. Cluster 2 demonstrated the most balanced soil profile, featuring an optimal pH (6.17 ± 0.55) and moderate EC (147 ± 132 µS/cm) for turmeric [30]. It exhibited a comparable, high CEC (20.4 ± 3.74 meq Na/100g), abundant Ca (1,595 ± 299 mg/kg), and magnesium (Mg) (250 ± 67.7 mg/kg) for cell wall integrity [25], and high phosphorus (P) availability (68.8 ± 72.0 mg/kg) favorable for rhizome development [31]. Moderate nitrogen (N) levels likely balanced vegetative growth and curcuminoid biosynthesis [32], though low zinc (Zn) and manganese (Mn) concentrations may require monitoring [33]. Conversely, Cluster 3 had the most acidic soil (pH 4.72 ± 0.794), potentially impairing nutrient solubility and organic matter mineralization [25], but exhibited the lowest EC (38.7 ± 66.2 µS/cm), indicating minimal salinity stress [30]. However, low phosphorus (P) (3.64 ± 1.84 mg/kg) could limit rhizome development [34]. Thus, Cluster 3 requires pH adjustment and fertilization [31]. The K-means-based feature overview (**Figure 4(B)**) visually supported the ANOVA findings. Cluster 1 was characterized by relatively higher concentrations and greater variance in EC, Ca, K, and nitrogen content, whereas Cluster 2 was distinguished by higher availability of P and Mg. In contrast, Cluster 3 showed lower and more uniform concentrations across these dominant parameters.

The relationship between soil clusters and curcuminoid parameters of turmeric cultivars

To evaluate the relationship between soil environments and the chemical profiles of cultivar T1, seventeen samples were analyzed: Cluster C1 (n = 4), C2 (n = 2), and C3 (n = 11). ANOVA analysis revealed no significant differences ($p > 0.05$) in extraction yields or curcuminoid contents between these environments (**Figure 5(A)**). This consistency indicates that cultivar T1 exhibits phenotypic stability across different soil conditions, suggesting that its quality traits are primarily influenced by genotype rather than environmental factors. To assess environmental influences on T84-2 (n = 7), ANOVA analysis compared samples between the C1 (n = 2), C2 (n = 3), and C3 (n = 2) clusters (**Figure**

5(B)). The T84-2 cultivar grown in C3 exhibited significantly higher extraction yields (15.3 ± 0.42 %w/w, $p = 0.029$), and BDMC (2.36 ± 0.178 %w/w, $p = 7.44\times10^{-6}$) among the three clusters. In contrast, C2 exhibited significantly higher CUR (spectroscopic) (10.950 ± 3.931 %w/w**,** $p = 0.017$). However, C1 exhibited significantly lower DMC (2.100 ± 0.110 %w/w, $p = 5.24\times10^{-5}$) compared to other clusters. Unlike the stable T1 cultivar, T84-2's quality traits were highly responsive to external soil environments. Interestingly, although both C1 and C2 soil possessed higher nutrient density, C3's lower-nutrient conditions appeared more favorable for biosynthetic accumulation in T84-2. These findings demonstrate that cultivation environments strongly modulate phytochemical expression in this sensitive genotype.

Heritability analysis (**Table 5**) showed broad-sense heritability (H^2) ranged from 11.1% for DMC to 72.6% for BDMC. Extraction yield exhibited a moderate heritability of 48.0%, indicating that genetics controls approximately half of its phenotypic variation (V_P), while the other half is strongly influenced by environmental factors (V_E) [35-36]. As shown in **Figure 2**, T1 exhibits significantly higher BDMC compared to T84-2 ($p = 0.001$), and BDMC has an H^2 of 72.6%. These findings suggest that T1's genetic background strongly influences the elevated accumulation of BDMC. T1 demonstrated higher overall potential, with a mean yield of 17.38 and maximum yield reaching 22.62. However, T1 exhibited a wide extraction yield range of 10.73 (11.89 to 22.62 %w/w). This indicated that while T1 has a higher overall yield and its quality parameters are resistant to changes in soil cluster conditions (ANOVA $p > 0.05$), it exhibits wider baseline phenotypic variance among individual samples compared to T84-2. Conversely, T84-2 displayed a narrow extraction yield range of 5.02 (10.88 to 15.90 %w/w), albeit with a lower mean yield of 13.85. Total curcuminoids also showed a similar trend to extraction yield, where T84-2 showed a minimal fluctuation range of 2.94 (10.00–12.94 %w/w) compared to T1's range of 7.23 (8.38–15.61 %w/w). This indicates that while T84-2 maintains consistent baseline yields, its phytochemical traits are highly responsive to specific soil parameters **(**ANOVA $p < 0.05$**)**, as shown in **Figure 5(B)**. However, sample distribution limitations exist; for T1 ($n = 17$), samples S1–S10 originated exclusively from Mae Lao district. This spatial confounding suggests that localized environmental conditions or uniform management practices within this district might still modulate the baseline data. Additionally, the T84-2 sample size was limited ($n = 7$) due to restricted local cultivation. These preliminary results require cautious interpretation as the small sample size limits multivariate robustness. Future studies with larger, more balanced cohorts across diverse locations are warranted to validate these findings.

Correlation analysis between soil properties and turmeric cultivar quality

Pearson correlation analysis (**Tables 6** and **7**) revealed distinct cultivar-specific responses to soil parameters. For T1, organic carbon (OC) was the predominant positive driver for extraction yield (r = 0.642) and significant curcuminoid fractions (r = 0.434 - 0.525), while primary macronutrients (N, P, K) showed no significant correlations. Conversely, T84-2 displayed strong negative correlations with multiple soil variables, particularly potassium (r = -0.586 to -0.846), magnesium (r = -0.644 to -0.852), sodium, calcium, nitrogen (NO_3-N and NH_4-N), and electrical conductivity (EC). This negative impact of excessive nitrate and potassium contrasts with traditional reports [37,38], but aligns with the growth–differentiation and carbon–nutrient balance hypothesis [39], where abundant nutrients promote vegetative growth but suppress secondary metabolite biosynthesis by prioritizing carbon allocation for primary metabolism. Furthermore, excessive potassium and associated chloride salinity stress, reflected in the negative EC correlation, can induce nutrient imbalances that downregulate curcuminoid synthesis [30,40,41]. These contrasting behaviors underscore profound genotype-by-environment (G×E) interactions in turmeric [42,43]. T1 may possess highly stable, heritable phenotypic traits less susceptible to environmental influences, making it optimal for cost-effective production with consistent bioactive compound levels. Conversely, T84-2 requires targeted, site-specific soil management that strictly avoids over-fertilization to achieve its maximum phytochemical potential.

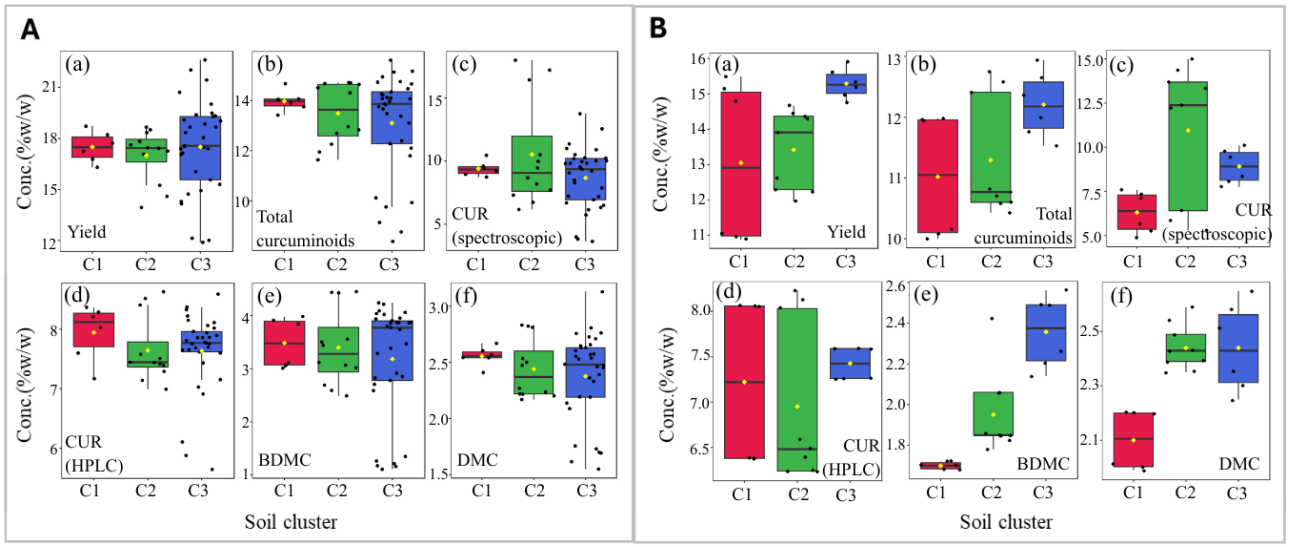


Figure 5 Comparison of extraction yield and curcuminoid contents (% w/w) of turmeric cultivars T1 (A: Cultivated in soil clusters C1, C2, and C3) and T84-2 (B: Cultivated in soil clusters C1, C2, and C3). The subplots represent: (a) extraction yield, (b) total curcuminoids, (c) spectroscopic CUR, (d) HPLC CUR, (e) BDMC, and (f) DMC. Bold horizontal lines and yellow diamonds indicate median and mean values, respectively, with black dots representing individual data points.

Table 5 Broad-sense heritability (H^2) for extraction yield and phytochemical profiles of T1 and T84-2 turmeric cultivars.

Parameters	Mean (Min-Max)		Genotypic Variance (V_G)	Environmental Variance (V_E)	Phenotypic Variance (V_P)	Broad-sense heritability (H^2) (%)
	Cultivar T1	Cultivar T84-2				
Extraction Yield	0.83	0.65	4.85	5.25	10.10	48.0
CUR (Spectroscopy)	0.72	0.54	0.82	4.58	5.40	15.2
CUR (HPLC)	0.79	0.57	0.28	0.45	0.73	38.4
BDMC (HPLC)	0.86	0.47	1.62	0.61	2.23	72.6
DMC (HPLC)	0.74	0.50	0.01	0.08	0.09	11.1
Total Curcuminoids (HPLC)	0.88	0.60	3.25	2.54	5.79	56.1

Table 6 Pearson correlation coefficients (*r*) between soil physicochemical properties and quality parameters (extraction yield and curcuminoids) of the T1 turmeric cultivar.

Soil nutrient	Range of parameter	Pearson correlation (*r*)					
		Extraction yield	Total curcuminoid	CUR (HPLC)	CUR (Spectro)	BDMC (HPLC)	DMC (HPLC)
OC	1.4 - 5.5%	**0.642**[a]	**0.525**[b]	**0.437**[b]	0.148	**0.510**[b]	**0.434**[b]
pH	3.5 - 6.8	**-0.412**[c]	-0.308	-0.327	-0.032	-0.293	-0.277
EC	10.0 - 415.0 µS/cm	-0.376	-0.275	-0.358	-0.089	-0.229	-0.219
CEC	13.0-28.0 meq Na/100 g	**0.493**[b]	0.326	0.309	-0.023	0.307	0.236

Soil nutrient	Range of parameter	Pearson correlation (*r*)					
		Extraction yield	Total curcuminoid	CUR (HPLC)	CUR (Spectro)	BDMC (HPLC)	DMC (HPLC)
NO_3-N	0 - 18.0 mg/kg	-0.028	0.095	0.035	0.100	0.069	0.162
NH_4-N	0 - 32.0 mg/kg	0.190	0.290	0.081	0.324	0.361	0.345
P	0.9 - 210.0 mg/kg	-0.290	-0.157	-0.231	-0.008	-0.127	-0.099
K	29.0 - 525.0 mg/kg	0.0025	0.054	-0.046	0.022	0.110	0.017
S	1.0 - 10.0 mg/kg	-0.100	0.016	0.024	0.181	-0.061	0.071
Na	0 - 27.0 mg/kg	0.058	0.143	0.188	0.205	0.090	0.104
Ca	200.0 - 3200.0 mg/kg	-0.257	-0.096	0.062	-0.068	-0.195	-0.093
Mg	25.0 - 330.0 mg/kg	-0.108	-0.071	-0.136	0.054	-0.015	-0.079
Mn	0.03 - 2.55 mg/kg	0.260	0.211	0.106	0.118	0.250	0.191
Fe	9.8 - 143.1 mg/kg	**-0.396^{c}**	-0.297	-0.245	-0.020	-0.285	-0.232
Zn	0 - 0.16 mg/kg	-0.109	-0.096	-0.089	-0.200	-0.077	-0.113
Cu	0 - 0.03 mg/kg	**0.490^{b}**	0.309	0.255	0.004	0.304	0.279

Note: Superscript letters denote the strength and direction of the Pearson correlation: a = strong positive, b = moderate positive, and c = moderate negative linear correlation.

Table 7 Pearson correlation coefficients (*r*) between soil physicochemical properties and quality parameters (extraction yield and curcuminoids) of the T84-2 turmeric cultivar.

Soil nutrient	Range parameter	Pearson correlation (*r*)					
		Extraction yield	Total curcuminoid	CUR (HPLC)	CUR (Spectro)	BDMC (HPLC)	DMC (HPLC)
OC	1.0 - 3.7%	**-0.438^{b}**	**-0.440^{b}**	-0.329	0.375	**-0.527^{b}**	-0.0423
pH	4.4 - 6.9	**-0.589^{b}**	**-0.652^{c}**	-0.356	**-0.436^{b}**	**-0.649^{c}**	-0.394
EC	18 - 757 µS/cm	**-0.585^{b}**	**-0.700^{c}**	**-0.564^{b}**	-0.226	**-0.594^{b}**	**-0.467^{b}**
CEC	4.0 - 13.0 meq Na/100 g	-0.280	-0.130	0.094	**0.399^{b}**	**-0.435^{b}**	-0.230
NO_3-N	0 - 100.0 mg/kg	-0.228	**-0.397^{b}**	-0.132	-0.342	**-0.787^{c}**	-0.352
NH_4-N	0 - 109.0 mg/kg	-0.221	**-0.530^{b}**	-0.332	-0.242	**-0.742^{c}**	-0.332
P	4.8 - 149.0 mg/kg	-0.394	0.041	0.196	0.197	-0.077	-0.292
K	41.0 - 710.0 mg/kg	**-0.827^{d}**	**-0.846^{d}**	**-0.701^{c}**	-0.353	**-0.650^{c}**	**-0.586^{b}**
S	3.4 - 7.4 mg/kg	-0.205	-0.220	0.042	-0.387	-0.361	**-0.678^{c}**
Na	0 - 90.0 mg/kg	**-0.756^{c}**	**-0.865^{d}**	**-0.809^{d}**	-0.137	**-0.600^{c}**	-0.342
Ca	510 – 2,775 mg/kg	**-0.580^{b}**	**-0.455^{b}**	-0.103	-0.387	**-0.757^{c}**	**-0.877^{d}**

Soil nutrient	Range parameter	Pearson correlation (*r*)					
		Extraction yield	Total curcuminoid	CUR (HPLC)	CUR (Spectro)	BDMC (HPLC)	DMC (HPLC)
Mg	49.0 - 409.0 mg/kg	**-0.793**[c]	**-0.852**[d]	**-0.815**[d]	-0.241	**-0.644**[c]	-0.277
Mn	0.18 - 1.55 mg/kg	0.303	0.051	0.262	**-0.516**[b]	0.030	**-0.550**[b]
Fe	47.6 - 130.0 mg/kg	0.192	-0.124	-0.191	0.287	-0.122	0.264
Zn	0 - 0.22 mg/kg	-0.126	0.276	0.371	0.376	0.092	-0.001
Cu	0 - 0.023 mg/kg	0.114	0.200	0.325	-0.128	-0.066	-0.156

Note: Superscript letters indicate the strength and direction of the linear correlation: a = moderate positive, b = moderate negative, c = strong negative, and d = very strong negative correlation.

Conclusions

This study demonstrates that the impact of soil properties on *Curcuma longa* L. yield and quality is highly cultivar specific. Cultivar T1 consistently produced higher extraction yields and BDMC levels, driven primarily by soil organic carbon rather than inorganic chemical nutrients. Conversely, T84-2 showed consistent baseline performance across varied environments, but its phytochemical potential can be significantly capped by its high sensitivity to nitrate, potassium and excessive cations (e.g. Mg, and Na). These findings underscore the necessity of targeted management: Maximizing turmeric yield and phytochemical quality requires organic matter enrichment for T1, while T84-2 requires careful nutrient management. This targeted approach will help maximize both the extraction yield and the phytochemical quality of the turmeric.

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Declaration of generative AI in scientific writing

The authors used generative AI tools (Google's Gemini and NotebookLM, ChatGPT, and QuillBot) solely for language editing, sentence refinement, and drafting the graphical abstract. The AI was not involved in data interpretation or drawing conclusions. The authors retain full responsibility for the manuscript's integrity and content.

CRediT author statement

Naronk Duangkaew: Conceptualization; Methodology; Investigation; Formal analysis; Data curation; Writing – original draft. **Tharakorn Maneerat:** Methodology; Resources; Writing – review & editing. **Plaipol Dedvisitsakul:** Supervision; Formal analysis; Validation; Writing – review & editing. **Kanchana Watla-iad:** Conceptualization; Methodology; Supervision; Resources; Validation; Formal analysis; Data curation; Writing – review & editing.

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