International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 23s, 2025
https://www.theaspd.com/ijes.php

Meta-Analysis Of Soil Properties Influencing Curcumin Content In The Curcuma Genus: Statistical Evaluation

Rana Mukherjee[1], Dr. Deboja Sharma[2]*
[1]Department of Biotechnology, University of Science and Technology Meghalaya, Ri-Bhoi, Meghalaya-793101, India, mukherjeerana.jan7@gmail.com
[2]Department of Biotechnology, University of Science and Technology Meghalaya, Ri-Bhoi, Meghalaya-793101, India, debu1000@gmail.com

Abstract
Curcumin, the principal bioactive compound of Curcuma species, is widely recognized for its pharmacological importance, yet its accumulation is highly variable and influenced by environmental and soil factors. This study conducted a meta-analysis to evaluate how soil parameters like pH, nitrogen (N), phosphorus (P), potassium (K), organic carbon (OC), and the carbon-to-nitrogen (C:N) ratio affect curcumin content across species of the Curcuma genus. Relevant studies were retrieved from PubMed, Google Scholar, and specialized plant science journals following defined inclusion criteria. Statistical analyses, including Spearman correlation, linear regression, and one-way ANOVA, were employed to examine the relationships between soil properties and curcumin concentration. Results demonstrated that potassium (K) exhibited the strongest positive association with curcumin content ($r = 0.772$, $p < 0.001$; $\beta = 1.9433$), whereas N, P, pH, and organic carbon showed negligible or non-significant effects. The dataset was limited in sample size and largely concentrated in South Asian regions, particularly India, with notable gaps regarding Curcuma caesia Roxb., a species of emerging pharmacological interest. These findings highlight potassium as a key soil determinant of curcumin biosynthesis and provide practical insights for optimizing turmeric cultivation through targeted soil management strategies. However, further interdisciplinary research incorporating climatic, genetic, and microbiome factors is needed to validate and expand these conclusions. This meta-analysis contributes to the growing field of agro-pharmacology by consolidating fragmented evidence and identifying actionable soil parameters relevant to both agricultural productivity and medicinal value.
Keywords: *Curcuma, Curcumin, Soil nutrients, Meta-analysis, Secondary metabolites*

1. INTRODUCTION

Turmeric (*Curcuma longa* L.) is one of the most important spice and medicinal crops cultivated across tropical and subtropical regions. India is the largest producer and exporter of turmeric, contributing more than 75% of the global supply [5]. Within India, production is concentrated in a few major states such as Telangana, Maharashtra, and Tamil Nadu [14]. The establishment of the National Turmeric Board by the Government of India reflects the increasing emphasis on productivity, value addition, and global competitiveness [9].

Curcumin, the principal bioactive compound in turmeric, is well known for its antioxidant, anti-inflammatory, and pharmacological properties, making it highly valuable to both the nutraceutical and pharmaceutical industries [2]. However, curcumin content is highly variable across growing regions, cultivars, and soil environments. Previous studies in Odisha and Uttar Pradesh have shown that soil potassium levels strongly influence curcumin accumulation in turmeric rhizomes [7,8,1]. In contrast, soil nitrogen and phosphorus appear to primarily affect biomass rather than secondary metabolite accumulation [2].

Although turmeric is widely studied, research on *Curcuma caesia Roxb.*, another species of medicinal importance, remains limited. Only a few studies have documented its curcumin variability and genetic diversity, highlighting both conservation needs and potential pharmaceutical value [11,6]. Given these gaps, a systematic synthesis of evidence is needed to clarify which soil parameters most influence curcumin biosynthesis and to provide guidance for agronomic management and breeding strategies.

Objectives of this study were to:

- Systematically compile and synthesize published data on soil properties and curcumin content in *Curcuma* species.
- Statistically evaluate the relative contributions of key soil parameters; pH, N, P, K, organic carbon (OC), and C:N ratio to curcumin accumulation.
- Identify the most influential soil factor(s) for curcumin biosynthesis.
- Highlight gaps in current knowledge, particularly regarding understudied species such as *Curcuma caesia Roxb*., and suggest directions for future research.

By addressing these objectives, the present study seeks to provide a clearer understanding of soil-curcumin interactions, thereby contributing to both scientific knowledge and practical applications in turmeric cultivation and agro-pharmacology.

2. METHODOLOGY

This meta-analysis was conducted following a systematic review framework. Relevant studies on turmeric and *Curcuma caesia Roxb.* were collected through searches of Scopus, Web of Science, and Google Scholar databases using combinations of keywords such as "*Curcuma*," "turmeric," "curcumin," "soil properties," and "nutrient effects." Studies were included if they reported soil parameters (pH, organic carbon, nitrogen, phosphorus, potassium, and C:N ratio) along with curcumin content. Reports that lacked quantitative data, duplicates, or studies not involving *Curcuma* species were excluded [12].

Data on soil properties and curcumin concentrations were extracted and standardized. When necessary, values reported in different units were converted into comparable forms. Statistical analyses included Spearman's rank correlation, interquartile range (IQR) analysis, multiple linear regression, and one-way ANOVA to test for associations between soil parameters and curcumin content [1,7].

The physiological basis for focusing on potassium derives from its known role in secondary metabolite biosynthesis. Potassium regulates enzyme activation, osmotic balance, and metabolite transport in higher plants [4], and it has been demonstrated to enhance secondary metabolite accumulation in medicinal species [13]. These insights provide a rationale for evaluating potassium alongside other soil parameters in this meta-analysis.

2.1 Literature Search and Data Sources

A systematic search was performed across PubMed, Frontiers, MDPI, and Google Scholar to identify studies reporting curcumin content in *Curcuma* species with corresponding soil property data. Keywords used included "*Curcuma longa*," "*Curcuma caesia Roxb*.," "soil composition," "soil nutrients," "pH," "nitrogen," "phosphorus," "potassium," "organic carbon," and "C:N ratio."

The search identified seven relevant studies from Japan, India, Uzbekistan, and Cameroon, with *C. longa* dominating the dataset and *C. caesia Roxb.* represented only minimally.

2.2 Inclusion and Exclusion Criteria

2.2.1 Inclusion:

- Studies reporting quantitative curcumin content and at least one soil parameter.
- Primary experimental or field data.
- Peer-reviewed journal articles in English.

2.2.2 Exclusion:

- Review papers, editorials, or studies without curcumin quantification.
- Studies reporting soil properties but no curcumin values.

2.3 Extracted Data

From each study, the following variables were compiled: location, soil type, pH, N, P, K, organic carbon, C:N ratio, environmental variables (temperature, rainfall, humidity), and curcumin content (% dry weight). Consolidated datasets included reports from: Okinawa, Japan (soil type effects on turmeric) [3], Uttar Pradesh, India (nutrient sources, mulching, agroclimatic zones), Odisha, India (multi-site survey with soil-environmental variables), Uzbekistan and Cameroon (soil composition and microbial effects).

2.4 Statistical Analysis

Data were standardized and analyzed using:

Spearman correlation to test non-parametric associations between soil factors and curcumin content.

Multiple linear regression to identify predictors of curcumin variation.

One-way ANOVA to assess differences in curcumin across soil nutrient categories.

Significance was set at $p < 0.05$. Model fit was evaluated using R^2 and F-statistics.

The statistical framework applied in this study is summarized in Table 1, which outlines the hypotheses, test types, and interpretation criteria used for analysis.

Table 1. Summary of statistical tests applied to evaluate the relationship between soil parameters and curcumin content in *Curcuma* species.

Test	*What It Tests*	*Hypothesis Being Tested*	*Interpretation*
Spearman Correlation	Relationship between each soil property and curcumin content	H_0: No correlation H_1: Significant correlation	If $p < 0.05$, reject H_0 (soil property affects curcumin).
Linear Regression (Simple)	Predicts curcumin content based on nitrogen (N) levels	H_0: No significant relationship H_1: N significantly predicts curcumin	If R^2 is high and $p < 0.05$, reject H_0 (Nitrogen influences curcumin).
Multiple Linear Regression	Effect of all soil properties (pH, N, P, K, etc.) on curcumin content	H_0: No soil factor significantly influences curcumin H_1: At least one soil factor influences curcumin	If $p < 0.05$ for any variable, reject H_0.
One-Way ANOVA	Compares curcumin levels across different nitrogen levels	H_0: Nitrogen levels do not significantly impact curcumin H_1: At least one nitrogen level affects curcumin	If $p < 0.05$, reject H_0 (Nitrogen levels impact curcumin).

3. RESULTS

3.1 Correlation Analysis

Spearman correlation analysis (Table 2) demonstrated that potassium (K) was the only soil factor with a strong and significant positive association with curcumin content ($r = 0.772$, $p < 0.001$), while other parameters showed no significant effects.

Table 2. Spearman correlation between soil properties (pH, N, P, K, organic carbon, C:N ratio) and curcumin content.

Soil Property	***Spearman Correlation (r)***	***P-value***	***Interpretation***
Soil pH	0.113	0.634	No significant effect on curcumin.
N_Content	0.181	0.444	Weak positive correlation, not significant.

P_Content	0.012	0.959	No correlation with curcumin.
K_Content	0.772	0.000067	Strong significant correlation with curcumin.
Organic Carbon	-0.148	0.534	No significant correlation.
C_N_Ratio	-0.008	0.975	No correlation.

3.2 Variability of Soil Parameters

Interquartile range (Table 3) indicated wide variability in nitrogen levels (IQR = 73.0), which may explain its weak and inconsistent association with curcumin.

Table 3. Interquartile range (IQR) analysis of soil parameters and curcumin content, showing variability across regions.

Feature	*IQR Value*
Soil pH	0.47500
N_Content	73.02500
P_Content	1.75000
K_Content	2.70000
Organic Carbon	0.42175
C_N Ratio	1.27500
Curcumin Content	3.27500

3.3 Regression Modeling

The multiple regression model explained 76% of variance in curcumin ($R^2 = 0.760$, Table 4). Among predictors, potassium was the only significant determinant ($\beta = 1.9433$, $p < 0.001$), whereas all other soil factors were non-significant (Table 5).

Table 4. Performance of the multiple linear regression model explaining variance in curcumin content.

Metric	*Value*
R^2 (Goodness of Fit)	**0.760**
Adjusted R^2	**0.649**
F-statistic	**6.857**
P-value (Model Significance)	**0.00188**

Table 5. Regression coefficients and significance of soil parameters in predicting curcumin content.

Soil Factor	*Coefficient*	*P-value*	*Interpretation*
Soil pH	-0.2821	0.474	No significant effect.
N_Content	-0.0716	0.854	No significant effect.
P_Content	0.2076	0.718	No significant effect.
K_Content	**1.9433**	**0.000**	**Highly significant positive effect.**
Organic Carbon	-0.1588	0.772	No significant effect.
C_N Ratio	0.0070	0.983	No significant effect.

3.4 ANOVA (Nitrogen Effect)

One-way ANOVA confirmed that different nitrogen levels did not significantly affect curcumin content (F = 1.986, p = 0.168; Table 6).

Table 6. One-way ANOVA results for nitrogen levels and their effect on curcumin content.

Test	*F-statistic*	*P-value*	*Interpretation*
ANOVA (N vs Curcumin)	1.986	0.168	No significant effect of nitrogen on curcumin.

Overall, the meta-analysis revealed that potassium (K) was the only soil parameter with a significant positive association with curcumin content in *Curcuma* species (r = 0.772, β = 1.9433, p < 0.001). In contrast, nitrogen (N), phosphorus (P), soil pH, organic carbon, and the C:N ratio did not show statistically significant effects. These results were consistent across correlation and regression models, with potassium explaining nearly 76% of the observed variation in curcumin levels (Table 5). Thus, potassium availability emerged as the primary determinant of curcumin biosynthesis, while other soil factors exerted comparatively minor influences.

4. DISCUSSION

The findings of this meta-analysis provide clear evidence that potassium (K) is the most critical soil parameter influencing curcumin biosynthesis in *Curcuma* species. Both correlation and regression analyses (Tables 2 and 5) demonstrated that potassium levels were strongly and positively associated with curcumin concentration, accounting for nearly 76% of the variation in the dataset. In contrast, other macronutrients such as nitrogen (N) and phosphorus (P), as well as soil pH, organic carbon, and the C:N ratio, did not exhibit statistically significant effects. Similar patterns were reported by Pandey et al. [7,8], who observed strong associations between soil potassium and curcumin yield across agroclimatic zones in India, and by Akbar et al. [1], who found potassium to be a major determinant of curcumin variation across districts of Odisha.

These results are consistent with the physiological roles of potassium in plants. Potassium regulates enzyme activation, osmotic balance, and metabolite transport, all of which can enhance secondary metabolite synthesis [4]. Singh et al. [13] further emphasized that potassium fertilization enhances the accumulation of phenolics and alkaloids in medicinal plants, supporting the present conclusion that curcumin biosynthesis is similarly dependent on potassium availability. The negligible effect of N and P in this analysis suggests that while these nutrients are essential for biomass production, they may not directly contribute to secondary metabolite pathways responsible for curcumin accumulation, a point also raised in earlier soil fertility reviews [2].

The lack of significant associations with soil pH and organic carbon also warrants attention. While pH and organic matter are often considered important for nutrient availability and microbial interactions, the present analysis suggests that within the ranges studied, these factors exert minimal influence on curcumin content compared to potassium. This observation underscores the need to differentiate between soil properties that support general plant growth and those that specifically regulate secondary metabolite pathways. Comparable findings were noted in field studies from Okinawa, Japan, where soil type variation influenced turmeric quality but did not show strong direct effects of pH on curcumin levels [3].

Despite these insights, several limitations constrain the generalizability of the findings. The dataset was relatively small, and the majority of included studies originated from India and East Asia, leading to regional bias. Moreover, *Curcuma caesia Roxb.*, despite its emerging pharmacological importance, was underrepresented, limiting conclusions about species-specific responses. Only a handful of studies have examined its curcumin variability and conservation challenges [11,6], underscoring a major gap. Environmental variables such as rainfall,

temperature, and soil microbial communities were not consistently reported, preventing analysis of their potential interactions with soil nutrients [1,7].
From a practical perspective, these results have direct implications for turmeric cultivation. Potassium management—whether through balanced NPK fertilization, organic manures, or site-specific nutrient strategies—could serve as an effective means to enhance curcumin yield. This aligns with the objectives of India's National Turmeric Board, which emphasizes research-driven approaches to improve productivity, value addition, and global competitiveness [9]. Adoption of potassium-focused soil management practices could therefore benefit both farmers and industries reliant on high-curcumin turmeric varieties, in line with broader agricultural policies [5].
Future studies should expand the geographic and species coverage of datasets, particularly focusing on *C. caesia Roxb*., which remains largely unexplored in relation to soil–curcumin interactions. Experimental research integrating soil chemistry, plant genetics, and biochemical assays will also be essential to clarify the mechanistic basis of potassium's effect on curcumin biosynthesis [12]. In addition, incorporating environmental variables such as rainfall, humidity, and soil microbiota into predictive models could enable precision agriculture approaches tailored to optimize curcumin production [10].

5. CONCLUSION
This meta-analysis demonstrates that among the major soil parameters evaluated, potassium (K) is the only significant determinant of curcumin biosynthesis in *Curcuma* species. Correlation and regression analyses consistently showed that higher potassium levels were strongly associated with increased curcumin content ($r = 0.772$, $\beta = 1.9433$, $p < 0.001$), whereas nitrogen, phosphorus, soil pH, organic carbon, and C:N ratio did not exhibit significant effects. These findings highlight the importance of potassium management in turmeric cultivation and provide a scientific basis for strategies aimed at enhancing curcumin yield.
Expanding datasets to include additional geographic regions, species such as *Curcuma caesia Roxb*., and broader environmental factors will be essential for refining these conclusions and informing future agro-pharmacological applications. By addressing these gaps, future research can strengthen both scientific understanding and the practical improvement of turmeric cultivation.
Copyright Statement: This manuscript is original, has not been published before, and is not currently being considered for publication elsewhere. All authors consent to its publication in this journal.
Ethics Approval: Not applicable.
Declaration of Competing Interest: The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.
Acknowledgments
The authors express their gratitude to the University of Science and Technology Meghalaya for providing institutional support. We thank the researchers whose data contributed to this meta-analysis and the reviewers for their valuable insights. We also acknowledge ProwessisAI Solutions for their assistance in data analysis and statistical evaluation.
Authorship Contribution
Rana Mukherjee: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft.
Deboja Sharma: Supervision, Resources, Validation, Investigation, Visualization, Writing – review & editing.

REFERENCES
[1] Akbar, A., Behera, D., Mohanty, S., Sahoo, S., Rout, G. R., and Nayak, S., 2016, "Effect of environmental factors and soil properties on curcumin content in turmeric (*Curcuma longa* L.) accessions of Odisha, India," Journal of Applied Research on Medicinal and Aromatic Plants, 3(3), pp. 138–144.
https://doi.org/10.1016/j.jarmap.2016.04.004

[2] Gupta, R., Singh, A., Pandey, V., and Kumar, R., 2019, "Soil fertility management and curcumin yield in turmeric (*Curcuma longa* L.): a review," Journal of Spices and Aromatic Crops, 28(1), pp. 1–10.
[3] Hossain, M. A., and Ishimine, Y., 2005, "Growth, yield and quality of turmeric (*Curcuma longa* L.) cultivated on different soil types in Okinawa, Japan," Plant Production Science, 8(1), pp. 84–91. https://doi.org/10.1626/pps.8.84
[4] Marschner, H., 2011, Marschner's Mineral Nutrition of Higher Plants, 3rd ed., Academic Press, London.
[5] Ministry of Agriculture and Farmers Welfare (MOA&FW), 2021, Horticultural Statistics at a Glance 2021, Government of India, New Delhi.
[6] Mohanty, S., Sahoo, S., Behera, D., and Rout, G. R., 2017, "Curcumin content variation in *Curcuma caesia Roxb.* collected from Eastern India," Industrial Crops and Products, 95, pp. 629–635. https://doi.org/10.1016/j.indcrop.2016.11.041
[7] Pandey, V., Singh, A., Gupta, R., Srivastava, R., and Kumar, R., 2020a, "Influence of nutrient sources and mulching on curcumin content of turmeric (*Curcuma longa*) in sodic soils," Indian Journal of Agricultural Sciences, 90(7), pp. 1299–1304.
[8] Pandey, V., Singh, A., Kumar, R., and Gupta, R., 2020b, "Variation in curcumin content of turmeric (*Curcuma longa* L.) across different agroclimatic zones of Odisha, India," Industrial Crops and Products, 154, 112728. https://doi.org/10.1016/j.indcrop.2020.112728
[9] Press Information Bureau (PIB), 2023, "Government of India notifies establishment of National Turmeric Board," Press Information Bureau, New Delhi. Available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1960320
[10] Rout, G. R., Sahoo, S., Mohanty, S., and Behera, D., 2014, "Biotechnological approaches for conservation and improvement of medicinal *Curcuma* species," Plant Cell Reports, 33(3), pp. 299–314. https://doi.org/10.1007/s00299-013-1513-0
[11] Sahoo, S., Rout, G. R., and Nayak, S., 2018, "Genetic variability in curcumin content of *Curcuma caesia Roxb*. and its conservation implications," Genetic Resources and Crop Evolution, 65(3), pp. 721–731. https://doi.org/10.1007/s10722-017-0575-8
[12] Singh, A., Pandey, V., Gupta, R., and Kumar, R., 2021, "Agronomic practices influencing curcumin yield in turmeric: a systematic review," Agriculture Reviews, 42(4), pp. 357–364. https://doi.org/10.18805/ag.R-2147
[13] Singh, S., Upadhyay, A. K., Singh, A. K., Kumar, K., and Gupta, R., 2020, "Potassium fertilization enhances secondary metabolite accumulation in medicinal plants: a review," Journal of Plant Nutrition, 43(12), pp. 1856–1870. https://doi.org/10.1080/01904167.2020.1744642
[14] Statista, 2025, "India: Turmeric production volume by state 2024," Statista Research Department.