



Soil Fertility Status of Different Grape Growing Orchards in Nandi Valley, Karnataka, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/ijpss/2025/v37i85610>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://pr.sdiarticle5.com/review-history/128113>

Original Research Article

Received: 08/10/2024
Published: 21/07/2025

ABSTRACT

A comprehensive study evaluated the Soil fertility status of different grape growing orchards in Nandi Valley, Karnataka - Bangalore Blue, Dilkush, Sharad Seedless and Red Globe. A total of 200 soil samples were collected from 100 grape gardens, with 25 gardens per variety. From each garden, two soil samples were taken: surface soil (0–20 cm) and sub-surface soil (20–40 cm) near the root zone of grape vines. The analysis revealed significant variability in soil fertility status among

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Cite as: Muradi, Pavan Kumar, Sathish, A., Vasundhara, R., and Manjunatha, M. H. 2025. "Soil Fertility Status of Different Grape Growing Orchards in Nandi Valley, Karnataka, India". *International Journal of Plant & Soil Science* 37 (8):55-74. <https://doi.org/10.9734/ijpss/2025/v37i85610>.

the grape varieties and depths. Soil pH and electrical conductivity (EC) increased with depth, with Dilkush surface soils showing a neutral pH (7.22), while Bangalore Blue recorded the lowest EC (0.31 dSm⁻¹). Organic carbon (OC) and cation exchange capacity (CEC) decreased with depth, with Sharad Seedless surface soils exhibiting the highest OC (7.59 g kg⁻¹) and CEC (17.87 cmol(p⁺) kg⁻¹). Available nitrogen (N), phosphorus (P), and potassium (K) also declined with depth. Red Globe recorded the highest surface N (413.63 kg ha⁻¹), Bangalore Blue had the highest P (63.07 kg ha⁻¹) and Sharad Seedless had the highest K (392.24 kg ha⁻¹). Exchangeable calcium (Ca) and magnesium (Mg) increased with depth, with Red Globe soils showing the highest Ca (4.72 meq/100 g) and Mg (2.54 meq/100 g). Available sulphur (S), DTPA-extractable micronutrients (Fe, Mn, Cu, Zn), and hot water-soluble boron (B) declined with depth, with Sharad Seedless soils exhibiting the highest levels of micronutrients and boron. These results provide a scientific basis for soil management strategies aimed at optimizing grape production in the Nandi Valley region.

Keywords: Soil fertility; grape varieties; Nandi valley; macronutrients; micronutrients.

1. INTRODUCTION

Soil chemical properties are fundamental determinants of grapevine performance, affecting plant growth, fruit quality, and yield. In Nandi Valley of South Interior Karnataka, a prominent grape-growing region, soil attributes such as pH, nutrient availability, and organic carbon content significantly influence the productivity of various grape varieties. Maintaining an optimal chemical balance in the soil is crucial for ensuring efficient nutrient uptake and supporting physiological processes that enhance grape yield and quality (Reddy, 2019; Kumar, 2021).

Among these properties, soil pH plays a vital role by influencing the solubility and availability of essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). These nutrients are critical for vine vigor, flowering, and berry development. Imbalances in pH or deficiencies in elements like zinc and iron can result in reduced yields and inferior fruit quality, as observed in other Indian grape-growing regions (Patil et al., 2020; Sharma et al., 2018). Similarly, managing salinity levels, which often arise due to irrigation practices, is essential to prevent osmotic stress and nutrient transport issues in grapevines. Research highlights that salinity management through gypsum application and organic mulching improves soil structure and mitigates adverse effects on grape productivity (Rana, 2019; Rao, 2020).

Micronutrients including boron, manganese, and copper are also integral to grapevine health. Boron is critical for pollen viability and fruit set, while manganese enhances photosynthesis and sugar accumulation, impacting berry quality.

Deficiencies or toxicities of these nutrients can alter the biochemical composition of grapes, particularly in wine varieties. Foliar applications of micronutrients have been shown to effectively address deficiencies and improve grape quality in Indian viticulture (Verma, 2017; Singh, 2021).

The organic carbon content in soil is another critical factor, as it promotes microbial activity and nutrient cycling while improving water retention. Studies indicate that vineyards with balanced organic matter levels produce grapes with superior sugar content and resilience to environmental stressors. The use of organic amendments such as compost and biochar has proven effective in enhancing cation exchange capacity (CEC), reducing chemical fertilizer dependence, and improving soil health in semi-arid regions like Karnataka (Joshi, 2018; Mehta, 2020).

This study focuses on the impact of soil chemical properties on grape varieties and their yield in Nandi Valley. By assessing parameters such as pH, salinity, nutrient levels, and organic matter, the research aims to propose sustainable soil management strategies tailored to the region. Insights from previous studies in Indian viticulture provide a robust basis for addressing challenges and optimizing grapevine productivity (Desai, 2019; Yadav, 2021).

This research is essential in the present context as grape cultivation in Nandi Valley faces challenges such as declining soil fertility, increasing salinity due to irrigation practices, and nutrient imbalances, all of which directly affect yield and quality. Addressing these issues through a detailed understanding of soil

chemical properties can provide sustainable solutions to enhance productivity, meet market demands, and ensure the economic viability of grape farming in the region. Furthermore, the study supports precision agriculture, which is crucial for adapting to climate variability and conserving soil health in semi-arid regions.

2. MATERIALS AND METHODS

2.1 Location and General Description of the Study Area

The study area was chosen based on the area, production, and productivity data of major grape growing areas of Southern Karnataka, such as Nandi Valley, which includes parts of Chikkaballapur, Doddaballapur and Bangalore rural area. The study area is located at 13.37° N to 13.4° N Latitude 77.62° E to 77.68° E Longitude with an elevation of about 900 to 1,450 meters (2950 to 4760 feet) above mean sea level, providing a favorable climate for grape cultivation. Nandi Valley experiences a moderate climate with relatively cooler temperatures

compared to the surrounding plains. The average annual temperature ranges from 15° C to 32° C. The region receives an average annual rainfall of about 800 to 900 mm, primarily during the monsoon season from June to September. The valley is characterized by undulating terrain with gentle slopes and fertile soils, making it ideal for viticulture.

2.2 Soil Samples

In the study area, 200 soil samples were collected from 100 grape gardens with 25 gardens belonging to each of the four grape varieties (Bangalore blue, Dilkush, Sharad seedless, Red globe). From each grape garden, two soil samples were collected, consisting of surface (0-20 cm depth) and sub-surface (20-40 cm depth) near the root zone of grape vines. Samples were collected using GPS coordinates from each grape garden, to meet the objectives of the current study. These samples were dried in the shade, grounded using a wooden pestle and mortar, passed through a 2 mm sieve, and stored in bags for various chemical properties of soil by adopting standard procedures.

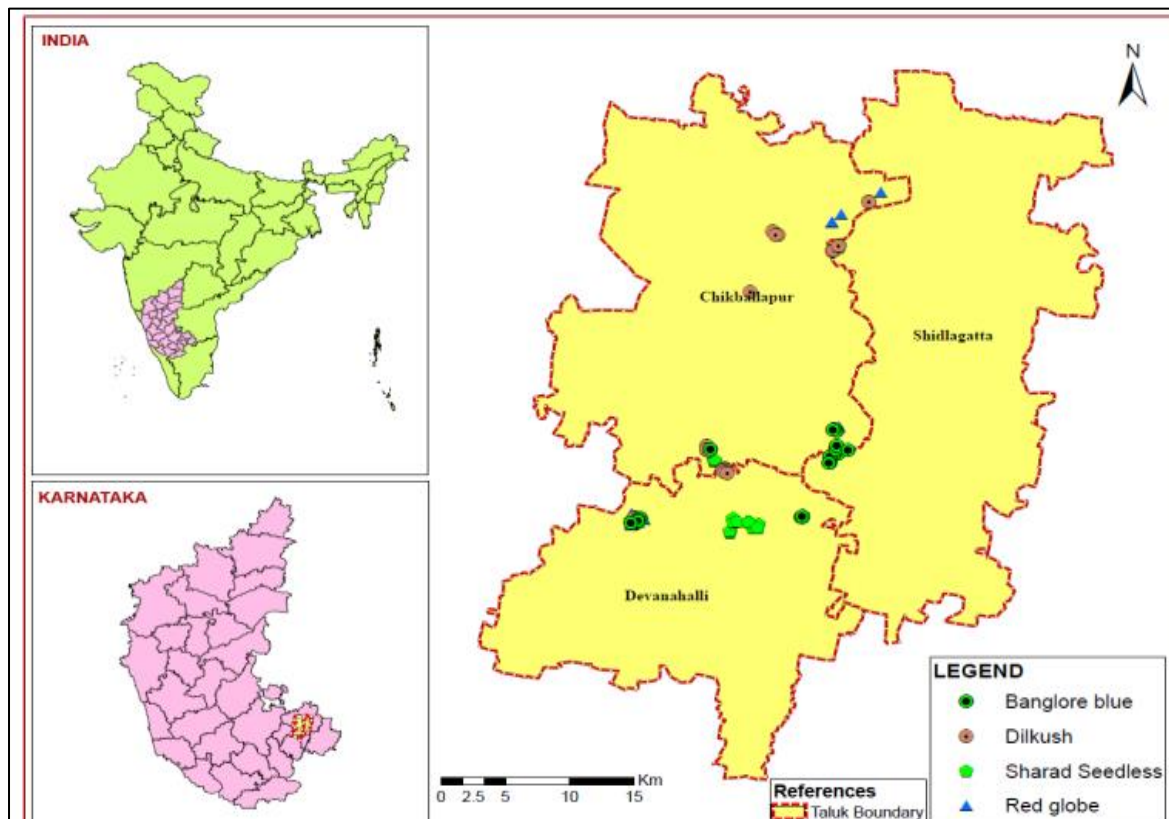


Fig. 1. Location map of the study area

2.3 Analysis of Samples

After the collection of all soil samples from every site, samples were air-dried under shade, processed, and sieved to pass through 0.2 mm for organic carbon (OC) and 2 mm for analysis of soil chemical parameters. All the chemical parameter analysis was carried out following standard protocols. Among chemical attributes, soil pH, electrical conductivity (EC) was measured with 1:2.5 soil: water ratio, cation exchange capacity (CEC), Soil available K, Soil exchangeable Ca and Mg was determined by 1 N ammonium acetate method (pH 7.0) Soil available S by turbidimetric method as per the method described by (Jackson, 1973). Soil available micronutrient cations (Fe, Mn, Cu and Zn) were extracted by DTPA-CaCl₂ extractant at pH 7.3 (Lindsay and Norvell 1978) and measured by using an atomic absorption spectrometer. Available B was extracted by the hot water-soluble B method (Page et al., 1982). Soil organic carbon was estimated by Walkley Black's wet oxidation method (WBOC) (Walkley and Black 1934). Soil available N was determined by the alkaline potassium permanganate method (Subbiah and Asija 1956). Available P was determined by Olsen's method by using 0.5 M NaHCO₃ extractant (Olsen et al. 1954).

3. RESULTS AND DISCUSSION

3.1 Electrochemical Properties of the Soil

Table 1 presents the electrochemical properties of surface soil (0-20 cm) and subsurface soil (20-40 cm) samples near the root zone of grapevines from different grape orchards in the Nandi Valley of Karnataka.

The pH of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depths increases with increasing depth with mean values of 6.67, 6.69, 6.66, and 6.75 for surface soil samples and in subsurface soils 6.98, 7.26, 7.30 and 7.22 respectively Fig. 2(a).

Under different grape varieties, Dilkush variety growing soils had a slightly neutral pH of 7.22 compared to other grape variety growing soils. pH of both surface and subsurface soils was slightly acidic in condition and the decreased soil pH in surface soil due to the acidic parent material, application of ammonical, urea fertilizer, and cultivation practices. Similar results

recorded by Pal et al. (2009) reported climate and vegetation majorly influence the change in pH of the soil. The lower mean pH of the surface soil is influenced by the acidic parent material and intensive cultivation of crops (Deepa shettar, 2022), and continuous application of chemical fertilizers over the years generates the hydrogen ion in the soil thereby decreasing the soil pH.

The electrical conductivity (EC) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depths increase with increasing depth with mean values of 0.31, 0.31, 0.34, and 0.32 dSm⁻¹ for surface soil samples respectively and in subsurface soils 0.19, 0.16, 0.17 and 0.17 dSm⁻¹ respectively Fig. 2(b).

Under different grape varieties, Bangalore blue variety growing soils had a low EC of 0.31 dSm⁻¹ compared to other grape variety growing soils.

Electrical conductivity of the soil was significantly higher in the near root zone of grape vines treated with fertilizers, lime, and FYM. Surface soil had higher EC values compared to subsurface soil due to the addition of salts through the fertilizer application over the years. These results are in agreement with the findings of Kumar et al. (2022).

The organic carbon (OC) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depths decrease with an increasing depth ranging from 6 to 8.70, 5.90 to 9, 5.50 to 8.6 and 4.60 to 8.50 g kg⁻¹ for surface soils respectively and in subsurface soils ranged from 2 to 5.40, 1.50 to 5.40, 2.20 to 6 and 2 to 5.10 g kg⁻¹ respectively Fig. 2(c).

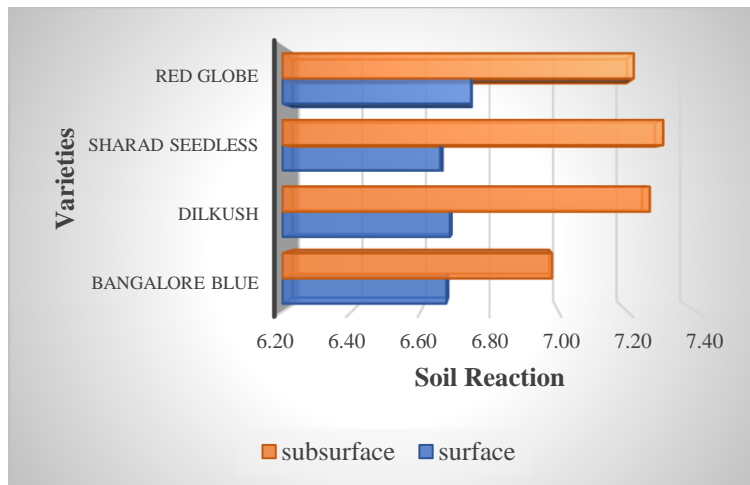
Under different grape varieties, Sharad seedless variety growing surface soils had higher OC of 7.59 g kg⁻¹ compared to other grape variety growing soils.

Here, surface soils that are near the root zone of grapevines that received FYM in addition to inorganic fertilizers had much higher OC values. This could be owing to the use of FYM alone or in combination with fertilizers, which resulted in higher biomass production and, as a result, a higher OC content in the surface soil and lowest carbon content subsurface soil due to low organic matter as a result of no fertilizer and manure application. Similar results were also reported by Bhattacharyya et al. (2011).

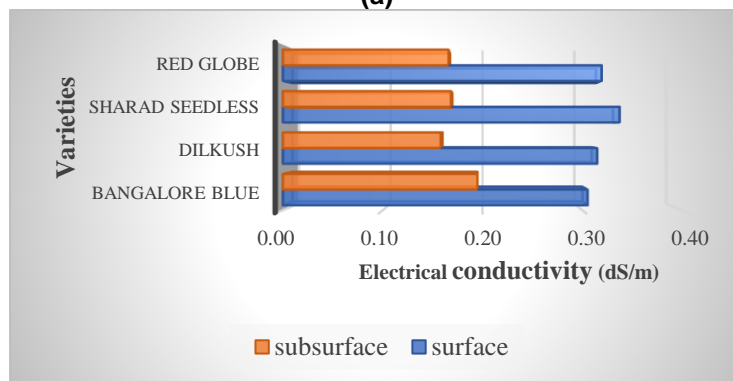
Table 1. Descriptive statistics of electro-chemical properties of surface and subsurface soil samples of grape varieties in Nandi Valley of Karnataka

Grape varieties	Statistical parameter	pH		EC (dSm ⁻¹)		OC (g kg ⁻¹)		CEC (cmol (p+) kg ⁻¹)	
		A	B	A	B	A	B	A	B
Bangalore Blue	Mean	6.67	6.98	0.31	0.19	7.37	3.29	13.98	6.59
	Range	6.20-7.92	6.46-7.68	0.22-0.40	0.10-0.27	6-8.70	2-5.40	10.02-18.95	4.80-8.15
	SD	0.39	0.29	0.04	0.05	0.80	0.87	2.52	0.85
	CV (%)	5.88	4.14	13.96	25.20	10.78	26.47	18.01	12.92
Dilkush	Mean	6.69	7.26	0.31	0.16	7.51	3.63	15.01	7.50
	Range	6.22-7.48	6.81-7.85	0.25-0.37	0.10-0.27	5.90-9.0	1.50-5.40	10.38-23.42	5.11-9.80
	SD	0.31	0.33	0.04	0.04	0.80	1.03	2.92	1.21
	CV (%)	4.57	4.54	11.68	25.32	10.69	28.27	19.45	16.17
Sharad Seedless	Mean	6.66	7.30	0.34	0.17	7.59	4.06	17.87	7.41
	Range	6.35-7.25	6.75-7.94	0.26-0.45	0.10-0.24	5.50-8.60	2.2-6.0	12.50-21.50	5.28-9.50
	SD	0.21	0.27	0.05	0.03	0.92	1.07	2.16	1.08
	CV (%)	3.13	3.65	15.18	20.69	12.13	26.22	13.98	14.65
Red Globe	Mean	6.75	7.22	0.32	0.17	6.70	3.42	15.50	7.11
	Range	6.21-7.63	6.80-7.89	0.20-0.45	0.09-0.25	4.60-8.50	2-5.10	12.05-23.50	5.99-8.51
	SD	0.35	0.31	0.06	0.05	0.91	1.02	3.42	0.63
	CV (%)	5.19	4.33	19.08	28.79	13.54	29.83	19.13	8.86

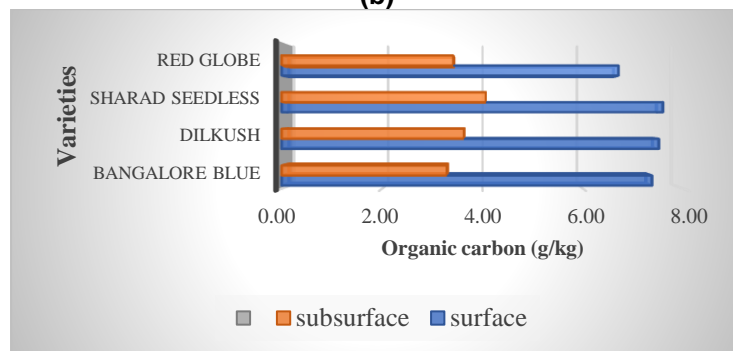
(A: Surface soil sample (0-20 cm); B: Subsurface soil sample (20-40 cm) near the root zone of grapevines)



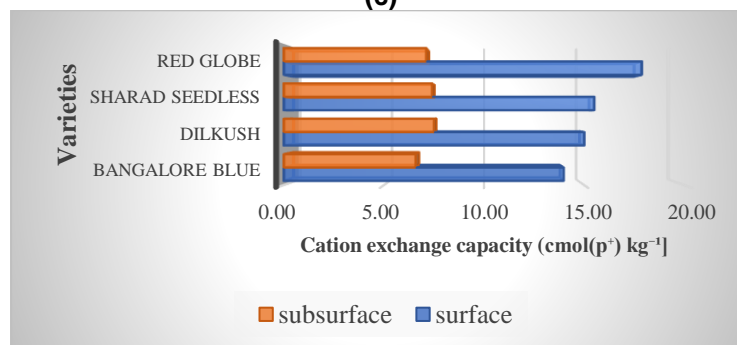
(a)



(b)



(c)



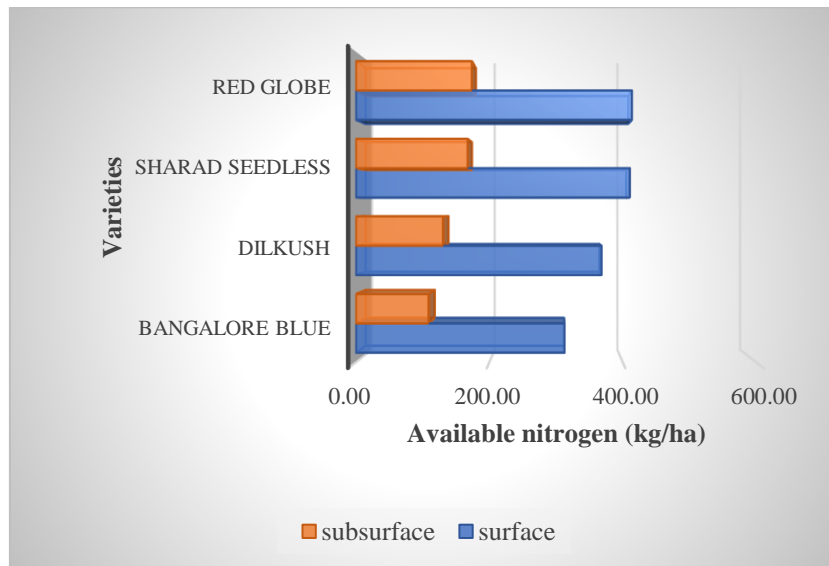
(d)

Fig. 2. (a) Soil reaction (b) EC (c) OC and (d) CEC in surface and subsurface depth across different grape varieties

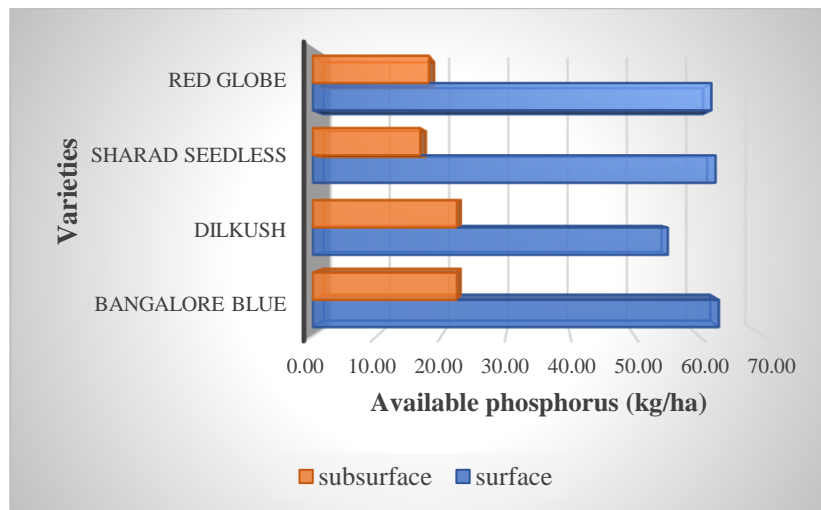
Table 2. Descriptive statistics of primary nutrients status of surface and subsurface soil samples of grape varieties in Nandi Valley of Karnataka

Grape varieties	Statistical parameter	Available N		Available P ₂ O ₅ (kg ha ⁻¹)		Available K ₂ O	
		A	B	A	B	A	B
Bangalore Blue	Mean	312.78	109.13	63.07	22.41	383.73	112.53
	Range	257.15-386.69	71.25-141.26	45.65-78.66	13.05-31.30	296.88-423.15	90.48-126.34
	SD	38.42	20.65	9.47	4.66	23.59	10.22
	CV (%)	12.28	18.93	15.01	20.78	6.14	9.09
Dilkush	Mean	368.23	130.71	55.15	22.42	388	101.47
	Range	254.02-490.2	95.26-181.22	43.11-69.76	15.90-31.80	358.21-430.57	70.44-120.87
	SD	57.17	16.99	7.02	4.14	20.49	12.11
	CV (%)	15.52	13	12.73	18.44	5.28	11.93
Sharad Seedless	Mean	410.49	167.66	62.56	16.71	392.24	104.83
	Range	358.63-489.66	135.62-206.97	49.60-131.31	11.95-22.50	311.02-484.08	84.60-133.20
	SD	38.99	17.74	15.53	3.14	42.30	14.24
	CV (%)	9.50	10.58	24.82	18.77	10.79	13.58
Red Globe	Mean	413.63	173.92	61.91	18.07	363.06	105.98
	Range	304.18-577.12	120.55-210.11	49.50-76.58	15.33-21.07	279.22-423.72	85.08-181.23
	SD	82.23	22.59	5.35	1.68	36.22	19.84
	CV (%)	19.88	12.99	8.64	9.29	9.98	18.72

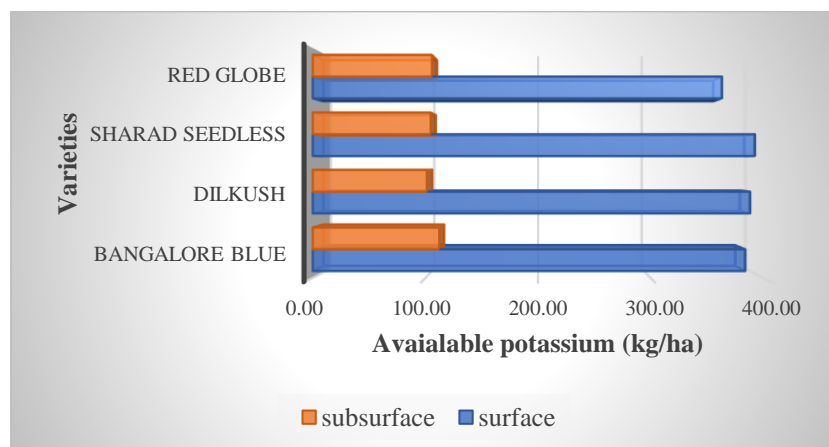
(A: Surface soil sample (0-20 cm); B: Subsurface soil sample (20-40 cm) near the root zone of grapevines)



(a)



(b)



(c)

Fig. 3. (a) Avail. N (b) Avail. P₂O₅ and (c) Avail. K₂O in surface and subsurface depth across different grape varieties

The cation exchange capacity (CEC) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depths decrease with increasing depth with mean values of 13.98, 15.01, 17.87, and 15.50 cmol (p+) kg⁻¹ surface soil samples respectively and in subsurface soils 6.59, 7.50, 7.41 and 7.11 cmol (p+) kg⁻¹ respectively Fig. 2(d).

Under different grape varieties, Sharad seedless variety growing soils had higher CEC of 17.87 cmol (p+) kg⁻¹ compared to other grape variety growing soils.

Continuous application of balanced chemical fertilizers in combination with FYM and lime improved the CEC of the surface soil, possibly due to higher levels of organic colloids in these soils. The decrease in CEC values in subsurface soil is mainly due to low OM content. CEC was majorly dependent on the clay content of the soil than coarser particles because of a higher proportion of colloids which is attributed to dominant clay mineralogy (Habtamu et al., 2014; Chaithra, 2019).

3.2 Primary Nutrient Status of the Soil

Table 2 presents the primary nutrient status of surface soil (0-20 cm) and subsurface soil (20-40 cm) samples near the root zone of grapevines from different grape orchards in the Nandi Valley of Karnataka.

The available nitrogen (N) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 312.78, 368.23, 410.49 and 413.63 kg ha⁻¹ for surface soil samples respectively and in subsurface soils 109.13, 130.71, 167.66 and 173.92 kg ha⁻¹ respectively Fig. 3(a).

Under different grape varieties, Red globe variety growing surface soils had higher available nitrogen of 413.63 kg ha⁻¹ compared to other grape variety growing soils.

Available nitrogen was higher in surface soils and decreased with increase in depth due to continuous mineralization of external application of organic and inorganic materials and regular addition of plant residue on the surface soils (Veerasha and Patil, 2019) and observed low to medium available nitrogen due to low organic

carbon, low vegetation cover, accelerated degradation of organic and inorganic materials in subsurface soil similar results reported by Naik and Gurumurthy (2022). Losses of N through leaching, volatilization, runoff and NH₄⁺ fixation leads to low availability of available nitrogen.

The available phosphorus (P) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 63.07, 55.15, 62.56 and 61.91 kg ha⁻¹ for surface soil samples respectively and in subsurface soils 22.41, 22.42, 16.71 and 18.07 kg ha⁻¹ respectively Fig. 3(b).

Under different grape varieties, Bangalore blue variety growing soils had higher available phosphorus of 63.07 kg ha⁻¹ compared to other grape variety growing soils.

The available phosphorus content decreased with increasing depths. The higher phosphorus content on the surface layer can be attributed to the application of fertilizers like SSP, DAP etc and organic matter like FYM in the surface soil. The decrease in available phosphorus content with depth is attributed to low mobility of phosphorus to sub-surface layers. Similar results showing decline in available phosphorus with increasing depth was also reported by Ahmadi et al. (2021) and Shekhawat et al. (2022).

The available potassium (K) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless, and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 383.73, 388, 392.24 and 363.06 kg ha⁻¹ for surface soil samples respectively and in subsurface soils 112.53, 101.47, 104.83 and 105.98 kg ha⁻¹ respectively Fig. 3(c).

Under different grape varieties, Sharad seedless variety growing soils had higher available potassium of 392.24 kg ha⁻¹ compared to other grape variety growing soils.

This variability in the content of available potassium in the soils of the studied area may be attributed to the application of variable amounts of organic and inorganic inputs by the farmers and available potassium content was found to decrease with increase in soil depth. This may be due to intense weathering processes and the release of labile potassium from organic and

inorganic inputs in the surface layer. Lower potassium content in sub-surface layers as compared to the surface layer was also reported by Shekhawat et al. (2022).

3.3 Secondary Nutrient Status of the Soil

Table 3 presents the secondary nutrients status of surface soil (0-20 cm) and subsurface soil (20-40 cm) samples near the root zone of grapevines from different grape orchards in Nandi Valley of Karnataka.

The exchangeable calcium (Ca) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth increases with increasing depth with mean values of 4.29, 4.45, 4.28 and 4.72 meq/100g for surface soil samples respectively and in subsurface soils 5.45, 6.02, 4.86 and 5.43 meq/100g respectively Fig. 4(a).

The exchangeable magnesium (Mg) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth increases with increasing depth with mean values of 2.40, 2.37, 2.51 and 2.54 meq/100g for surface soil samples respectively and in subsurface soils 2.84, 2.91, 3.04 and 3.06 meq/100g respectively Fig. 4(b).

Under different grape varieties, Red globe variety growing soils had higher available calcium and magnesium of 4.72 and 2.54 meq/100g compared to other grape variety growing soils. The increase of calcium and magnesium with increasing soil depths in different grape orchards may be attributed due to different composition compared to top soil, also leaching and accumulation and presence of more prominent parent material of Ca and Mg in deeper layers. Also, exchangeable magnesium content increased with increase depth due to high mobility of magnesium through percolating water loss, adsorption of Mg on clay particles and strong relationship of clay particles with calcium reported by Siddharam et al. (2015).

The availability of exchangeable magnesium was less than the exchangeable calcium which depends on the soil texture, moisture percentage, fertilizers applied and crop uptake and adsorption of calcium by the clay particles on surface soils (Chaithra et al., 2019).

The available sulphur (S) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with increasing depth mean values of 24.32, 27.16, 26.96 and 27.24 mg kg⁻¹ for surface soil samples respectively and in subsurface soils 10.35, 10.06, 9.29 and 8.78 mg kg⁻¹ respectively Fig. 4(c).

Under different grape varieties, Red globe variety growing surface soils had higher available sulphur of 27.24 mg kg⁻¹ compared to other grape variety growing soils.

Available sulphur content decreased with as depth of soil increase its due to low presence of organic matter, type of vegetation and parent material. Due to the continuous addition of farm residues, organic manures and S containing fertilizers, high concentration of available S was observed in the top layer of the surface soil. Similar results were recorded by Khanday et al. (2017).

3.4 Micronutrient Status of the Soil

The Table 4 presents the micro nutrients status of surface soil (0-20 cm) and subsurface soil (20-40 cm) samples near the root zone of grapevines from different grape orchards in Nandi Valley of Karnataka.

The DTPA extractable iron (Fe) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 25.86, 27.62, 27.80 and 26.77 ppm for surface soil samples respectively and in subsurface soils 6.59, 6.47, 5.81 and 5.20 ppm respectively Fig. 5(a).

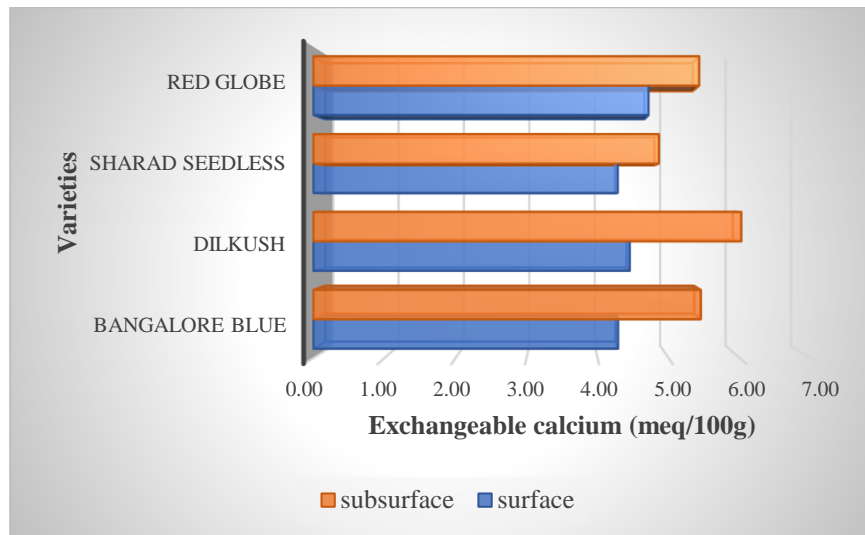
The DTPA extractable manganese (Mn) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 38.27, 39.64, 40.61 and 38.57 ppm for surface soil samples respectively and in subsurface soils 11.20, 12.35, 11.58 and 12.07 respectively Fig. 5(b).

The DTPA extractable copper (Cu) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with

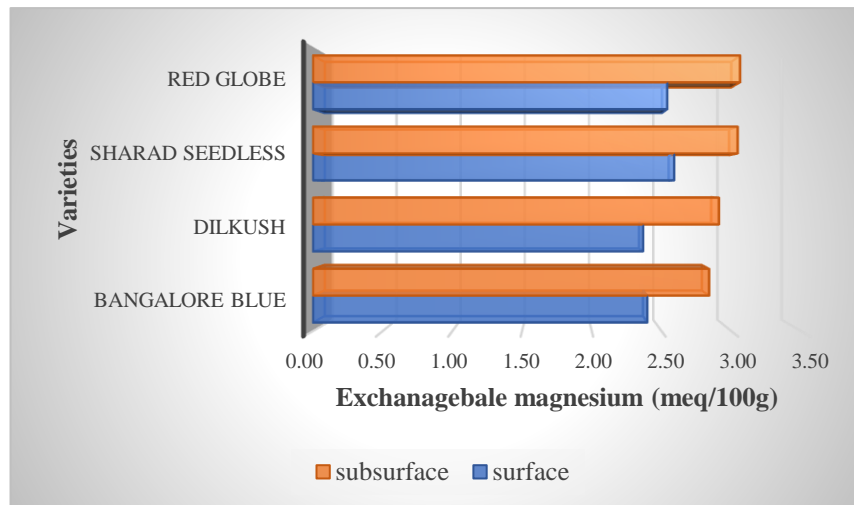
Table 3. Descriptive statistics of secondary nutrients status of surface and subsurface soil samples of grape varieties in Nandi Valley of Karnataka

Grape varieties	Statistical parameter	Exchangeable Ca		Exchangeable Mg (meq/ 100g)		Available S (mg kg ⁻¹)	
		A	B	A	B	A	B
Bangalore Blue	Mean	4.29	5.45	2.40	2.84	24.32	10.35
	Range	3.10-5.82	3.95-6.88	1.90-2.88	2.27-3.11	11.14-34.50	7.90-16.39
	SD	0.68	0.85	0.29	0.24	5.31	1.90
	CV (%)	15.81	15.58	12.26	8.29	21.85	18.36
Dilkush	Mean	4.45	6.02	2.37	2.91	27.16	10.06
	Range	2.95-6.55	4.22-8.25	1.93-2.70	2.27-3.25	17.45-35.47	4.47-15.60
	SD	1.02	0.99	0.23	0.23	4.60	2.88
	CV (%)	22.93	16.42	9.60	7.84	16.94	28.63
Sharad Seedless	Mean	4.28	4.86	2.51	3.04	26.96	9.29
	Range	2.25-5.66	2.85-6.90	1.73-3.45	2.19-3.80	18.60-36.62	6.50-13.22
	SD	0.89	0.96	0.44	0.37	5.03	1.77
	CV (%)	20.72	19.76	17.11	12.14	18.64	19.08
Red Globe	Mean	4.72	5.43	2.54	3.06	27.24	8.78
	Range	3.82-5.68	4.21-6.55	2.10-2.96	2.58-3.38	19.50-36	5.78-13.20
	SD	0.50	0.60	0.28	0.21	4.84	1.81
	CV (%)	10.50	11.07	11.09	7.00	17.79	20.62

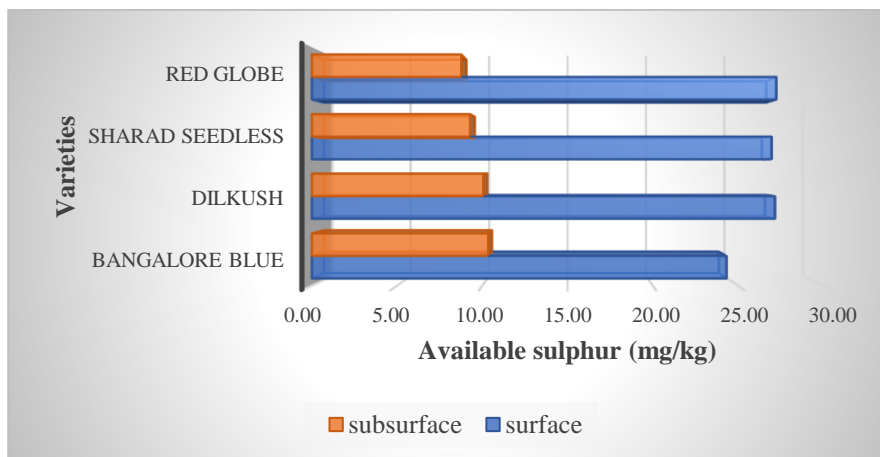
(A: Surface soil sample (0-20 cm); B: Subsurface soil sample (20-40 cm) near the root zone of grapevines)



(a)



(b)



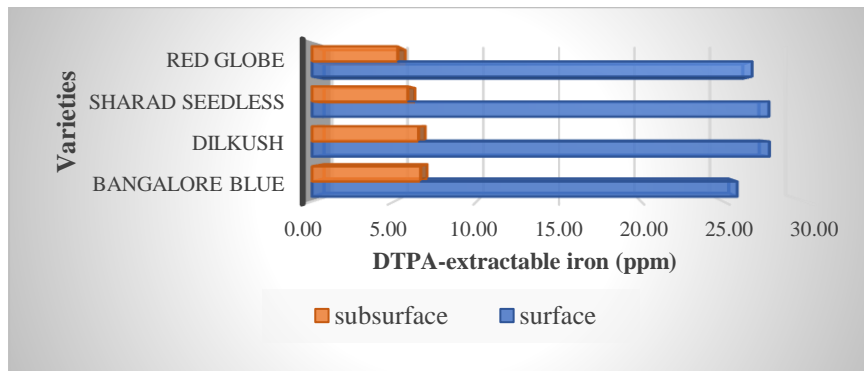
(c)

Fig. 4. (a) Exch. Ca (b) Exch. Mg and (c) Avail. S in surface and subsurface depth across different grape varieties

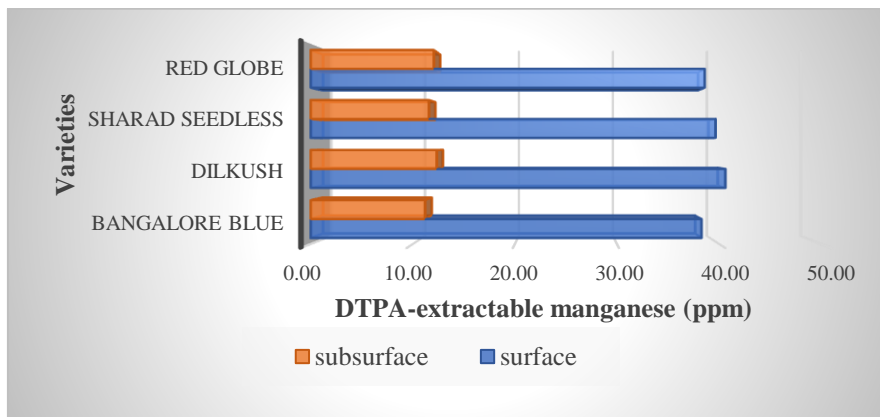
Table 4. Descriptive statistics of micro nutrients status of surface and subsurface soil samples of grape varieties in Nandi Valley of Karnataka

Grape varieties	Statistical parameter	DTPA extractable (ppm)								Hot water-soluble B (ppm)	
		Fe		Mn		Cu		Zn		A	B
		A	B	A	B	A	B	A	B		
Bangalore Blue	Mean	25.86	6.59	38.27	11.20	9.00	1.24	7.11	0.86	0.75	0.23
	Range	22.50-29.50	3.51-8.70	32.50-43.75	7.80-14.90	4.88-13.44	0.41-1.95	4.95-10.74	0.18-2.14	0.38-1.09	0.11-0.40
	SD	1.91	1.48	2.79	1.80	2.02	0.41	1.32	0.47	0.17	0.08
Dilkush	CV (%)	7.38	22.51	7.30	16.07	22.39	33.21	18.54	54.88	22.98	32.75
	Mean	27.62	6.47	39.64	12.35	9.29	1.60	6.89	0.73	0.79	0.29
	Range	23.55-29.77	1.97-8.55	35.60-47.50	9.64-15.64	6.50-13.07	0.97-2.18	5.28-9.64	0.21-1.64	0.53-0.94	0.11-0.55
Sharad Seedless	SD	1.39	1.47	3.03	1.58	1.32	0.33	0.98	0.44	0.10	0.10
	CV (%)	5.01	22.71	7.46	12.82	14.18	20.74	14.20	59.39	13.13	34.40
	Mean	27.80	5.81	40.61	11.58	9.76	1.61	7.62	0.82	0.81	0.26
Red Globe	Range	10.68-31.05	3.80-8.82	35.48-42.77	7.12-14.05	8.27-11.73	0.93-2.12	5.20-10.47	0.21-1.77	0.59-0.97	0.15-0.45
	SD	3.69	1.10	2.20	1.75	0.64	0.36	1.57	0.41	0.11	0.08
	CV (%)	13.29	19.04	5.57	15.11	6.60	22.29	20.65	49.98	13.56	30.52
Red Globe	Mean	26.77	5.20	38.57	12.07	9.58	1.46	6.42	0.79	0.77	0.28
	Range	19.15-29.60	2.02-7.25	30.77-42.50	9.26-15.80	6.90-11.56	0.77-2.12	5.82-7.40	0.21-1.88	0.63-0.97	0.15-0.46
	SD	2.58	0.97	3.13	1.69	0.87	0.42	0.44	0.57	0.08	0.06
	CV (%)	9.62	18.74	8.12	14.00	9.08	28.88	6.88	72.11	9.83	21.15

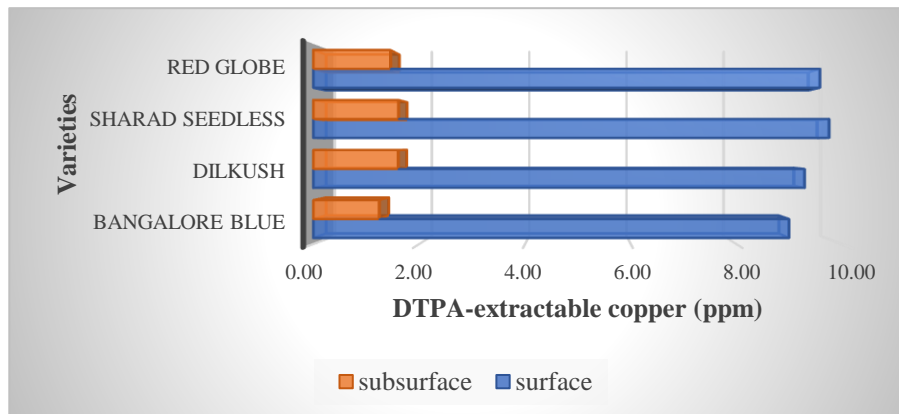
(A: Surface soil sample (0-20 cm); B: Subsurface soil sample (20-40 cm) near the root zone of grapevines)



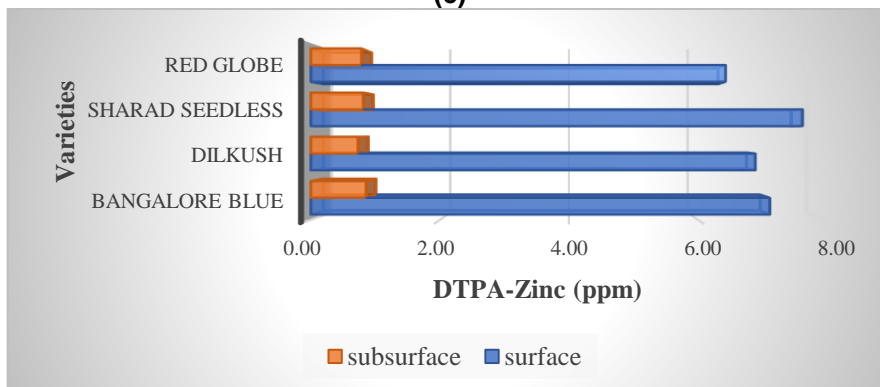
(a)



(b)



(c)



(d)

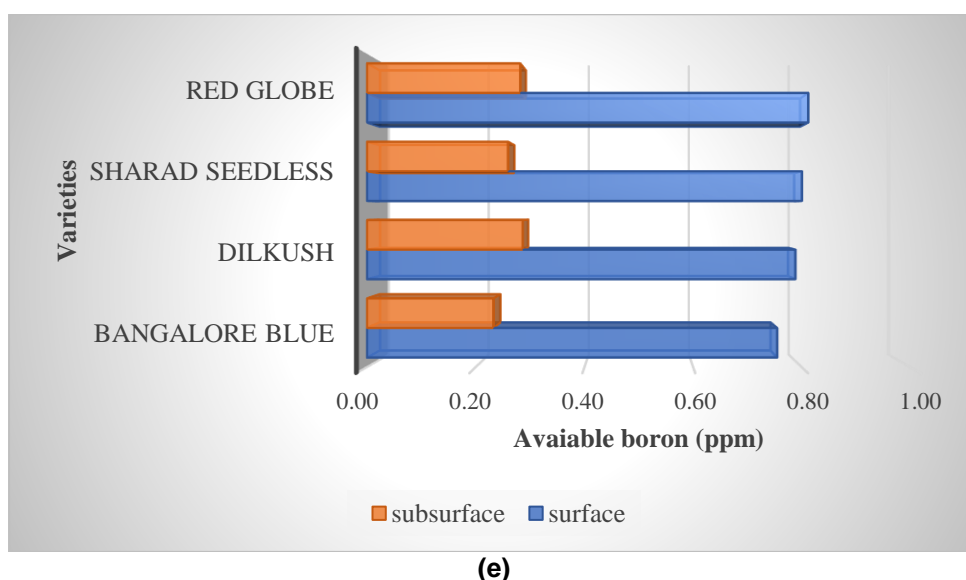


Fig. 5. DTPA extractable (a) Fe (b) Mn (c) Cu (d) Zn and (e) Hot water-soluble B in surface and subsurface depth across different grape varieties

increasing depth with mean values of 9, 9.29, 9.76 and 9.58 ppm for surface soil samples respectively and in subsurface soils 1.24, 1.60, 1.61 and 1.46 ppm respectively Fig. 5(c).

The DTPA extractable zinc (Zn) of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with increasing depth with mean values of 7.11, 6.89, 7.62 and 6.42 ppm for surface soil samples respectively and in subsurface soils 0.86, 0.73, 0.82, 0.79 respectively Fig. 5(d).

Under different grape varieties, Sharad seedless variety growing surface soils had higher micronutrients status compared to other grape variety growing soils.

Overall, there was lower DTPA extractable Zn, Cu, Fe, and Mn content in subsoil compared to surface soil, which may ascribe to increase in pH and decrease in organic matter content with depth. The addition of organic materials to the soil may have increased microbial activity and hence the production of complex organic chemicals such as humic and fulvic acids, which function as chelating agents during the decomposition of organic manure and crop residue. This could have increased the solubility, mobility, and availability of micronutrients by preventing precipitation, fixing, oxidation, and leaching. Similar findings were reported by Prasad et al. (2010).

The hot water-soluble boron (B) levels of different grape varieties *i.e.* Bangalore blue, Dilkush, Sharad seedless and Red globe growing soils at different soil depth decreases with increasing depth ranged from 0.38 to 1.09, 0.53 to 0.94, 0.59 to 0.97 and 0.63 to 0.97 ppm in surface soils respectively and in subsurface soils ranged from 0.11 to 0.40, 0.11 to 0.55, 0.15 to 0.45 and 0.15 to 0.46 ppm respectively Fig. 5(e).

Under different grape varieties, Sharad seedless variety growing surface soils had higher boron status compared to other grape variety growing soils.

The decrease in boron levels with increasing soil depth is influenced by several factors. Boron is highly mobile in soil and tends to leach downward with water movement, particularly in sandy soils or soils with low organic matter content. This leaching is exacerbated by high rainfall or excessive irrigation, which carries boron away from the upper soil layers where it is more accessible to plant roots. Additionally, boron tends to accumulate in the soil's organic matter. As organic matter decreases with soil depth, so does the concentration of boron. Soil pH also plays a role; boron availability decreases in soils with high pH levels, which are often found deeper in the soil profile. Similar findings were reported by Tlili et al. (2019).

The study on soil fertility in the Nandi Valley, Karnataka, provides critical insights into the

spatial and varietal variability of soil characteristics in vineyards. The detailed profiling of surface and subsurface soil layers across 100 grape gardens highlights the heterogeneity in key fertility parameters, including organic carbon, macronutrients, cation exchange capacity (CEC), and micronutrient levels. The observed variation among grape varieties, such as the higher nitrogen levels in Red Globe soils and elevated phosphorus in Bangalore Blue soils, underscores the necessity of tailored nutrient management strategies to optimize production. This data-driven approach contributes to sustainable viticulture by aligning fertilizer application with the specific nutrient needs of different grape varieties.

When compared to studies on soil quality of tropical crops in Latin America, similar patterns of nutrient stratification and variability linked to agro-environmental factors are observed (Lopez et al. 2019; Campos, 2023). For example, in Latin American banana plantations, soil pH, organic carbon (Campos et al. 2023), and macronutrients often exhibit gradients influenced by management practices and microclimatic conditions (Araya-Alman et al. 2020; Lobo et al. 2023). However, the Nandi Valley study emphasizes the role of grape varietal characteristics, a focus less explored in the context of tropical crops, where attention is often directed at regional soil typologies and their responses to agroforestry or intercropping systems (Lopez and Olivares, 2019).

A notable divergence arises in the role of agro-environmental factors. In Latin America, factors such as deforestation, rainfall variability (Hernandez and Olivares, 2019; Hernandez et al. 2020), and soil erosion (Olivares et al. 2011; Olivares et al. 2015) are dominant in shaping soil fertility, particularly in smallholder systems (Hernandez et al. 2018a; 2018b). Conversely, the Nandi Valley research reflects controlled vineyard conditions, where nutrient dynamics are influenced more by deliberate interventions, such as irrigation and fertilization schedules (Olivares et al. 2017a; 2017b). This difference highlights the broader anthropogenic versus natural dichotomy in soil fertility studies across these regions, emphasizing the need for site-specific solutions (Olivares and Zingaretti, 2019; Hernandez and Olivares, 2020).

Both the Nandi Valley and Latin American studies underscore the critical importance of integrating soil health data into crop

management practices (Olivares, 2016). While the former focuses on optimizing grape production, the latter often targets food security and resilience in staple crops like rice, maize, and bananas (Olivares et al. 2022a; 2022b; 2022c). Together, these studies illustrate the universal relevance of soil fertility monitoring but also the necessity of adapting methodologies and interventions to local environmental and agricultural contexts (Pitti et al. 2021; Rodriguez-Yzquierdo et al. 2023a). This comparative understanding fosters knowledge transfer between distinct agro-ecosystems, enriching global agricultural sustainability efforts (Montenegro et al. 2021; Rodriguez-Yzquierdo et al. 2023b; López-Beltrán et al., 2019).

4. CONCLUSION

This study emphasizes the soil fertility status of different grape varieties in Nandi valley, Karnataka. Key soil parameters including pH, electrical conductivity (EC), organic carbon (OC), cation exchange capacity (CEC) and nutrient availability exhibited significant variability across grape varieties and depths. Surface soils of Sharad Seedless recorded the highest OC (7.59 g kg^{-1}) and CEC ($17.87 \text{ cmol (p}^+) \text{ kg}^{-1}$), while Red Globe soils had the highest available nitrogen ($413.63 \text{ kg ha}^{-1}$) and sulphur (27.24 mg kg^{-1}). Micronutrients and boron levels decreased with depth, with Sharad Seedless soils showing superior values. These findings highlight the importance of optimizing soil chemical properties for improved grape production and underscore the need for site-specific soil management practices to ensure sustainable viticulture in the region.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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