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SOIL QUALITY INDEX ASSESSMENT FOR DIFFERENT GRAPE VARIETIES USING PCA IN NANDI VALLEY, KARNATAKA INDIA

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ABSTRACT

Soil quality assessment is valuable for agricultural production and is vital to understand the impact of existing land management practices, thus facilitating the adoption of more sustainable agricultural methods. In this research, 200 soil samples were collected from 100 grape gardens, with 25 gardens belong 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 at Nandi valley, Karnataka. Using principal component analysis (PCA), we identified minimum data-sets (MDS) from 20 different soil properties. The surface layer's MDS were bulk density (BD), pH, soil organic carbon (SOC), available sulphur (S), and microbial biomass carbon (MBC). For the subsurface layer, pH, iron (DTPA-Fe), dehydrogenase activity (DHA) and soil organic carbon (SOC) were identified as the MDS. The Soil Quality Index (SQI) developed for different grape varieties varied from 0.87 to 0.99 at the surface soil depth. SQI followed decreasing order for Sharad seedless (0.99) > Dilkush (0.97) > Red globe (0.91) > Bangalore blue (0.87). At subsurface depth, SQI varied from 0.85 to 0.96. SQI followed decreasing order for Sharad seedless (0.96) > Dilkush (0.95) > Red globe (0.90) > Bangalore blue (0.85). The study recommends that INM practice comprising organic and reduced inorganic fertilizers could enhance soil quality and yield sustainability of grapes.

Keywords: Soil Quality, Grape Varieties, Principal Component Analysis (PCA), Minimum Data Set (MDS), Soil Quality Index (SQI), Integrated Nutrient Management (INM).

Introduction

Soil quality is a central component of sustainable agricultural practices, significantly affecting plant growth, productivity, and crop quality. In viticulture, soil quality directly influences grapevine vigor, fruit quality and consequently wine characteristics (Karlen *et al.*, 2021). Both surface and subsurface soil layers contribute to the overall productivity of vineyards, affecting factors such as root penetration, water retention and nutrient uptake (Costantini *et al.*, 2016). The complex interactions between soil properties at different depths underscore the need for a

comprehensive multi-layered assessment of soil quality in vineyard ecosystems Belmonte *et al.* (2018). Nandi Valley, located in Karnataka, India, is emerging as a prominent grape-growing region due to its conducive climatic conditions and diverse soil characteristics. However, the region's vineyards experience considerable spatial variability in both surface and subsurface soil properties, resulting from factors such as variations in topography, vineyard management practices and geological history (Schmidt *et al.*, 2018). This spatial heterogeneity can lead to significant differences in vine growth, grape yield and overall fruit quality (Raiesi and Kabiri, 2016). Consequently,

precise assessment and management of soil quality across different soil depths are critical to ensuring sustainable fruit productivity in the region (Oliver *et al.*, 2020).

Surface soil, typically the top 0-20 cm, is directly influenced by vineyard management practices such as tilling, fertilization, irrigation and organic matter incorporation. Subsurface soil i.e. 20-40 cm on the other hand, plays a crucial role in water retention, deep-root nutrient absorption and the overall resilience of the grapevines to environmental stressors like drought. Studies have shown that variations in subsurface soil properties, such as soil texture and compaction can significantly affect root distribution and function (Patra *et al.*, 2020). Despite its importance, subsurface soil often receives less attention in soil quality assessments, even though it can have profound long-term effects on vineyard health and productivity (Lalitha *et al.*, 2022).

Assessing soil quality is complex due to the multitude of interacting variables, including physical, chemical and biological properties that affect plant growth and soil function. Soil parameters such as pH, organic matter content, nutrient levels (nitrogen, phosphorus, potassium), texture and moisture retention all contribute to the overall quality and productivity of the soil (Masto *et al.*, 2008). However, the sheer volume of data generated from soil testing can make interpretation challenging. Traditional univariate analyses often fail to capture the full picture of soil health, especially when multiple soil properties are interrelated. This has led researchers to adopt multivariate statistical techniques like Principal Component Analysis (PCA) to simplify and interpret complex soil datasets. PCA is a powerful data reduction technique that allows researchers to identify the most important variables influencing soil quality by transforming correlated variables into a smaller set of uncorrelated components (Sinha *et al.* 2014; Cherubin *et al.* 2016). In viticulture, PCA has been used to evaluate soil quality by focusing on key factors such as soil texture, organic matter and nutrient availability, which are critical to grapevine performance.

The assessment of surface and subsurface soil quality in Nandi Valley is essential for the development of precision viticulture strategies. Precision viticulture involves tailoring vineyard management practices to specific spatial variations within the vineyard, optimizing grape production while

minimizing inputs like water and fertilizers (Jena *et al.*, 2008). Recent studies have emphasized the need for such approaches in regions like Nandi Valley, where climatic conditions and soil variability can dramatically affect grape yield and wine quality. Precision agriculture techniques rely heavily on accurate soil data, making PCA an invaluable tool for simplifying and interpreting soil information (Qi *et al.* 2009). By applying PCA to both surface and subsurface soils, this study aims to identify the primary components that influence soil quality in grape vineyards, helping to address site-specific variability and inform better management practices.

Materials and Methods

Location and general description of the study area

The study area was chosen based on area, production and productivity data of major grape growing areas of Southern Karnataka, as Nandi Valley, this 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 favourable 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.

Soil samples

In the study area, 200 soil samples were collected from 100 grape gardens, with 25 gardens belong 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 objective 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 physical, chemical and biological properties of soil by adopting standard procedures.

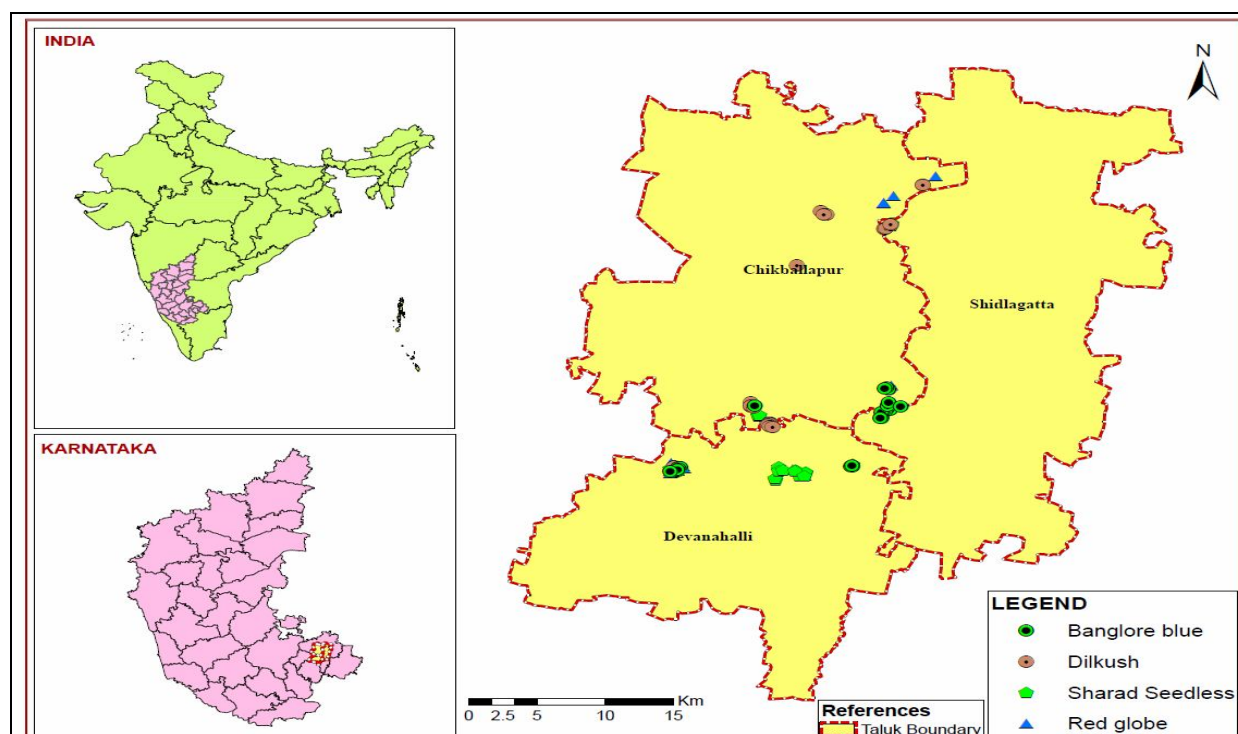


Fig. 1: Location map of the study area

Analysis of samples

After the collection of all soil samples from every site, samples were divided into three parts. The first part was stored at 5°C in the refrigerator for analysis of soil biological parameters. The second part was air-dried under shade, processed and sieved to pass through 2 mm for analysis of soil chemical parameters. The third part was used for the analysis of soil physical properties. All the analysis was carried out following standard protocols. The physical properties of soil i.e. soil bulk density (BD) was measured by core method (Jackson, 1973). Water holding capacity (WHC) was estimated using the Keen Raczowski box method described by Piper (1966). Among chemical attributes, soil pH and electrical conductivity (EC) was measured with 1:2.5 soil: water ratio as per the method described by (Jackson, 1973) soil organic carbon was estimated by Walkley Black's wet oxidation method (WBOC) (Walkley and Black 1934), cation exchange capacity (CEC) was determined by 1 N ammonium acetate method (pH 7.0) method (Jackson, 1973). Soil available N was determined by alkaline potassium permanganate method (Subbiah and Asija 1956). Available P was determined by Olsen's method by using 0.5 M NaHCO_3 extractant (Olsen *et al.* 1954). Soil available K was determined by neutral normal ammonium acetate method (Jackson, 1973). Soil exchangeable Ca and Mg by neutral normal ammonium acetate method (Jackson, 1973). Soil

available S by turbidimetric method (Jackson, 1973). Soil available micronutrient cations (Fe, Mn, Cu, and Zn) were extracted by DTPA- CaCl_2 extractant at pH 7.3 (Lindsay and Norvell 1978) and measured by using atomic absorption spectrometer. Available B was extracted by the hot water-soluble B method (Page *et al.*, 1982). Among soil biological attributes (i.e. microbial biomass C and N) (Cater 1991), dehydrogenase activity (Casida *et al.* 1964) were determined.

Computation of soil quality index

The current tool was developed using the three-step process of selecting the minimum data set (MDS) and integrating indicator scores into a soil quality index (Andrew *et al.*, 2002) (Figure 2). The univariate statistical analysis and indicators correlation matrix reduced the data to MDS. Significant variables ($P < 0.05$) from land use systems were chosen for MDS formation and included in Principal component analysis (PCA). PCA on each significant indicator was performed using SPSS software and varimax rotation to statistically group them into PC factors to examine their relationship. Now, Principal components (PCs) with an eigenvalue greater than 1 (Brejda *et al.*, 2000) and account for at least 5% of data variation were selected for indicator selection. In each PC, the indicator with the highest positive or negative factor loading is scored. To reduce data redundancy, multivariate correlation was used when multiple

factors were retained under one PC. Legaz *et al.* (2017) considered well-correlated variables (<0.60) redundant, so only one was used for the MDS. The rest were removed from the dataset. If highly weighted variables were uncorrelated, they were important for the MDS. Every MDS indicator observation was normalized for SQI computation. The normalized indicator value is the “indicator score” (S). Each indicator in the linear scoring method is categorized as “more is better”, “less is better”, or “optimum is better”. For “more is better,” divide each observation by the highest observed value, resulting in a score of 1 for the highest and a score of <1 for the rest. To score “less is better,” divide the lowest observed value by each observation, resulting in a score of 1 for the lowest value indicator and a score of <1 for others. Up to threshold level, indicator observations are scored as “more is better” for “optimum is better” and then as “less is better.”

$L(Y) = X/X_{max}$ “More is better” approach (1)

$L(Y) = X_{min}/X$ “Less is better” approach (2)

Where,

L(Y) is the linear score varying from 0 to 1

X is the soil indicator value

X_{max} is the maximum value of each soil indicator

X_{min} is the minimum value of each soil indicator

The SQI is computed by integrating the score and weight factor of each indicator. This can be explained by the following equation:

$$SQI = \sum_{i=1}^n W_i S_i$$

Where, S_i = Score for subscripted variable

W_i = Weighing factor derived from the PCA

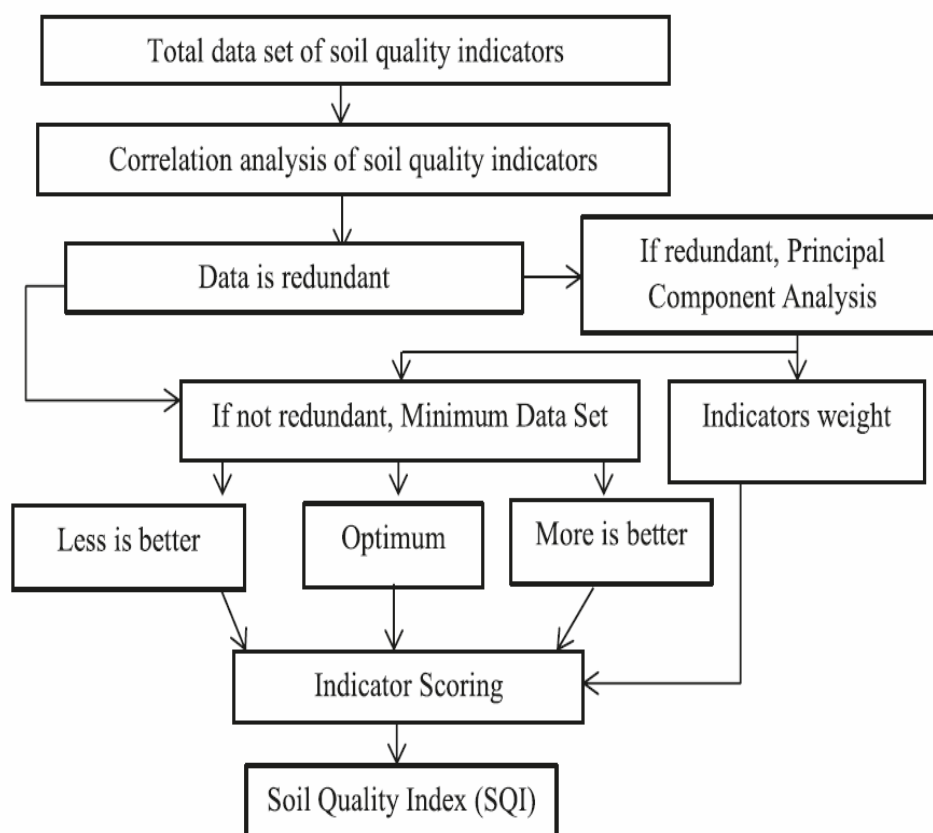


Fig. 2: Flow chart of soil quality index computation

Data Analysis

A descriptive analysis (range, average, and standard deviation) described the data. SPSS version 29.0.1.0 was used to analyse soil properties using a

one-factor approach. Differences in farming systems were statistically significant ($p = 0.05$). Pearson correlation was used to determine variable relationships. The SPSS 29.0 software also performed the MDS through PCA for SQI selection.

Results and Discussion

Computation of soil quality index (SQI)

Estimation of soil quality index of different grape varieties at surface soil (0-20 cm), Nandi Valley, Karnataka

Minimum data set (MDS) formulation for soil quality indicators at 0-20 cm

The data on soil quality parameters was statistically evaluated for their level of significance. To determine the minimum dataset for 0-20 cm soil, 20 soil quality parameters were subjected to principal

component analysis (PCA) using SPSS software. The variables that best characterize system qualities were believed to be main components with high Eigen values and variables with high factor loading (Brejda *et al.* 2000). Only the variables with the highest factor loading were kept for the MDS inside each main component. As a result, for the creation of SQI, only PCs with Eigen values of 1 or larger were considered (Wander and Bollero, 1999). The first three principal components with Eigen values greater than 1 explained roughly 100 per cent of the variance in the data, according to the PCA (Table 1).

Table 1: Eigen values from principal component analysis (PCA) of soil quality parameters of different grape varieties at surface soil (0-20 cm), Nandi Valley, Karnataka

Component	Initial Eigen values			
	Total	% Of Variance	Cumulative %	Weightage factor
1.	9.730	48.650	48.650	0.49
2.	6.828	34.141	82.791	0.34
3.	3.442	17.209	100.000	0.17
Total				1.00

The scree plot of PCA gives a graphical representation of principal components which are to be considered to assess the soil quality, here the 3

principal components have eigen value more than one is considered, rest of them are rejected shown in Fig. 3.

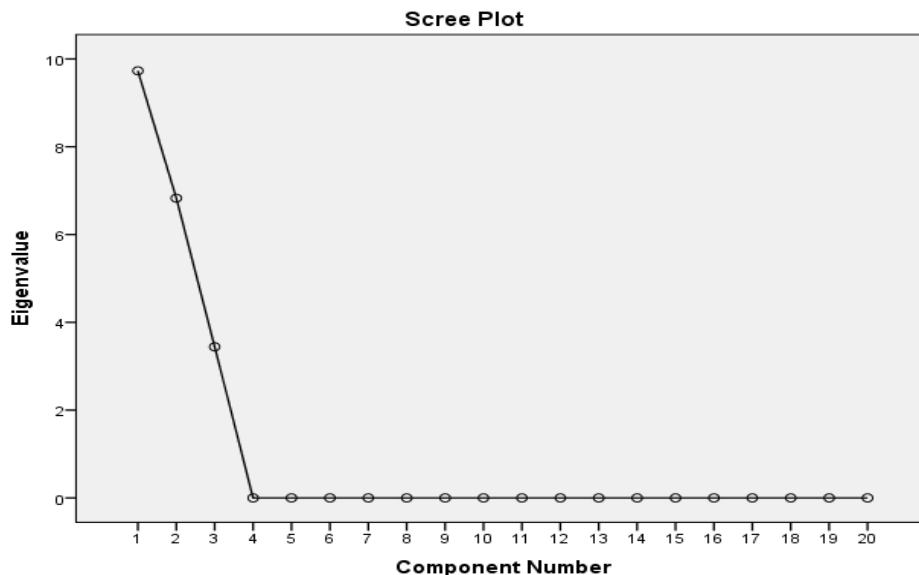


Fig. 3: Scree plot of PCA for 0-20 cm depth of soil

The Principal Component Analysis (PCA) conducted on the soil data from different grape varieties in Nandi Valley, Karnataka, provided significant insights into the soil quality indicators that influence grape productivity. A total of 20 soil properties with the highest factor loadings were identified and used to develop a Minimum Data Set (MDS) for Soil Quality Index (SQI) calculation. These variables, representing physical, chemical and

biological components, were chosen based on their correlation patterns and factor loadings.

Factor Loading and Selection of MDS

In PC1, the highest factor loadings were observed for bulk density (BD), moisture-holding capacity (MWHC), pH, electrical conductivity (EC), organic carbon (OC) and available nitrogen (N) with BD, pH and OC retained for the final MDS. These properties

are indicative of the soil's physical structure, nutrient availability and chemical environment, which are critical for grapevine growth. Specifically, BD and MWHC are essential for assessing soil texture and water retention capacity, while pH and OC represent the chemical balance and organic matter content, both of which influence microbial activity and nutrient availability. Multivariate correlation analysis showed that BD, pH and OC had low correlation ($r < 0.60$), which allowed their inclusion in the MDS without redundancy. The selected MDS were independent of each other with a correlation coefficient < 0.6 value (Andrews, Mitchell, *et al.*, 2002). In PC2, available sulphur (S), iron (Fe), and manganese (Mn) showed the highest factor loadings. However, since available sulphur (S) was the most significant variable, it was selected for the final MDS. The role of sulphur as an essential nutrient for plant growth, particularly in grape production, has been well established in other studies (Vasu *et al.*, 2016). Moreover, available S interacts with other soil nutrients, influencing their bioavailability and uptake by grapevines, making it a critical component of soil health. In PC3, microbial biomass carbon (MBC) had the highest factor loading, highlighting its importance as a biological indicator of soil quality. MBC serves as a proxy for microbial activity and biodiversity, reflecting the soil's biological health and its ability to decompose organic matter and cycle nutrients. MBC is especially significant in semi-arid regions, where soil microbial activity can be a limiting factor for nutrient cycling (Riches *et al.*, 2013). Thus, MBC was retained as part of the MDS due to its role in soil nutrient dynamics and biological function (Table 2 and 3).

Weighting and Scoring of MDS Variables

After selecting the key indicators for soil quality, each variable was transformed into a unitless score ranging from 0 to 1, based on its performance in relation to the optimal soil function. The linear transformation allowed for standardization of the variables, facilitating their comparison across different grape varieties and soil conditions. These transformed scores were then weighted according to the explained variance of each principal component (PC), with PC1 explaining 49%, PC2 explaining 34%, and PC3 explaining 17% of the total variance.

The weighting of the variables was crucial for the final calculation of the Soil Quality Index (SQI). The weighted factors were applied to the scores of each variable to compute the aggregate SQI for each treatment, providing a comprehensive measure of soil quality. The weightage derived from PCA indicated

that PC1 contributed most significantly to the SQI (49%), reflecting the dominant role of physical and chemical soil properties, such as BD, pH and OC in determining soil quality. PC2 contributed 34%, emphasizing the importance of nutrient availability (available S, Fe, Mn) in supporting grapevine health. PC3, with a 17% contribution, reinforced the role of biological activity, as reflected in the MBC values (Table 4).

Soil Quality Index (SQI) for Surface soil

The SQI values for the different grape varieties varied significantly, ranging from 0.86 to 0.99 (Table 4, Fig. 4). Sharad Seedless had the highest SQI (0.99), followed by Dilkush (0.97), Red Globe (0.91), and Bangalore Blue (0.86). These results are consistent with other studies that have reported varying soil quality levels across grape varieties, with different varieties responding differently to soil management practices (Biswas *et al.*, 2017; Lalitha *et al.*, 2019). The high SQI for Sharad Seedless suggests that this variety is more adapted to the soil conditions in Nandi Valley, likely benefiting from better nutrient availability, organic matter content and microbial activity compared to other varieties. On the other hand, Bangalore Blue exhibited the lowest SQI, indicating that it may be more sensitive to soil quality variations and may require specific management practices to optimize its growth and yield.

Implications for Soil Management

The findings of this study underscore the importance of integrated soil management practices tailored to the specific needs of different grape varieties. The identified MDS—BD, pH, OC, available S, and MBC are critical parameters for assessing and managing soil quality. Since these indicators are both dynamic and intrinsic, they can guide sustainable agricultural practices that optimize grapevine productivity while maintaining soil health over time (Ray *et al.*, 2014). The use of Integrated Nutrient Management (INM), which combines organic amendments with reduced inorganic fertilizers, is recommended to enhance soil quality and grape yield sustainability in Nandi Valley. This study also highlights the utility of PCA in identifying key soil quality indicators and creating a robust, scientifically grounded SQI. By quantifying soil quality through these indicators, farmers and agronomists can monitor soil health more effectively and implement targeted interventions to maintain or improve soil quality, ensuring the long-term sustainability of grape production in the region.

Table 2: Principal component analysis (PCA) of soil quality parameters of different grape varieties at surface soil (0-20 cm), Nandi Valley, Karnataka

Sl. No	Variables	Components		
		PC 1	PC 2	PC 3
1.	BD	0.999	-0.049	0.001
2.	MWHC	0.997	0.070	0.020
3.	pH	0.991	-0.125	-0.056
4.	EC	0.967	-0.231	0.104
5.	OC	0.963	0.046	-0.264
6.	N	0.923	0.027	0.385
7.	P	0.844	0.363	-0.396
8.	K	0.748	-0.145	-0.648
9.	Ca	0.738	-0.672	0.061
10.	Mg	0.733	0.596	0.327
11.	S	-0.167	0.980	-0.104
12.	Fe	-0.211	0.975	-0.065
13.	Mn	0.273	-0.908	0.316
14.	Cu	-0.023	0.823	-0.567
15.	Zn	0.455	0.790	0.411
16.	B	0.433	-0.789	0.435
17.	CEC	0.703	0.709	0.059
18.	DHA	0.385	0.704	0.596
19.	MBC	-0.092	-0.348	-0.933
20.	MBN	-0.703	0.092	0.705
	HF	0.999	0.980	0.933
	10%HF	0.100	0.098	0.093
	HF-10%HF	0.899	0.882	0.840

Abbreviations; PC: principal component; bold values under each component are highly weighted and underlined bold values are selected in the minimum data set.

Table 3: Correlation between the highly weighted variables of PC at 0-20 cm depth of soil

Variables	BD	MWHC	pH	EC	OC	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B	CEC	DHA	MBC	MBN
BD	1.000																			
MWHC	-.406	1.000																		
pH	.318	-.053	1.000																	
EC	.424	-0.839	-.524	1.000																
OC	-.259	.193	-.224	.201	1.000															
N	.395	-0.748	.566	.813	-.328	1.000														
P	-0.076	-0.625	-0.004	.165	-.260	.005	1.000													
K	-0.214	.134	-0.969	.257	.998	-.282	-.229	1.000												
Ca	.472	-0.070	.973	-.093	-.889	.503	-.171	-.891	1.000											
Mg	.753	-.996	.131	.835	-.257	.795	.586	-.199	.156	1.000										
S	.921	-.375	.349	.636	-.194	.889	-.453	-.167	.546	.437	1.000									
Fe	.704	-.230	-.237	.706	.405	.634	-.580	.428	-.010	.251	.519	1.000								
Mn	.352	.215	-.346	.344	.567	.260	-.837	.564	-.129	-.200	.304	.897	1.000							
Cu	.960	-.859	.138	.934	-.142	.963	.142	-.088	.266	.885	.788	.648	.246	1.000						
Zn	-.064	-.308	-.934	.504	.844	-.094	.245	.870	-.907	.231	-.217	.288	.232	.166	1.000					
B	.978	-.628	.507	.691	-.436	.981	-.105	-.398	.646	.690	.926	.606	.272	.894	-.271	1.000				
CEC	.770	-.538	.831	.355	-.815	.812	.109	-.788	.876	.610	.687	.161	-.152	.664	-.604	.876	1.000			
DHA	.993	-.680	.215	.859	-.144	.978	-.135	-.100	.386	.723	.930	.780	.446	.959	.023	.951	.691	1.000		
MBC	.668	-.387	-.433	.827	.539	.604	-.367	.572	-.229	.385	.690	.957	.805	.694	.534	.522	.046	.752	1.000	
MBN	.416	.043	-.463	.508	.648	.328	-.700	.656	-.247	-.041	.599	.939	.977	.366	.407	.300	-.170	.517	.904	1.000

Table 4: Score, weight and soil quality index (SQI) values of selected minimum data set (MDS) variables for each grape variety at 0-20cm depth of soil

Grape Varieties	BD			pH			OC			S			MBC			SQI
	S	W	T	S	W	T	S	W	T	S	W	T	S	W	T	
Bangalore blue	1.00	0.16	0.16	0.99	0.16	0.16	0.97	0.16	0.16	0.89	0.34	0.30	0.47	0.17	0.08	0.86
Dilkush	0.97	0.16	0.16	0.99	0.16	0.16	0.99	0.16	0.16	1.00	0.34	0.34	0.86	0.17	0.15	0.97
Sharad seedless	0.95	0.16	0.15	0.99	0.16	0.16	1.00	0.16	0.16	0.99	0.34	0.34	1.00	0.17	0.17	0.99
Red globe	0.95	0.16	0.15	1.00	0.16	0.16	0.88	0.16	0.14	1.00	0.34	0.34	0.61	0.17	0.11	0.91

W- Weightage factor, S- Score value and T – Total value

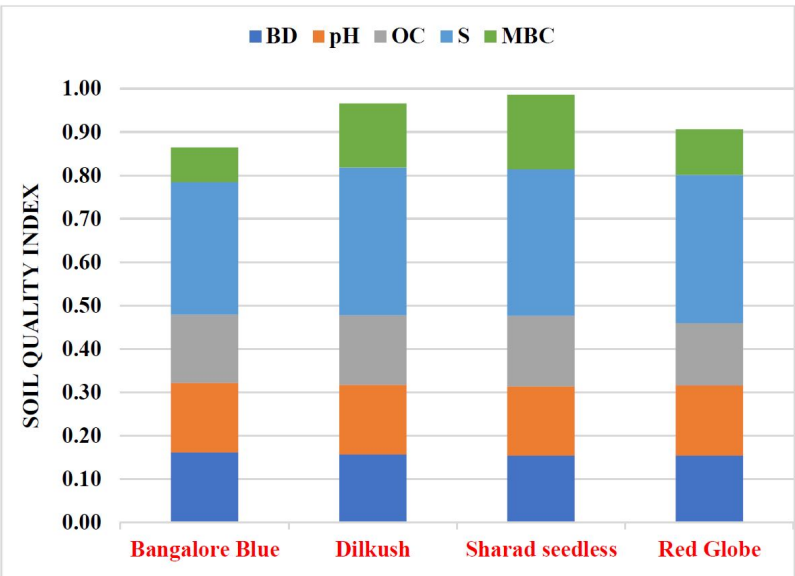


Fig. 4: Soil quality index of different grape varieties at 0-20 cm depth of soil

The magnitude of share of key soil quality indicators for influencing SQI were BD, pH, OC, available S and MBC. Mean contribution of key soil quality indicators towards SQI was soil BD (16.93%) followed by pH (17.32%), OC (16.75%), available

sulphur (35.58%) and MBC (13.42%) (Table 5). Percentage contribution of each of the MDS variables in each of the grape variety has also been presented in Table 5 and Fig. 5.

Table 5: Percentage contribution of each soil quality indicators towards SQI under different grape varieties at 0-20 cm depth of soil

Sl. No	Grape varieties	BD	pH	OC	S	MBC
1.	Bangalore blue	18.77	18.57	18.24	35.28	9.31
2.	Dilkush	16.27	16.62	16.57	35.20	15.30
3.	Sharad seedless	15.66	16.21	16.41	34.24	17.44
4.	Red globe	17.04	17.88	15.80	37.62	11.62
	Mean	16.93	17.32	16.75	35.58	13.42

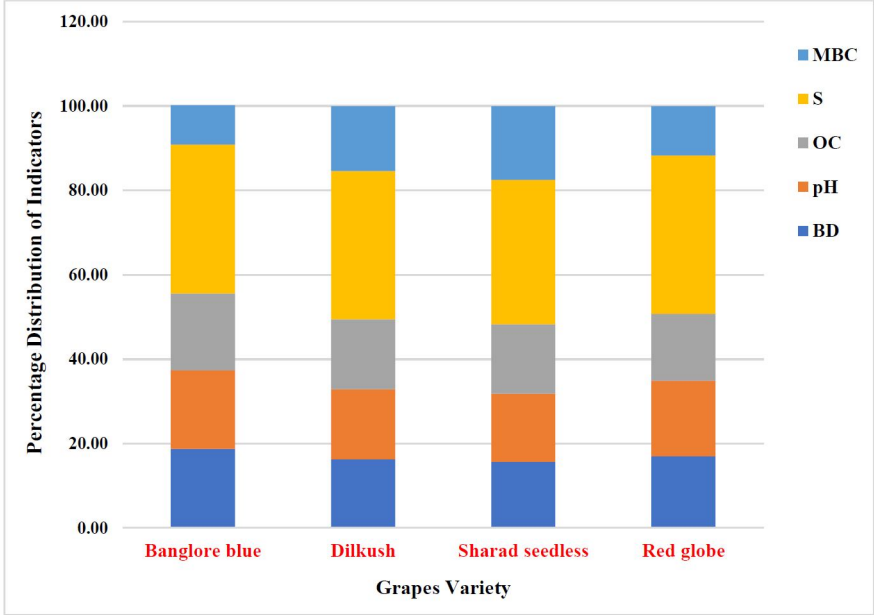


Fig. 5: Percentage contribution of each soil quality indicators towards SQI of different grape varieties at 0-20 cm depth of soil

Estimation of soil quality index of different grape varieties at subsurface soil (20-40 cm), Nandi Valley, Karnataka

The data on soil quality parameters was statistically evaluated for their level of significance. There were no significant differences in soil texture across the treatments. To determine the minimum dataset for 20-40 cm depth of soil, 20 soil quality parameters were subjected to principal component analysis (PCA) using SPSS software. The variables that best characterize system qualities were believed to be main components with high Eigen values and variables with high factor loading. Only the variables

with the highest factor loading were kept for the MDS inside each main component. As a result, for the creation of SQI, only PCs with Eigen values of 1 or larger were considered. The first three principal components with Eigen values greater than 1 explained roughly 100 per cent of the variance in the data, according to the PCA Table 6. The scree plot of PCA gives graphical representation of principle components which are to be considered to assess the soil quality, here the 3 principal components have eigen value more than one is considered, rest of them are rejected shown in the Fig. 6.

Table 6 : Eigen values from principal component analysis (PCA) of soil quality parameters of different grape varieties at sub surface soil (20-40 cm), Nandi Valley, Karnataka

Component	Initial Eigen values			
	Total	% of Variance	Cumulative %	Weightage factor
1.	11.167	55.834	55.834	0.56
2.	5.800	29.002	84.837	0.29
3.	3.033	15.163	100.000	0.15
Total				1.00

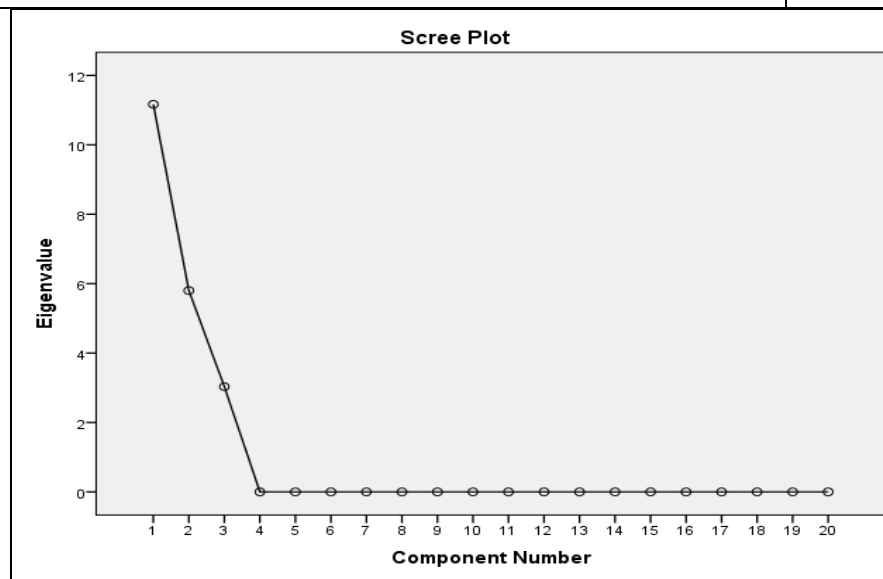


Fig. 6: Scree plot of PCA for 20-40cm depth of soil

Principal Component Analysis (PCA) conducted on sub-surface soil samples from different grape varieties in Nandi Valley, Karnataka, identified key soil quality parameters that influence grapevine growth and productivity. A total of 20 soil variables with the highest factor loadings were selected to form the Minimum Data Set (MDS) for Soil Quality Index (SQI) calculation. These variables, representing a mix of chemical and biological indicators, were critical for assessing soil quality at the sub-surface depth. The following sections explain the factor loadings,

correlation analysis, and development of the SQI for the sub-surface soil.

Factor Loadings and Selection of MDS

In PC1, the highest factor loadings were found for pH, copper (Cu), cation exchange capacity (CEC) and electrical conductivity (EC). These properties are essential indicators of soil chemical status and its capacity to retain nutrients and regulate water movement. The high correlation between these variables ($r = 0.60^*$) suggested their redundancy in the MDS. Therefore, pH was retained in the final MDS

because it is the most influential factor in determining the soil's acidity or alkalinity, which significantly impacts nutrient availability and microbial activity in the soil (Biswas *et al.*, 2017). The correlation analysis confirmed that pH could adequately represent the combined effects of the other variables in PC1, making it the most critical parameter for assessing soil quality at the sub-surface depth. In PC2, the highest factor loadings were observed for dehydrogenase activity (DHA), iron (Fe), available sulphur (S), and available phosphorus (P). These variables are primarily related to nutrient cycling and microbial activity. DHA is a key biological indicator, as it reflects the soil's microbial metabolic activity, which is essential for organic matter decomposition and nutrient mineralization (Riches *et al.*, 2013). Fe, a micronutrient, is critical for plant growth and interacts with other soil nutrients, influencing their uptake by grapevines. The non-significant correlation between DHA and Fe ($r < 0.60$) allowed both to be retained in the MDS, as they represent distinct aspects of soil health: DHA as a biological indicator and Fe as a chemical nutrient. Therefore, both variables were selected for the final MDS, emphasizing the importance of microbial and chemical properties for soil quality at the sub-surface depth. The selected MDS were independent of each other with a correlation coefficient < 0.6 value (Andrews, Mitchell, *et al.*, 2002). In PC3, organic carbon (OC) had the highest factor loading, underlining its role as a crucial biological component in soil quality assessment. OC is integral to soil fertility as it serves as a source of energy for soil microorganisms and influences water retention and nutrient availability (Vasu *et al.*, 2016). Given its high loading and biological relevance, OC was retained in the MDS as a key indicator of soil organic matter and microbial activity (Table 7 and 8).

Weighting and Scoring of MDS Variables

After selecting the key indicators, each MDS variable was scored based on its function and the variability observed across different treatments. The variables were transformed into unitless scores ranging from 0 to 1 using linear transformation. This allowed for consistent comparison and aggregation of the data. The PCA results were used to assign weights to each MDS variable, reflecting the relative importance of each principal component in explaining the total variability in the soil data. The variance explained by each PC was used to calculate the weighting factors for the variables.

The weightage derived from the PCA indicated that PC1 contributed the most (56%) to the variability

in the dataset, highlighting the significance of soil chemical properties such as pH, Cu, CEC, and EC in determining soil quality. PC2 accounted for 29% of the variability, emphasizing the role of microbial activity and nutrient availability, particularly DHA, Fe, and available S. PC3 had the lowest contribution (15%) but still reinforced the importance of organic carbon (OC) in influencing soil quality at the sub-surface level (Table 9).

Soil Quality Index (SQI) for Sub-Surface Soil

The weighted MDS variables were then applied to an additive model to compute the Soil Quality Index (SQI) for each treatment. The calculated SQI values, shown in Table 9, reflect the overall soil quality status based on the combined effect of the selected indicators. The SQI values varied across the different grape varieties, reflecting the variations in soil quality within the study area. These values offer a comprehensive measure of soil health at the sub-surface depth and provide valuable insights into the suitability of the soil for grape cultivation.

The contribution of each principal component (PC1, PC2, and PC3) to the final SQI was 56%, 29%, and 15%, respectively, with pH, Fe, DHA, and OC emerging as the most influential soil quality indicators. These findings suggest that soil quality at the sub-surface depth is strongly influenced by the chemical environment (pH, Fe), microbial activity (DHA), and organic matter content (OC). The results emphasize the need for effective soil management practices that address these key factors to enhance soil quality and grape yield sustainability (Biswas *et al.*, 2017; Lalitha *et al.*, 2019).

Implications for Soil Management

The selected MDS pH, Fe, DHA, and OC are critical indicators for assessing sub-surface soil quality in grape production systems. The results highlight the importance of maintaining optimal pH levels, nutrient availability (particularly Fe and S), and organic carbon content to ensure sustainable grapevine growth. The use of Integrated Nutrient Management (INM) practices that incorporate both organic and reduced inorganic fertilizers could help maintain or improve these indicators, leading to enhanced soil health and grape yield (Ray *et al.*, 2014). Monitoring and managing these key soil quality parameters will be essential for optimizing agricultural practices in Nandi Valley, Karnataka, and ensuring the long-term sustainability of grape cultivation in the region.

Table 7: Principal component analysis (PCA) of soil quality parameters of different grape varieties at sub surface soil (20-40 cm), Nandi Valley, Karnataka

Sl. No	Variables	Components		
		PC 1	PC 2	PC 3
1.	pH	<u>0.991</u>	0.037	0.130
2.	Cu	0.954	0.235	0.188
3.	CEC	0.941	0.326	0.089
4.	EC	-0.928	-0.248	0.278
5.	MWHC	-0.875	0.328	-0.357
6.	K	-0.873	-0.459	0.162
7.	BD	0.831	-0.496	-0.253
8.	B	0.822	0.247	-0.514
9.	N	0.788	-0.614	-0.051
10.	Zn	-0.778	-0.430	0.459
11.	Mg	0.777	-0.630	-0.010
12.	Mn	0.690	0.410	-0.596
13.	DHA	0.545	0.794	0.270
14.	Fe	-0.557	0.779	0.289
15.	S	-0.618	0.754	0.224
16.	P	-0.600	0.740	-0.304
17.	MBN	0.481	0.712	0.512
18.	Ca	-0.145	0.705	-0.694
19.	MBC	0.510	0.684	0.521
20.	OC	0.684	-0.036	0.728
	HF	0.991	0.794	0.728
	10% HF	0.099	0.079	0.073
	HF-10% HF	0.892	0.714	0.655

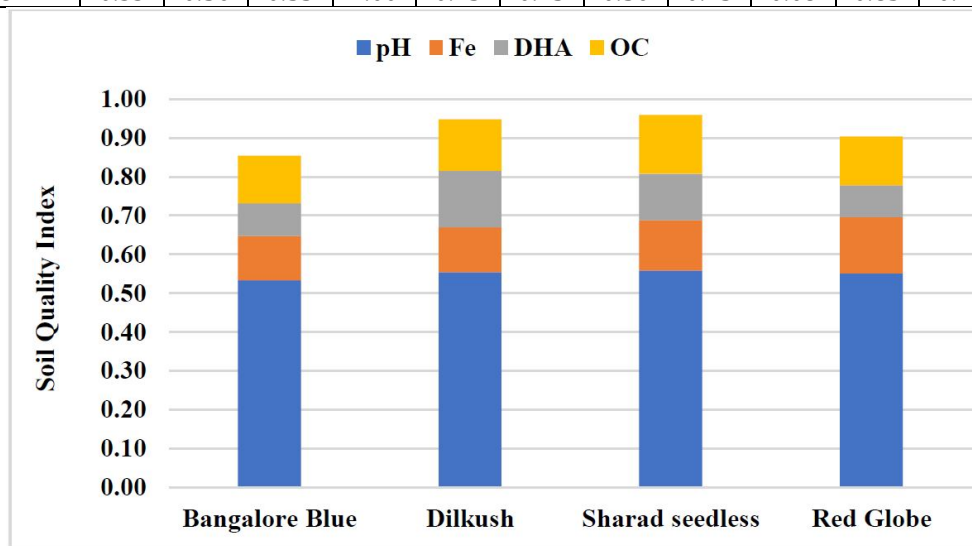
Abbreviations; PC: principal component; bold values under each component are highly weighted and underlined bold values are selected in minimum data set.

Table 8: Correlation between the highly weighted variables of PC at 20-40 cm depth of soil

Variables	BD	MWHC	pH	EC	OC	N	P	K	Ca	Mg	S	Fe	Mn	Cu	Zn	B	CEC	DHA	MBC	MBN
BD	1.000																			
MWHC	-.799	1.000																		
pH	.772	-.901	1.000																	
EC	-.718	.632	-.493	1.000																
OC	.771	-.870	.402	-.424	1.000															
N	.972	-.872	.752	-.593	.524	1.000														
P	-.789	.876	-.607	.290	-.659	-.912	1.000													
K	-.538	.556	-.861	.969	-.463	-.414	.135	1.000												
Ca	-.295	.606	-.209	-.232	-.331	-.512	.820	-.309	1.000											
Mg	.960	-.882	.745	-.568	.547	.999	-.929	-.390	-.550	1.000										
S	-.944	.708	-.556	.449	-.287	-.961	.861	.230	.466	-.957	1.000									
Fe	-.922	.639	-.486	.404	-.199	-.931	.423	.175	.429	-.926	.996	1.000								
Mn	.520	-.256	.621	-.908	.023	.322	.071	-.888	.603	.283	-.250	-.236	1.000							
Cu	.628	-.824	.578	-.891	.781	.597	-.456	-.910	-.104	.590	-.370	-.293	.642	1.000						
Zn	-.548	.375	-.726	.956	-.183	-.372	.009	.951	-.509	-.337	.259	.230	-.986	-.756	1.000					
B	.690	-.454	.756	-.967	.179	.522	-.155	-.914	.411	.488	-.437	-.414	.974	.745	-.981	1.000				
CEC	.598	-.748	.456	-.930	.697	.537	-.351	-.957	.031	.525	-.317	-.245	.730	.991	-.831	.808	1.000			
DHA	-.010	-.313	.604	-.627	.541	-.071	.178	-.797	.292	-.079	.322	.393	.541	.757	-.641	.505	.795	1.000		
MBC	-.047	-.408	.598	-.498	.705	-.044	.041	-.675	.046	-.040	.316	.399	.322	.746	-.452	.320	.749	.962	1.000	
MBN	-.083	-.371	.570	-.481	.677	-.083	.082	-.664	.076	-.080	.353	.434	.319	.723	-.446	.308	.730	.965	.999	1.000

Table 9: Score, weight and soil quality index (SQI) values of selected minimum data set (MDS) variables for each grape variety at 20-40 cm depth of soil

Grape Varieties	pH			Fe			DHA			OC			SQI
	S	W	T	S	W	T	S	W	T	S	W	T	
Bangalore blue	0.95	0.56	0.53	0.79	0.15	0.11	0.58	0.15	0.08	0.80	0.15	0.12	0.85
Dilkush	0.99	0.56	0.55	0.80	0.15	0.12	1.00	0.15	0.15	0.88	0.15	0.13	0.95
Sharad seedless	1.00	0.56	0.56	0.90	0.15	0.13	0.82	0.15	0.12	1.00	0.15	0.15	0.96
Red globe	0.99	0.56	0.55	1.00	0.15	0.15	0.56	0.15	0.08	0.83	0.15	0.13	0.90

**Fig. 7:** Soil quality index of different grape varieties at 20-40 cm depth of soil**Table 10:** Percentage contribution of each soil quality indicators towards SQI under different grape varieties at 20-40 cm depth of soil

Sl. No	Grape varieties	pH	Fe	DHA	OC
1.	Bangalore blue	62.38	13.40	9.91	14.32
2.	Dilkush	58.38	12.26	15.29	14.07
3.	Sharad seedless	58.18	13.54	12.44	15.85
4.	Red globe	60.97	16.05	9.03	13.95
	Mean	59.98	13.81	11.66	14.55

The magnitude of share of key soil quality indicators for influencing SQI were pH, Fe, DHA and OC. Mean contribution of key soil quality indicators towards SQI was soil pH (59.98%) followed by Fe (13.8 %), DHA (11.66%) and OC (14.55%) (Table 10). Percentage contribution of each of the MDS variables in each of the treatment has also been presented in Table 10 and Fig. 8.

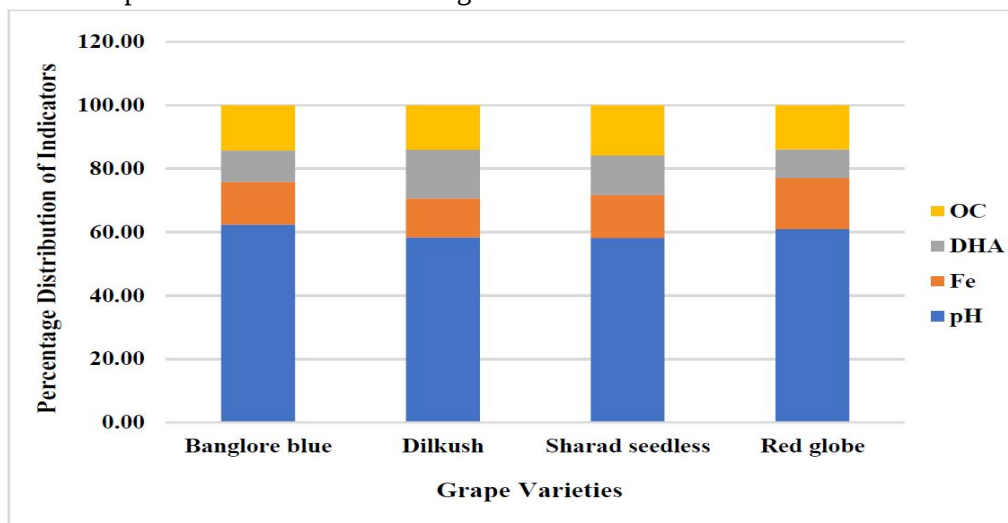


Fig. 8: Percentage contribution of each soil quality indicators towards SQI of different grape varieties at 20-40 cm depth of soil

The SQI recorded lower in sub surface soil compared to surface soil in all the grape varieties orchards due to increased bulk density and less microbial activity. Similar findings were found by Lalitha *et al.* (2024).

Among the four grape varieties in the study area Sharad seedless variety was recorded highest SQI in both surface and sub-surface soil may be due to several factors like region's favourable climate, optimal soil conditions rich in essential nutrients *i.e.* mainly due to integrated use of FYM along with balanced fertilization combined with land management practices *viz.*, mulching, efficient irrigation system. The presence of well drained soils and the application of appropriate rootstocks improved better soil health led to sustained soil quality.

Conclusion

The assessment of soil quality for different grape varieties in Nandi Valley, Karnataka, using PCA identified critical soil properties influencing productivity. Minimum Data Sets (MDS) for surface and subsurface soils revealed essential indicators such as pH, SOC and microbial activity. SQI values ranged from 0.87 to 0.99 in the surface layer and 0.85 to 0.96 in the subsurface, with Sharad seedless consistently exhibiting the highest soil quality, followed by Dilkush, Red Globe and Bangalore Blue. The study underscores the importance of adopting Integrated Nutrient Management (INM) practices combining organic amendments and reduced inorganic fertilizers to improve soil quality and ensure sustainable grape cultivation.

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