PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp3): 179-187
https://doi.org/10.14719/pst.5995

HORIZON
e-Publishing Group
HePG

RESEARCH ARTICLE

Site-specific online fertilizer recommendations in small cardamom (*Elettaria cardamomum* (L.) Maton through *CardSApp* offers fertilizer savings and higher economic returns

Manoj Oommen[1]*, John Jo Varghese[1], Amith Mohan E[1], Anuja VR[1], Hareesh M[1], Suparna A[1], Thulasimani P[1], Pradeep B[2], Radhakrishnan T[3], Jessy M D[2] & Rema Shree AB[1]

[1]Division of Agronomy and Soil Science, Indian Cardamom Research Institute, Spices Board, Myladumpara, Idukki 685 553, Kerala,India

[2]Division of Geospatial Technology, Rubber Research Institute of India, Rubber Board, Kottayam 686 009, Kerala, India

[3]GeoSpatial Analytics Division, Kerala University of Digital Science Innovation and Technology, Pallipuram, Thiruvananthapuram695 317, Kerala, India

OPEN ACCESS

ARTICLE HISTORY
Received: 05 October 2024
Accepted: 10 November 2024
Available online
Version 1.0 : 27 December 2024
Version 2.0 : 09 September 2025

Check for updates

Additional information
Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Manoj O, Varghese JJ, Amith ME, Anuja VR, Hareesh M, Suparna A, Thulasimani P, Pradeep B, Radhakrishnan T, Jessy MD, Rema SAB. Site-specific online fertilizer recommendations in small cardamom (*Elettaria cardamomum* (L.) Maton through *CardSApp* offer fertilizer savings and higher economic returns . Plant Science Today. 2024; 11(sp3): 179-187. https://doi.org/10.14719/pst.5995

Abstract

The cultivation of small cardamom in the Indian Cardamom Hill (ICH) region of the Western Ghats, southern India, has become highly intensive, with heavy use of fertilizers and pesticides. The cultivation of small cardamom in the Indian Cardamom Hill (ICH) region of the Western Ghats, Southern India, has become highly intensive, with heavy use of fertilizers and pesticides. The ICH region is one of the world's biodiversity hotspots. Numerous studies have reported that the excessive use of chemical fertilizers has caused soil acidification (lowering of pH) and nutrient imbalances. This has resulted in unsustainable production of cardamom, a high-value spice crop that contributes significantly to India's export earnings. This study aimed to conduct a geo-tagged soil fertility survey in selected cardamom-growing areas within the ICH, assess soil fertility and provide site-specific fertilizer recommendations to farmers via a mobile- or web-based application. A digital application, *CardSApp*, designed for the small cardamom sector, offers tailored fertilizer recommendations based on local soil and crop requirements. A representative geo-tagged soil survey was conducted in Udumbanchola taluk, located in Idukki district of Kerala, within the ICH. The surveyed area spanned from 76°59'01.19'' - 77°16'11.55'' East longitude and 9° 38'21.54'' - 10°04'46.60'' North latitude. Spatial interpolation techniques were used to generate maps showing the distribution of primary, secondary and micronutrients in the soil. The study revealed a high availability of NPK nutrients in cardamom soils.

The study also revealed deficiencies in secondary nutrients like magnesium and sulfur, as well as micronutrients such as boron. Most of the soils showed signs of acidification. These findings highlight opportunities to optimize fertilizer usage and improve soil health. Specifically, NPK usage can be reduced or phosphatic fertilizers omitted in 58% of the area, potentially savings of ₹12.27 crores annually in the surveyed taluk alone. Additionally, addressing deficiencies in secondary and micronutrients can further enhance soil health and crop productivity.

To aid farmers in decision-making, the Android- and web-based application *CardSApp* leverages interpolated soil fertility data. *CardSApp* offers site-specific recommendations tailored to the soil nutrient profiles identified in the survey. *CardSApp* enables farmers to optimize fertilizer use, correct nutrient imbalances and apply amendments for pH correction. These practices can improve both farm productivity and income. The adoption of this online fertilizer recommendation system by farmers in the ICH is expected to rationalize fertilizer usage in cardamom cultivation, improve both soil and plant health and support sustainable production with higher economic returns.

Keywords

CardSApp; geotagged soil survey; micronutrient deficiencies; online fertilizer recommendations; saving in fertilizer cost

Introduction

Intensive cardamom cultivation in the Indian Cardamom Hills (ICH) has led to significant ecological and environmental impacts, posing challenges to the long-term sustainability of cardamom production. The ICH, located in the southern Western Ghats, are part of a global biodiversity hotspot and have been a centre of cardamom cultivation for centuries. This tropical mixed forest agro-ecosystem is one of India's primary agricultural zones, traditionally known for cultivating high-value spices. Approximately 86,000 ha within the ICH are dedicated solely to the cultivation of small cardamom. Recently, cultivation practices have shifted towards increased use of chemical fertilizers to achieve higher yields. Popular cardamom varieties among farmers have shown greater responsiveness to applied fertilizers (increasing from 350 kg NPK ha^{-1} in 1993 - 800 kg NPK ha^{-1} in 2007) and manures (from 3 t ha^{-1} in 1993 -10 t ha^{-1} in 2007). The heavy application of chemical fertilizers in a monoculture cardamom ecosystem may threaten long-term soil sustainability (1).

Effective soil resource management and identification of fertility limitations in an area rely on assessing spatial variability in soil fertility indices. Several studies have documented that soil properties, including nutrient status, exhibit spatial and temporal variations across small to large scales (2-4). Understanding spatial variability in soil nutrient status is crucial for implementing appropriate fertility management practices, optimizing soil resource management and enhancing crop yields with minimal environmental impact. Geostatistical techniques have recently been successfully applied to evaluate spatial variability in soil characteristics (5, 6). By gathering adequate representative samples during soil surveys, the Global Positioning System (GPS) and Geographic Information System (GIS), combined with geostatistical techniques, can efficiently generate geographical distribution maps of soil fertility parameters (5, 7). Kriging, a geostatistical simulation technique, is widely used to estimate values in unsampled locations by leveraging spatial correlation (8, 9).

The primary limitations in soils within spice-growing regions of India include low pH and reduced availability of Ca, Mg, B and Zn (10). This study forms part of a broader initiative aimed at mapping soil fertility in cardamom-growing areas within the ICH. This research aims to use GIS-based interpolation techniques to establish baseline data. To include cardamom-growing regions within the scope of soil test-based fertilizer recommendations, the Indian Cardamom Research Institute (Spices Board) conducted an analysis of cardamom-growing soils in its Agronomy and Soil Science Laboratory. Soil samples were analyzed for fertility status across 12 nutrient parameters.

In collaboration with the Rubber Research Institute of India (RRII), soil nutrient levels were spatially interpolated using GIS. Soil fertility maps were generated using the Geostatistical Analysis tool in ArcGIS software. Village-level spatial variability maps of 12 soil nutrients were generated in GeoTIFF format with a 30 m resolution. In partnership with Kerala University of Digital Science Innovation and Technology (formerly IIITM-K), an online mobile and web-based fertilizer recommendation system, *CardSApp,* was developed using the interpolated soil fertility data. At present, *CardSApp* covers Udumbanchola taluk in the Idukki district of ICH.

This approach integrates multiple soil fertility factors based on ICRI's soil test-based fertilizer recommendations. The second phase of the project aims to extend coverage of *CardSApp* to additional areas of cardamom-growing regions in southern India. The app is expected to play a crucial role in boosting productivity by providing data-driven insights to farmers for the rational use of fertilizers. The free Android version of *CardSApp* is available on the Google Play Store and the web version can be accessed at https://cardsapp.spicesboard.org.in/.

This study proposed on the potential for developing a decision-making tool that enables to help farmers to assess the field fertility status of their fields and receive site-specific online fertilizer recommendations. This tool is expected to help cardamom planters minimize excess fertilizer use, reduce environmental hazards in the ecologically sensitive ICH and restore the traditional reputation of small cardamom as the 'Queen of Spices' while promoting sustainable production.

Materials and Methods

Study area

part of a larger project on fertility mapping in cardamom-growing regions of the Indian Cardamom Hills (ICH). The initial phase covers eighteen villages (administrative units) located within the coordinates 76°59'01.19'' - 77°16'11.55'' East longitude and 9°38'21.54'' - 10°04'46.60'' North latitude. Key geographical and agricultural data about the study areas were incorporated. The goal was to assess the regional variability of soil fertility indices. Soil fertility in these regions was evaluated through systematic sampling using GPS, followed by laboratory analysis. The surveyed cardamom-growing area was divided into 10 ha grids and soil samples were collected from each grid. Geospatial analysis and mapping were employed to delineate the spatial variability of various soil fertility parameters.

Soil sample collection

Soil samples were collected over three years, focusing on areas with significant cardamom cultivation. In total, 1,512 soil samples were gathered from major cardamom-growing villages in Udumbanchola taluk, Idukki district. The collected samples were air-dried, sieved (2 mm) and stored in plastic containers for subsequent analyses. The sample locations were recorded using GPS (Model: Garmin eTrex 10). Spatial variability in various soil fertility parameters was then mapped using geostatistical analysis.

Analysis of soil samples

Standard analytical procedures were followed to analyze the soil samples. Soil pH was measured in a 1:2.5 soil-water suspension. The Walkley and Black (11) wet digestion method was used to determine organic carbon. Bray I reagent (0.03 N NH_4F and 0.025 N HCl) was used to extract available phosphorus (P). The extracted P was then quantified using UV-visible spectrophotometry (SHIMADZU UV Spectrophotometer, Model UV1800, Japan) (12). Available potassium (K), calcium (Ca) and magnesium (Mg) were extracted using neutral normal ammonium acetate. Potassium was quantified with a flame photometer (SYSTRONICS microcontroller-based flame photometer 128, India) (13). Calcium and magnesium concentrations were measured using an atomic absorption spectrophotometer (AAS, PinAAcle 900H, Serial No: PHCSl 7040302, USA). Available sulphur (S) was extracted with a 0.15% $CaCl_2$ solution and measured by turbidimetry as described by Vogel (14). Available zinc (Zn), manganese (Mn), iron (Fe) and copper (Cu) were quantified using AAS after extraction with 0.1 N HCl. Available boron (B) in the soil was determined using azomethine-H with the hot water extraction method and UV-visible spectrophotometry (15).

Statistical and geostatistical analysis

Descriptive statistical analysis of the soil characteristics was conducted using SPSS 16.0. The Kriging interpolation technique, as described in earlier studies (16, 17), was applied to map soil fertility status in the region, creating geographical variability maps of available nutrients across different cardamom-growing villages. The spatial structure of the data was analyzed using the Geostatistical Analyst extension of ArcGIS software from ESRI. Additionally, spatial analysis was used to estimate the extent of cardamom areas with low or adequate nutrient levels.

The Geostatistical Analyst extension of ArcGIS creates continuous surface models from point data using geostatistical methods. The Geostatistical Analyst extension of ArcGIS creates continuous surface models from point data using geostatistical methods. Geostatistical Analyst uses sample points from various locations to generate a continuous surface, predicting values for unsampled areas based on measured data. This method relies on the similarity of nearby sample points to create the surface using mathematical functions for interpolation.

In this study, cardamom soil samples were highly clustered in certain areas due to the nature and distribution of cardamom holdings. Therefore, the Inverse Distance Weighted (IDW) interpolation method available in ArcGIS software version 10.1 was used to generate soil nutrient maps (18). This technique is widely used in scientific disciplines for mapping and monitoring various environmental parameters (18-20). To ensure uniform spatial distribution, locations were cross-checked in GIS and additional samples were collected from underrepresented villages. The sample locations were incorporated into the GIS environment and converted to shapefile format for further analysis.

IDW interpolation assumes that objects closer to each other are more similar than those farther apart. It is based on the principle that the value of an unsampled location is a weighted average of known values within a neighbourhood (19). To predict values for any unmeasured location, IDW uses the measured values surrounding the location. Measured values closest to the prediction location have a greater influence on the predicted value than those farther away. IDW assumes each measured point has a local influence that decreases with distance, assigning greater weight to closer points, with the weights diminishing as a function of distance. The mathematical formula used in IDW techniques is illustrated in the following equation.

$$Z(S0) = \sum_{i=1}^{n} \lambda i \, z(si)$$

Z(S0) is the value to predict for location S0

'n' is the number of measured samples surrounding the prediction location used in the prediction

λi are the weights assigned to measured samples

z(si) is the observed value at the location Si

Economic analysis

The soil nutrient classes and corresponding areas for each class were tabulated from the nutrient maps. Rational fertilizer recommendations from the site-specific online fertilizer recommendation system (*CardSApp*) were matched to various soil fertility classes in the cardamom-growing regions. Fertilizer application rates were also computed for farmers following the general package of practices (POP) recommendation, which does not consider soil test values. Excess fertilizer use resulting from the blanket POP approach was calculated and compared to site-specific recommendations from *CardSApp.* The savings in fertilizer use and cost were computed and discussed.

Results and Discussion

The analytical data for each soil parameter were grouped into distinct classes and spatial variability in soil fertility parameters was mapped using geostatistical analysis.

Soil reaction

Soil pH was classified into five categories: extremely acidic (3.5 -4.5), very strongly acidic (4.5-5.0), strongly acidic (5.0-5.5), moderately acidic (5.5-6.0), slightly acidic (6.0-6.5) and neutral (6.5-7.3). Significant spatial variability was observed in the soil pH of cardamom-growing regions in Udumbanchola Taluk, Idukki District. These soils were highly acidic, with 3 % in the extremely acidic category, 22 % in the very strongly acidic category and 35 % in the strongly acidic category, respectively (Table 1, Fig. 1). Low pH and high soil erosion, coupled with nutrient loss from heavy rainfall, were identified as major constraints for spice soils in India (20).

Organic carbon

Soil organic carbon (OC) was classified into 4 categories: low (<1.5 %), medium (1.5-2.0 %), high (2.0-5.0 %) and very high (>5.0 %) (21). In Udumbanchola Taluk, the mean OC value ranged from 0.01 % - 29 % across the surveyed villages (Table 1). High OC content was common, with 62 % of the area in the high category, 4 % in the medium category and 30 % in the very high category, respectively (Fig. 2).

Available phosphorus and potassium

Available phosphorus (P) was categorized as low (<0.5 mg/100g), medium (0.5-1.25 mg/100 g), high (>1.25 mg/100 g),

Table 1. Descriptive statistics: Nutrient content of soils in the traditional cardamom growing regions of Udumbanchola Taluk in Indian Cardamom Hill

Nutrients	Min.	Max.	Mean	Median	Mode	SD	CV%
Soil pH	4.00	6.90	4.26	5.40	5.24	1.65	39
OC %	0.08	8.90	4.32	4.12	3.67	6.59	153
Phosphorus	0.20	28.62	9.89	5.33	1.00	20.37	206
Potassium	4.00	111.40	5.44	32.00	5.24	0.53	10
Sulphur	0.08	31.04	7.69	4.26	0.25	8.28	108
Boron	0.02	2.75	0.58	0.35	0.13	0.60	103
Mg	8.96	860.00	194.17	184.00	115.00	94.63	49
Ca	5.04	2827.00	877.75	836.00	706.50	478.18	54
Zn	0.70	44.00	12.18	9.75	4.25	8.49	70
Fe	2.25	90.00	33.19	28.50	2.50	19.65	59
Mn	0.55	119.25	35.66	30.25	3.55	24.52	69
Cu	0.75	85.00	16.53	12.00	4.25	13.19	80

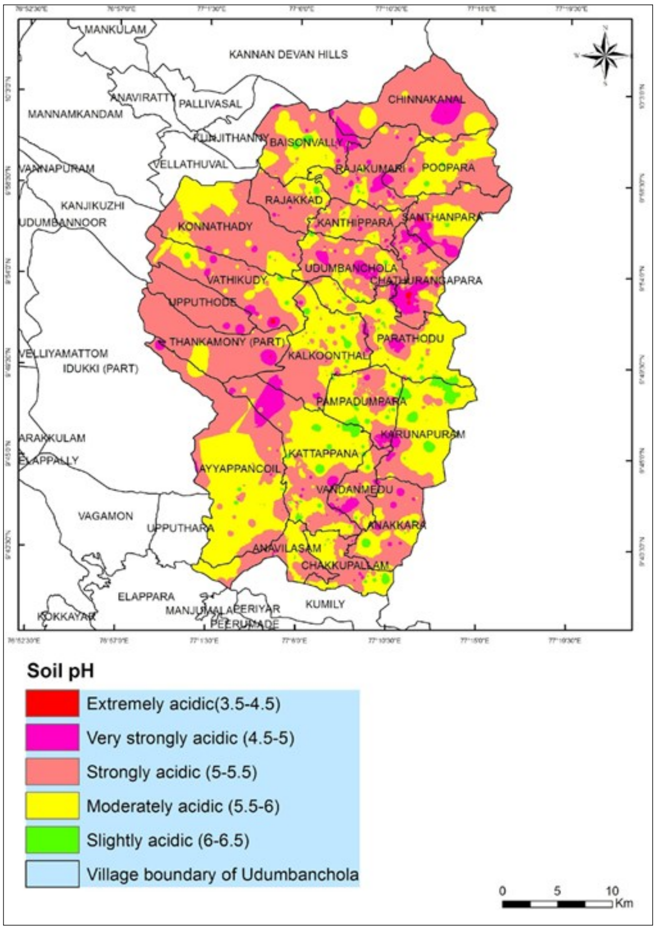

Fig. 1. Geographical variability of pH in cardamom growing soils of Udumbanchola taluk.

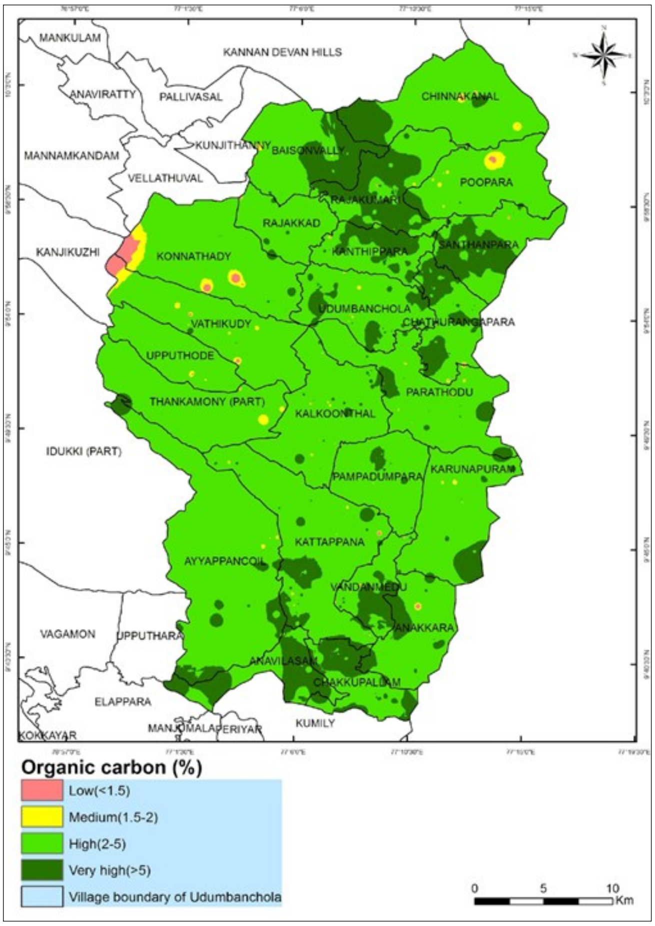

Fig. 2. Geographical variability of Organic Carbon in cardamom growing soils of Udumbanchola taluk.

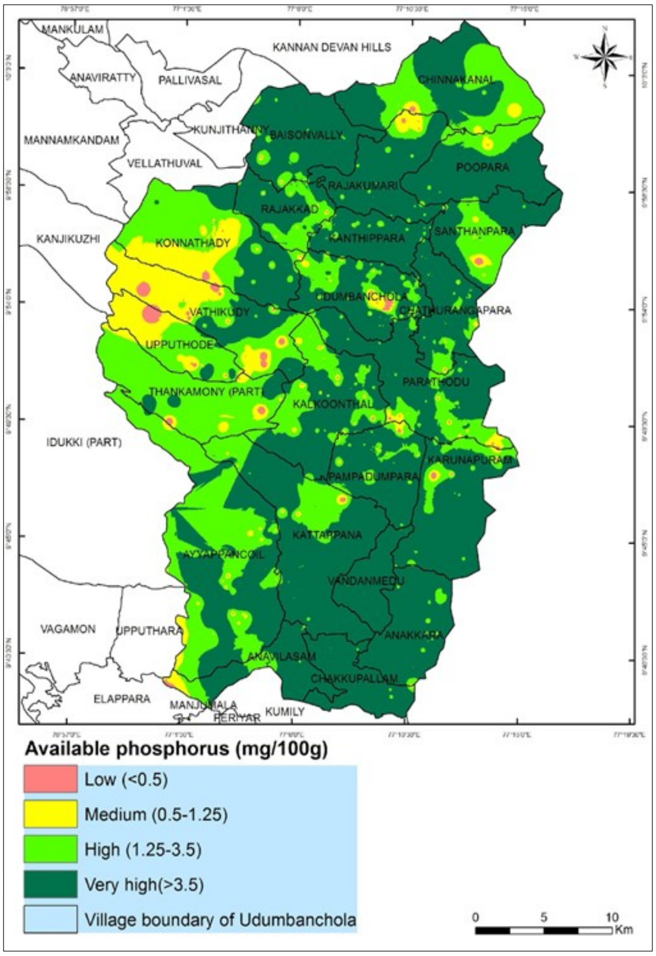

Fig. 3. Geographical variability of Phosphorus in cardamom growing soils of Udumbanchola taluk.

and very high (>3.25 mg/100 g). Most of the cardamom-growing areas had high to very high levels of available P (1.25-3.5 mg/100 g), with 18 % classified as high and 59 % as very high. Available P ranged from 0.01 mg/100 g to 28 mg/100 g (Table 1, Fig. 3). Available potassium (K) was grouped into 5 classes: low (<5.0 mg/100 g), medium (5.0-12.5 mg/100 g), high (>12.5 mg/100 g), very high (15-30 mg/100 g) and extremely high (>30 mg/100 g). In general, these soils had high to extremely high levels of K, with 53 % in the extremely high category and 26 % in the high category (Table 1, Fig. 4).

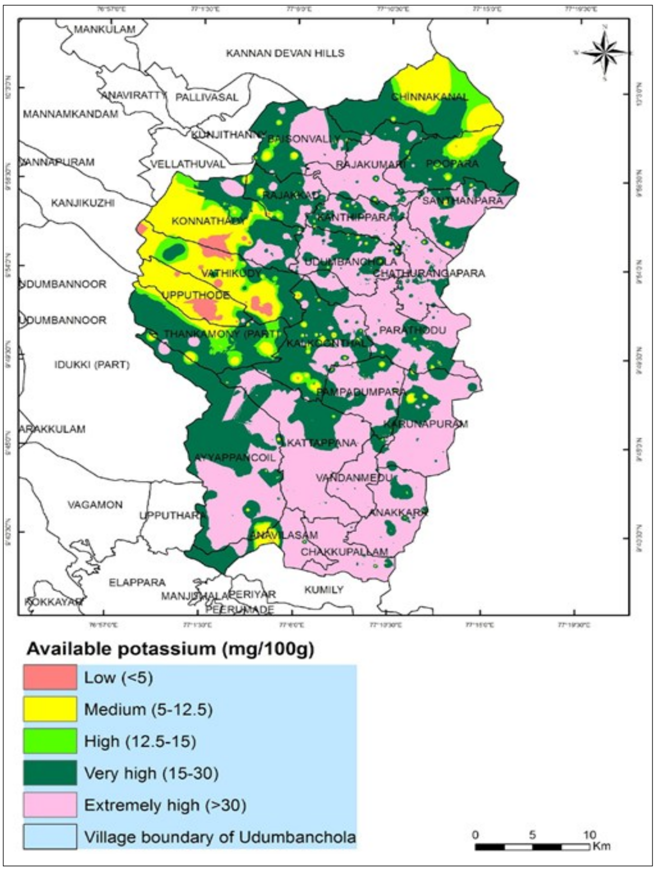

Fig. 4. Geographical variability of Potassium in cardamom growing soils of Udumbanchola taluk.

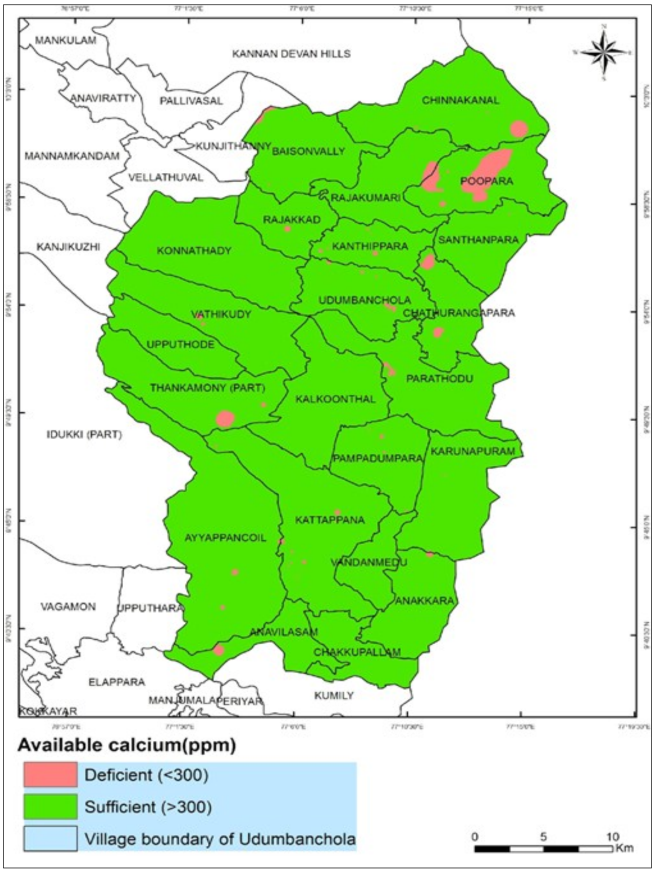

Fig. 5. Geographical variability of Calcium in cardamom growing soils of Udumbanchola taluk.

Available calcium, magnesium and sulphur

Available calcium (Ca) was categorized as adequate (>300 mg/kg) or inadequate (<300 mg/kg). Ca levels ranged from 5 ppm - 2827 ppm, with 83 % of the area classified as adequate and 17 % as deficient (Fig. 5) (22). Available magnesium (Mg) was similarly classified, with 78 % of the area in the sufficient category and 22 % in the deficient category, ranging from 9 ppm - 860 ppm (Table 1, Fig. 6). For available sulfur (S), 55 % of the area was adequate and 45 % was deficient, with S levels ranging from 0.08 ppm - 31 ppm. Sulfur deficiency was attributed to low pH and low sulfur mineral content (Fig. 7) (23).

Available zinc and boron

Available zinc (Zn) was categorized as inadequate (<1 mg/kg) and adequate (>1 mg/kg) (24). Zn levels varied from 0.7 ppm - 44 ppm, with 98 % of soils meeting adequate levels (Fig. 8). Available boron (B) was classified as inadequate (<0.5 mg/kg) or adequate (>0.5 mg/kg). Most of the cardamom-growing areas (69 %) were deficient in B, which ranged from 0.02 ppm - 3 ppm (Table 1, Fig. 9).

Available Iron, manganese and copper

Available iron (Fe) was categorized as deficient (<5 mg/kg) or sufficient (>5 mg/kg) (24). Fe levels ranged from 2 ppm - 90 ppm, with 98 % of samples exceeding the sufficiency level (Fig. 10). Available manganese (Mn) was classified as inadequate (<1 mg/kg) or adequate (>1 mg/kg), with Mn levels ranging from 0.55 ppm - 119 ppm and 100 % sufficiency (Table 1, Fig. 11). Available copper (Cu) was also classified similarly, with 98 % of soils sufficient in Cu, ranging from 0.75 ppm - 85 ppm

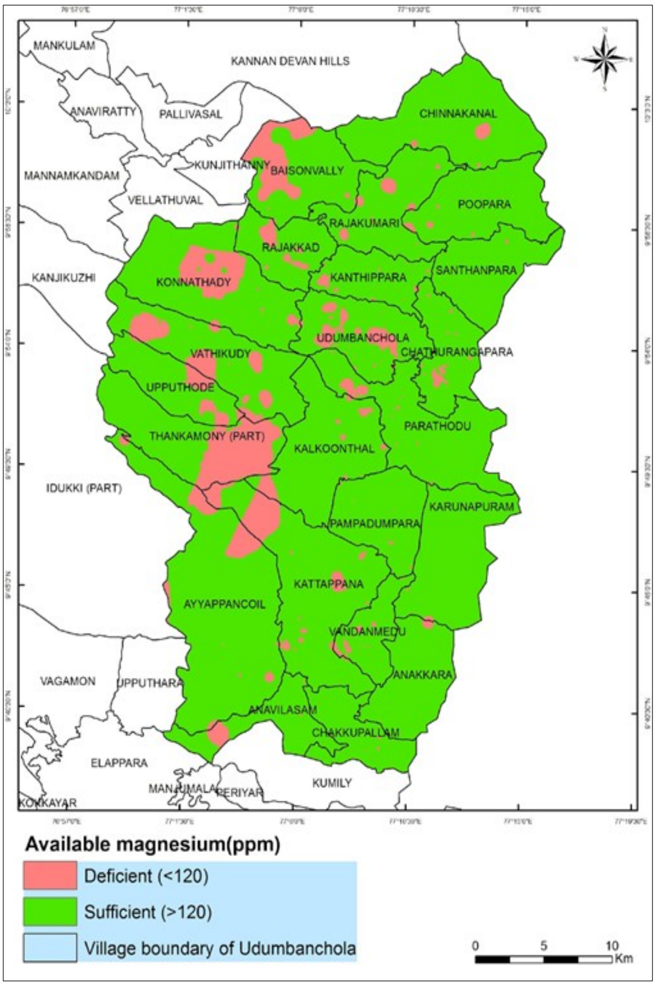

Fig. 6. Geographical variability of Magnesium in cardamom growing soils of Udumbanchola taluk.

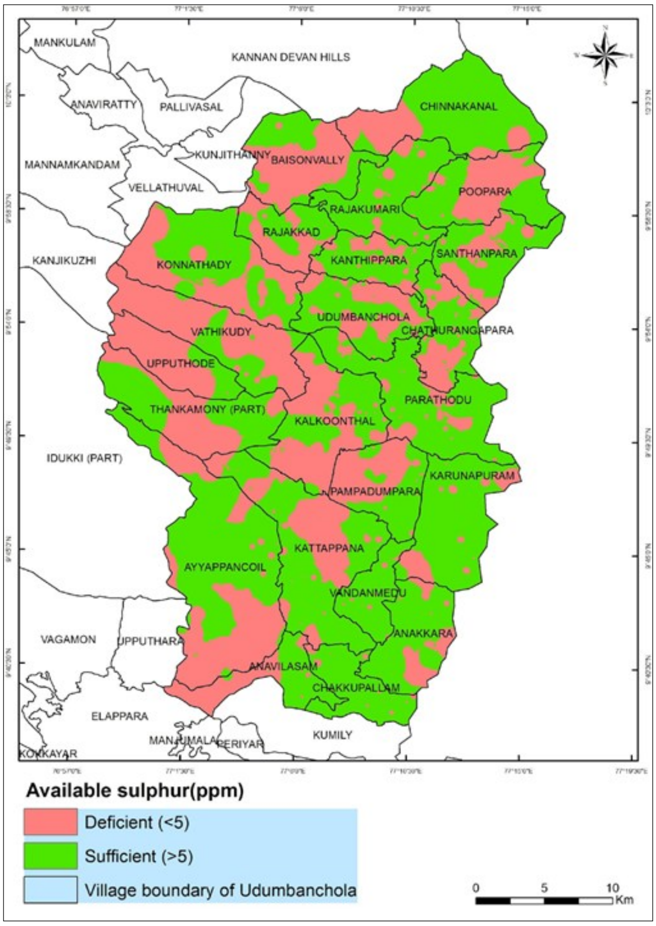

Fig. 7. Geographical variability of Sulphur in cardamom growing soils of Udumbanchola taluk.

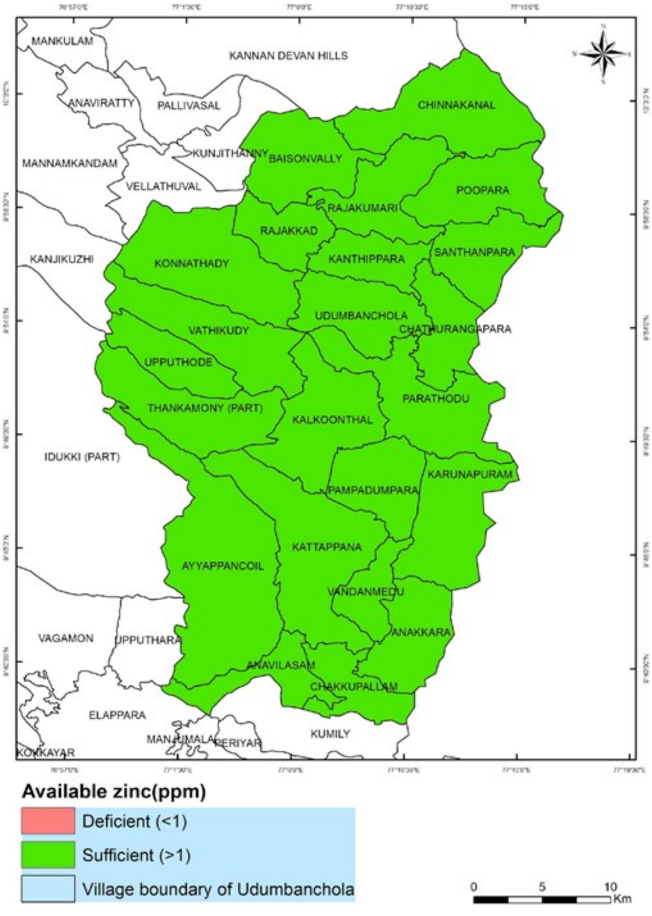

Fig. 8. Geographical variability of Zinc in cardamom growing soils of Udumbanchola taluk.

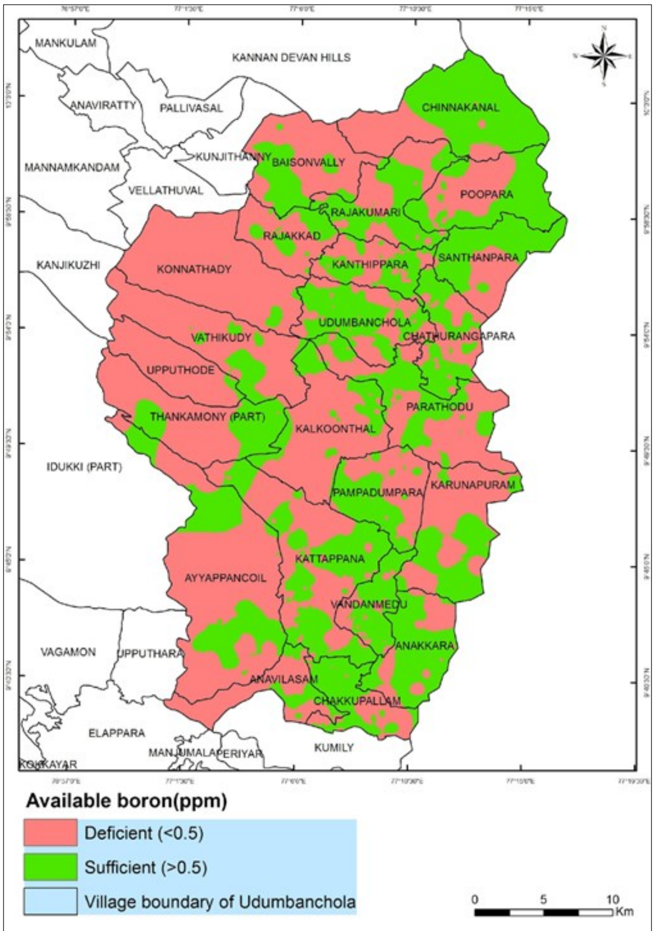

Fig. 9. Geographical variability of Boron in cardamom growing soils of Udumbanchola taluk.

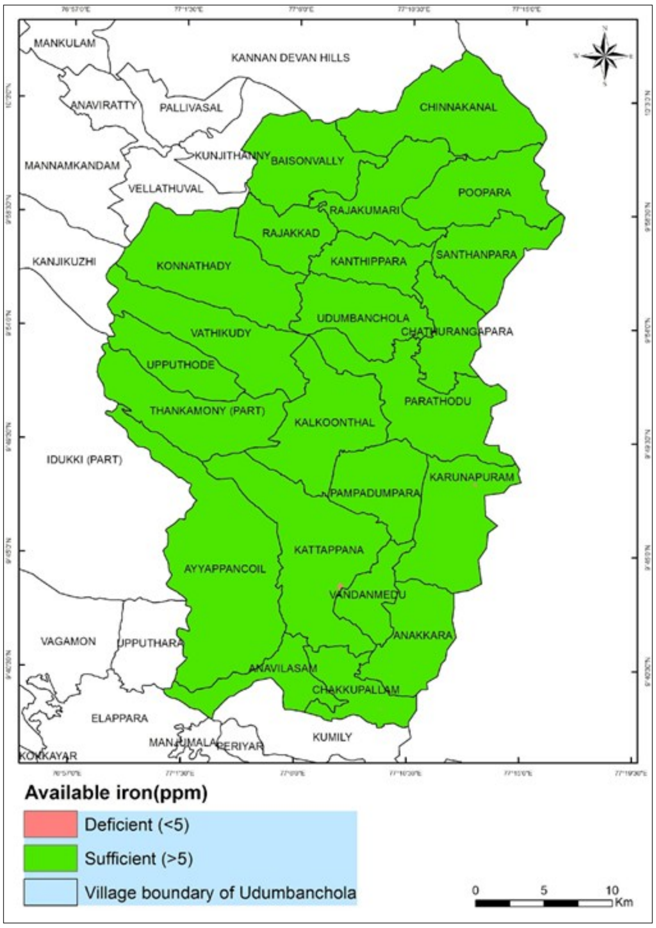

Fig. 10. Geographical variability of Iron in cardamom growing soils of Udumbanchola taluk.

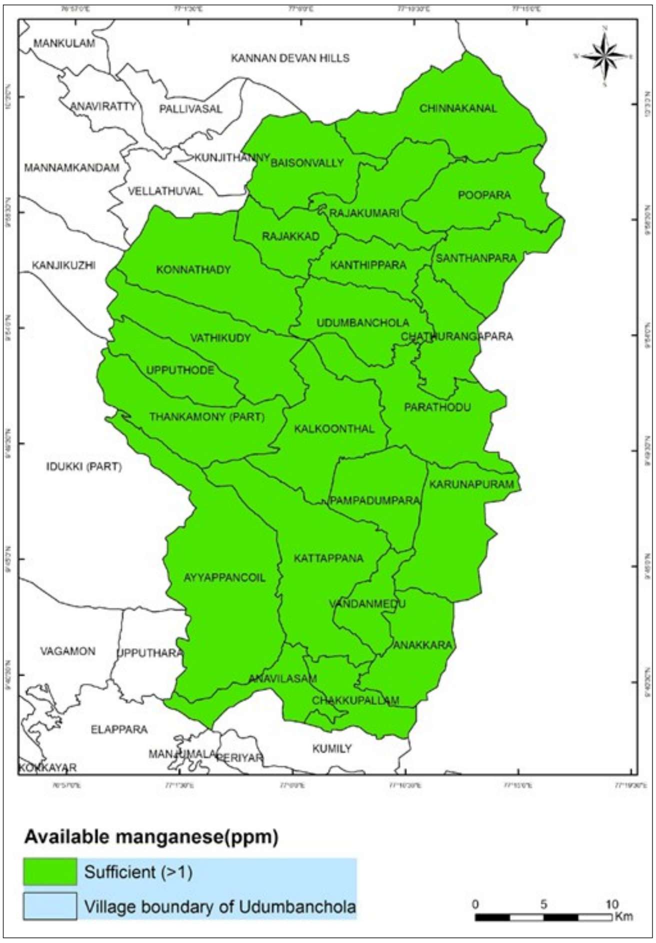

Fig. 11. Geographical variability of Manganese in cardamom growing soils of Udumbanchola taluk.

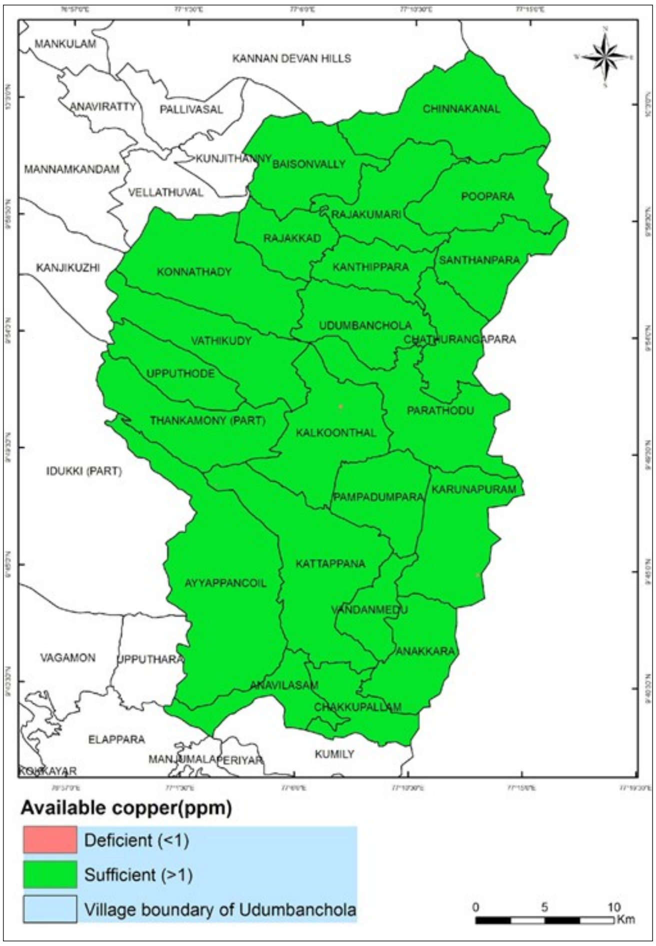

Fig. 12. Geographical variability of Copper in cardamom growing soils of Udumbanchola taluk.

(Table 1, Fig. 12).

Statistical analysis of soil data

A statistical overview of the soil fertility metrics showed moderate to high variability. The coefficient of variation (CV) was highest for available phosphorus (CV of 206), followed by organic carbon (CV of 153) and pH (CV of 39). Available potassium showed the lowest variability (CV of 10). Among secondary nutrients, sulfur had the highest variability (CV of 108), followed by calcium (CV of 54) and magnesium (CV of 49). For micronutrients, boron showed the highest variability (CV of 103), while iron had the lowest (CV of 59). Statistical analyses indicated moderate to high variability in soil fertility across cardamom plantations in the studied villages of ICH.

Soil fertility v/s cardamom production and productivity among various villages

Significant variations in production and productivity were observed among villages in Udumbanchola taluk. Productivity ranged from 2248.69 kg/ha in Vandanmedu to 253.31 kg/ha in Karunapuram (Fig. 13). The lowest mean NPK status was found in Karunapuram, with organic carbon at 3.89 %, available P at 5.34 mg/100 g and available K at 28.59 mg/100 g. Boron deficiency was also critical in Karunapuram (mean of 0.4 mg/kg) and the mean pH ranged from 5.39 (strongly acidic) in high-producing areas - 5.77 (moderately acidic) in Karunapuram (Fig. 16). The high productivity and inverse pH trend can be attributed to higher chemical fertilizer use in more productive areas. Karunapuram, being a peripheral area for cardamom, follows lower management practices. Spatial nutrient variations partially explain the production differences among villages (25).

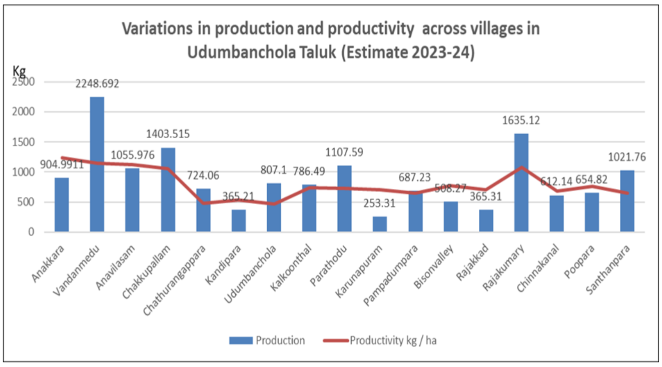

Fig. 13. Variations in production vs Productivity across villages.

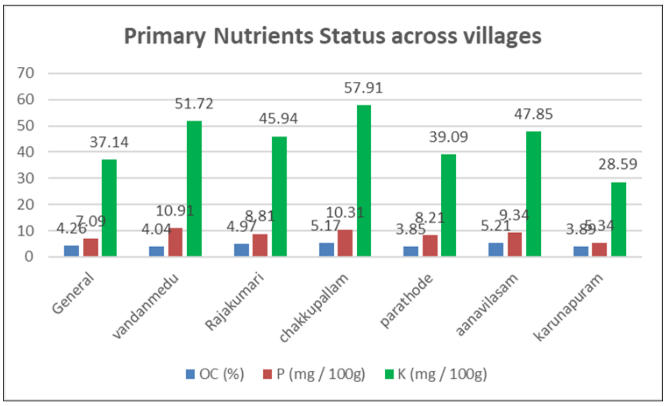

Fig. 14. Variations in primary nutrient status across villages.

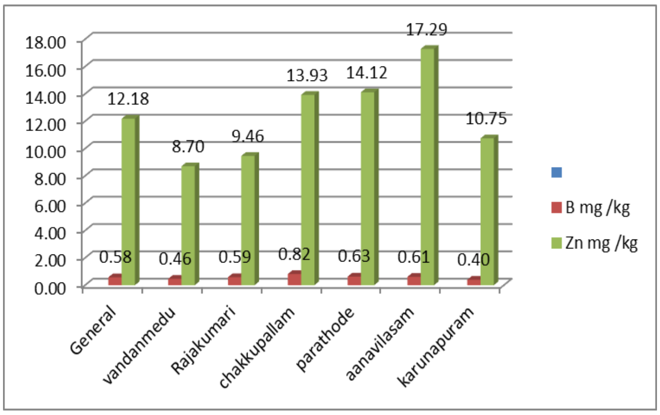

Fig. 15. Variations in available B and Zn status across villages.

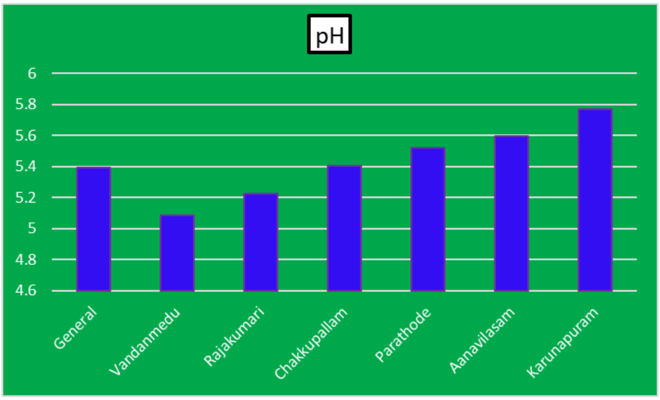

Fig. 16. pH variations among villages.

Development of *CardSApp*: online fertilizer recommendations system

In the initial phase, *CardSApp* aimed to provide soil test-based fertilizer recommendations across 18 villages in Udumbanchola taluk. Currently, *CardSApp* is operational in 8 villages in the north, 4 in the south, 3 in the east and 3 in the west of Udumbanchola taluk. Expansion to other areas in Idukki, Tamil Nadu and Karnataka is planned for the next phase. Developed using GIS-based soil fertility maps in collaboration with Kerala University of Digital Science Innovation and Technology, *CardSApp* integrates multiple soil fertility parameters based on ICRI guidelines for small cardamom. Nutrient data with geographical coordinates was processed as spatial data in GIS software, projected to UTM 43N for metric units. Nutrient data with skewed distribution underwent data transformation before semi-variogram analysis and kriging. The output was saved as raster data, clipped to district boundaries.

A vector-grid shapefile with 30m x 30m cells covered the study area, storing nutrient values in the attribute table. The shapefile was imported into a PostGIS/PostgreSQL database. The Android app sends GPS data to the server through RESTful web services, executing a spatial query to retrieve soil nutrient data as a JSON response. The app parses this response to extract nutrient values, categorizes them and calculates fertilizer recommendations, displayed to the user. *CardSApp* aims to update soil nutrient data in real-time with ICRI analyses, revisiting sites every two years for precision.

Financial analysis

The study found that using *CardSApp* could save 15,245 MT of fertilizers and Rs. 23.01 crores annually, compared to the blanket application of POP-recommended fertilizers. These savings were calculated for an area of 21,287 ha across 18 villages in ICH. Similar financial benefits from online fertilizer recommendations were reported in the rubber industry through RuBSiS (26).

Conclusion

Small cardamom cultivation in the Indian Cardamom Hills has become an intensively managed activity with high fertilizer and pesticide use. The study showed that while NPK levels were high in many regions, deficiencies existed in secondary and micronutrients such as magnesium, sulfur and boron. To promote sustainable and profitable cultivation, *CardSApp* should be popularized among ICH cardamom growers as a tool to guide rational fertilizer use, ensuring higher and more sustainable production. *CardSApp* offers substantial fertilizer and cost savings, supporting sustainable cardamom production with minimal environmental impact on the ecologically sensitive Indian Cardamom Hills. The online recommendation system will be essential for understanding spatial soil fertility variations, applying optimal fertilizers, addressing nutrient deficiencies and achieving sustainable production with improved profitability.

Acknowledgements

Authors greatly acknowledge the technical guidance and administrative approval granted by Sri Sathyan IFS, former Secretary, Spices Board and Dr K. G. Jagadeesha IAS, Secretary, Spices Board on record in carrying out the collaborative project.

Authors' contributions

MO and JJV were responsible for project conceptualization, initiation, soil sample collection, analysis, compilation, and manuscript writing; AME contributed to soil sample collection, analysis, compilation, and manuscript writing; AVR was involved in soil sample analysis, compilation, and manuscript writing; HM, SA, and TP participated in soil sample collection, analysis, and compilation; PB generated GIS-based nutrient maps; RT was responsible for the conceptualization, design, and development of the online fertilizer recommendation system; and JMD and RSAB conceived the study and participated in its design and coordination. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

References

1. Muthusamy M, Panigrahy BK, Shetty PK, Subbiah A, Ravi R. Effect of heavy metal and nutrient uptake by soils in Indian Cardamom Hills. J Soil Sci Environ Manage. 2012;3(8):196–206. https://doi.org/10.5897/jssem11.091
2. Sen P, Majumdar K, Sulewski G. Spatial variability in available nutrient status in an intensively cultivated village. Better Crops. 2007;91(2):10–11.
3. Liu X, Xu J, Zhang M, Si B, Zhao K. Spatial variability of soil available Zn and Cu in paddy rice fields of China. Environ Geol. 2008;55(7):1569–76. https://doi.org/10.1007/s00254-007-1107-x
4. Mali SS, Naik SK, Bhatt BP. Spatial variability in soil properties of mango orchards in eastern plateau and hill region of India. Vegetos. 2016;29(3):74–9. https://doi.org/10.5958/2229-4473.2016.00070.7
5. Behera SK, Suresh K, Rao BN, Mathur RK, Shukla AK, Manorama K, et al. Spatial variability of some soil properties varies in oil palm (*Elaeis guineensis* Jacq.) plantations of west coastal area of India. Solid Earth. 2016;7:979–93. https://doi.org/10.5194/se-2016-9
6. Ramzan S, Wani M, Bhat MA. Assessment of spatial variability of soil fertility parameters using geospatial techniques in Temperate Himalayas. Int J Geosci. 2017;8(10):1251–63. https://doi.org/10.4236/ijg.2017.810072
7. Brevik EC, Calzolari C, Miller BA, Pereira P, Kabala C, Baumgarten A, et al. Soil mapping, classification and pedologic modeling: History and future directions. Geoderma. 2016;264(B):256–74. https://doi.org/10.1016/j.geoderma.2015.05.017
8. Saito H, McKenna A, Zimmerman DA, Coburn TC. Geostatistical interpolation of object counts collected from multiple strip transects: ordinary kriging versus finite domain kriging. Stoch Environ Res Risk Assess. 2005;19(1):71–85. https://doi.org/10.1007/s00477-004-0207-3
9. Pereira P, Cerda A, Ubeda X, Mataix-Solera J, Martin D, Jordan A, et al. Spatial models for monitoring the spatiotemporal evolution of ashes after fire – a case study of burnt grassland in Lithuania. Solid Earth. 2013;4(1):153–65. https://doi.org/10.5194/se-4-153-2013
10. Srinivasan V, Murugan M, Dinesh R. Spices. In: Thomas GV, Krishnakumar V, editors. Soil health management for plantation crops. Singapore: Springer; 2024. p. 153–63. https://doi.org/10.1007/978-981-97-0092-9_5
11. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934;37:29–38. https://doi.org/10.1097/00010694-193401000-00003
12. Bray RH, Kurtz LT. Determination of total organic and available forms of phosphorus in soils. Soil Sci. 1945;59:39-46. https://doi.org/10.1097/00010694-194501000-00006
13. Jackson ML. Soil chemical analysis. New York: Prentice Hall Inc; 1973. 498 p.
14. Vogel AI. Textbook of qualitative inorganic analysis. 4th ed. London, New York: Longman; 1978. 318 p. https://doi.org/10.1080/00103628109367237
15. Parker DR, Gardner EH. The determination of hot water-soluble boron in some acid Oregon soils using a modified Azomethine-H procedure. Commun Soil Sci Plant Anal. 1981;12:1311–22. https://doi.org/10.1007/s00477-004-0207-3
16. Saito H, McKenna SA, Zimmerman DA, Coburn TC. Geostatistical interpolation of object counts collected from multiple strip transects: ordinary kriging versus finite domain kriging. Stoch Environ Res Risk Assess. 2005;19(1):71–85. https://doi.org/10.1007/s00477-004-0207-3
17. Shit PK, Bhunia GS, Maiti R. Spatial analysis of soil properties using GIS based geostatistics models. Model Earth Syst Environ. 2016;2:2–6. https://doi.org/10.1007/s40808-016-0160-4
18. Environmental Systems Research Institute (ESRI). ArcGIS Geostatistical Analyst. ArcGIS 9 user's manual. New York, USA: ESRI; 2003. p. 113-20.
19. Lu GY, Wong DW. An adaptive inverse-distance weighting spatial interpolation technique. Comput Geosci. 2008;34(9):1044-55. https://doi.org/10.1016/j.cageo.2007.07.010
20. Srinivasan V, Dinesh R, Hamza. Management of acid soils for sustainable production of spice in India. In: Proceedings of the 8th International Symposium on Plant-Soil Interactions at Low pH; 2012 Oct; Bengaluru. p. 153-68.
21. Karthikakuttyamma M, Joseph M, Nair ANS. Soils and nutrition. In: George PJ, Jacob CK, editors. Natural rubber: agro management and crop processing. Kottayam (India): Rubber Research Institute of India; 2000. p. 171-98.
22. Prasannakumari P, Jessy MD, Pradeep B, Jacob J, Abraham J, Philip A, et al. Spatial variability of available calcium and magnesium in soils in the rubber growing regions of South India. Rubber Sci. 2020;33(1):18-32.
23. Ananthanarayana R, Mithyantha MS, Perur MG. Fertility status of the acid soils of Karnataka. Mysore J Agric Sci. 1986;8:209-13.
24. KAU. Ad hoc recommendations for management of secondary and micronutrients in Kerala. Kerala Agricultural University; 2012.
25. Patil S, Anilkumar KS, Srinivasamurthy CA. Soil fertility status and nutrient index for primary nutrients in Western Ghats and coastal Karnataka under different agro-ecological systems. Asian J Soil Sci. 2017;12(2):314-9. https://doi.org/10.15740/has/ajss/12.2/314-319
26. Pradeep B, Jacob J, Jessy MD. Rubber soil information system (RUBSIS): A decision-making tool for skipping fertilizer application in rubber plantations. Rubber Sci. 2019;32(1):63-6.