



Comparative assessment of soil quality dynamics using SQI modelling approach: a study in rice bowl of West Bengal, India

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Abstract The study attempted to evaluate the agricultural soil quality using the Soil Quality Index (SQI) model in two Community Development Blocks, Ausgram-II and Memari-II of Purba Bardhaman District. Total 104 soil samples were collected (0–20 cm depth) from each Block to analyse 13 parameters (bulk density, soil porosity, soil aggregate stability, water holding capacity, infiltration rate, available nitrogen, available phosphorous, available potassium, soil pH, soil organic carbon, electrical conductivity, soil respiration and microbial biomass carbon) in this study. The Integrated Quality Index (IQI) was applied using the weighted additive approach and non-linear scoring technique to retain the Minimum Data Set (MDS). Principal Component Analysis (PCA) identified that SAS, BD, available K, pH, available N, and available P were the key contributing parameters to SQI in Ausgram-II. In contrast, WHC, SR, available N, pH, and SAS contributed the most to SQI in Memari-II. Results revealed that Ausgram-II (0.97) is notably higher SQI than Memari-II (0.69). In Ausgram-II, 99.72% of agricultural lands showed very high SQI (Grade I), whereas, in Memari-II, 49.95% of lands exhibited a moderate SQI (Grade III) and 49.90% showed a high SQI (Grade II). Sustainable Yield Index (SYI), Sensitivity Index (SI) and

Efficiency Ratio (ER) were used to validate the SQIs. A positive correlation was observed between SQI and paddy ($R^2=0.82$ & 0.72) and potato yield ($R^2=0.71$ & 0.78) in Ausgram-II and Memari-II Block, respectively. This study could evaluate the agricultural soil quality and provide insights for decision-making in fertiliser management practices to promote agricultural sustainability.

Keywords Soil Quality Index · Minimum Data Set · Sustainable Yield Index · Sensitivity Index · Fertiliser Management Practices

Introduction

Globally, the primary concern is food requirements, leading to land-use changes (Allen et al., 2011). In just 12 years, the population grew from 7 to 8 billion, exerting immense pressure on agriculture and questioning sustainable land management (Rudel et al., 2016; Zeifman et al., 2022; Kaur & Chauhan, 2023). By 2050, it is projected that the world's food consumption will have increased by around 60%, while one-third of the global soil is undergoing moderate to severe degradation (Bisht & Chauhan, 2020; Tahat et al., 2020). It becomes a huge challenge to meet this massive demand for food while minimising the harmful effect of intensive agricultural systems on soil quality (Tang et al., 2022). Maintaining good soil quality enhances crop production, environmental

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quality, and overall health for plants, animals, and humans (Sharma et al., 2005). Measurement of soil quality considering soil properties provides an early warning to implement sustainable land management practices (Rahmanipour et al., 2014; Guillot et al., 2021; Choudhury & Mandal, 2021). To evaluate agricultural sustainability, it is crucial to determine the soil properties causing changes in soil quality. These qualities may eventually be identified as soil quality indicators (Masto et al., 2007).

The term “soil quality” was first propounded by Warkentin and Fletcher in 1977 (Rattan, 2015; Wienhold et al., 2004). They emphasised the significance of soil as a resource for purposes beyond agricultural production, waste recycling, and recreational uses (Karlen et al., 2001). The concept of soil quality and its evolution was diffused from North America (Klingebiel & Montgomery, 1961). In the 1980s, North American scientists primarily focused on soil erosion and its impact on production. However, they shifted their attention towards soil quality, sustainable agriculture and environmental health in the following decades (Karlen et al., 2001). Soil Science Society of America (SSSA) defined soil quality as “the capacity (soil) to function.” Later on, Karlen et al., (1997) extended the definition of soil quality as “the capacity of specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation.” Therefore, the main objectives of a proper soil quality assessment are to ensure environmental quality, promote agronomic sustainability, and support socio-economic vitality (Andrews et al., 2002). Soil quality depends on inherent (subsurface) and dynamic (surface) processes. Inherent processes change more naturally, as Jenny (1941) attempted to explain, and these changes tend to happen gradually. In contrast, dynamic changes are influenced more by human decisions, which can be referred to as land management systems (Larson & Pierce, 1994; Karlen et al., 2001). Numerous methods for evaluating soil quality have developed. Larson and Pierce, (1991) were among the first to propose a quantitative formula for measuring soil quality (Karlen et al., 1999; Liebig & Doran, 1999); along with this, spatial variability of soil quality was also introduced (Smith et al., 1993).

For several decades in tropical countries, including India, research has focused on plant biomass,

soil productivity, and assessing specific soil-deficient nutrients (Masto et al., 2007). However, in recent times, there has been a shift towards agricultural sustainability, as numerous studies have indicated a decline in productivity resulting from long-term poor land management practices (Bhattacharyya et al., 2015; Srinivasarao et al., 2013; Srivastava et al., 2016). For the first time, the declining productivity of rice was noticed in India with the rice–wheat system (Nambiar & Ghosh, 1984; Nambiar, 1995) and in Philippines with the rice-rice cropping system (Flinn & De Datta, 1984). Farmers have adopted different nutrient management practices in various countries based on their food demands, land size, and available agrochemicals. The application rate (kg/ha) of primary nutrients (N-P₂O₅-K₂O) has been found to be highest in Columbia (615), followed by Egypt (543), China (375), Brazil (369), Chile (359) and Uzbekistan (296) in 2021 (The World Bank, 2023). Whereas India uses 193 kg/ha. In India, the usage of chemical fertilisers (NPK) has risen from 2.65 million tons in 1971–1972 to 41.4 million tons in 2018–2019 (Pahalvi et al., 2021). In the case of fertiliser management practices, NPK + Farm Yard Manure (FYM) has been identified as significantly positive in correlation with the Soil Quality Index (SQI) (Choudhary et al., 2018; Majhi et al., 2019; Manna et al., 2005). While some studies have shown a higher SQI in NPK + Crop residue (Rakshit et al., 2018), the absence of FYM only reduces the SQI by 23.3%. This suggests that applying FYM with NPK positively effects soil health (Saha et al., 2022). However, higher rice production was found under chemical fertiliser alone, followed by Integrated Nutrient Management (INM) in the alkaline soil of India (Ghosh et al., 2020). Although for long-term sustainable rice yield, INM with chemical fertiliser + FYM + crop residues improved the biological properties of the land and increased land productivity (Borase et al., 2021). Poor nutrient management results in a gradual yet significant change in soil properties, making it crucial to assess soil quality (Bhattacharyya et al., 2015; Zahedifar, 2023).

Assessing the soil quality and land productivity through individual soil properties is very complex due to the varied effects of diverse land management practices. (Griffiths et al., 2010; Raiesi & Kabiri, 2016). SQI integrates the physical, chemical, and biological properties of soil into a single quantitative measure (Doran et al., 1996; Karlen et al., 1997), providing

a more accurate representation of soil quality than relying solely on individual or paired soil parameters (Masto et al., 2007; Armenise et al., 2013). These soil parameters have been selected based on management goals, soil function and site-specific factors (Andrews et al., 2004). SQI reliably links soil health with management practices (Temjen et al., 2022). Spatial variability of soil quality provides crucial information about fertiliser management practices (Delsouz Khaki et al., 2017; Alabouvette & Cordier, 2018; Shukla et al., 2020; Bel-Lahbib et al., 2023). There are a few approaches; the Integrated Quality Index (IQI) and the Nemoro Quality Index (NQI) are reliable and suitable for evaluating soil quality and linking it with associated land management practices. Qi et al., (2009) addressed the three advantages of these methods: (1) due to their intuitive nature, both indices are very easily understandable (Sun et al., 2003; Wang & Gong, 1998). (2) Both the indices use mathematical equations, which makes them more reliable, practical, and efficient, and (3) the indices create a platform for agricultural planners and soil researchers to evaluate soil quality and other associated characteristics. Rahmanipour et al., (2014) attempted to compare the reliability of these two indices and obtained that compared to NQI, IQI identified the correct estimation of soil quality. Zhou et al., (2022) supported the previous study and showed that IQI and NQI are the most suitable for estimating soil quality up to 0–20 cm and 20–30 cm, respectively. Now, it has become popular in the scientific world, and many studies have applied IQI in their work (Bahena-Osorio et al., 2023; Kafei et al., 2023; Oliveira et al., 2024; Samaei et al., 2022). IQI is further subdivided into simple additive and weighted additive indexes. After analysing the Total Data Set (TDS) using Principal Component Analysis (PCA), the Minimum Data Set (MDS) is selected (Andrews et al., 2002). MDS is an appropriate approach for reducing data redundancy, clarifying data variability, and accelerating the identification of key properties for further analysis (Vasu et al., 2016).

In the recent era, there are numerous researchers of subtropical rice-dominated countries like China (Chen et al., 2021; Ji et al., 2020; Yu et al., 2018; Zhao et al., 2021), Iran (Bakhshandeh et al., 2019; Nehrani et al., 2020; Rezaee et al., 2020; Rezapour et al., 2021; Samaei et al., 2022), Pakistan (Abid et al., 2020; Hussain et al., 2021; Sheikh, 2022; Nasir et al., 2024), Turkey (Doğan and Gülser, 2019;

Alaboz et al., 2021), Bangladesh (Chowdhury et al., 2011; Hussain et al., 2013) and Philippines (Posadas et al., 2022) have focused on measurement of agricultural soil quality and nutrient management practices. The precision and reliability of predicting soil quality using geospatial techniques and machine learning approaches surpasses that of conventional soil mapping (Fathizad et al., 2020). The increasing popularity of spatial prediction of soil quality using these techniques is evident in numerous research studies (De et al., 2022; Li et al., 2023; Vaezi et al., 2020; Yadav et al., 2022). Kumar and Jhariya, (2015) utilised organic matter, soil pH, soil P, soil K, slope, and land use-land cover to identify agriculturally suitable areas using multi-criteria decision analysis (MCDA), obtaining a high agricultural suitability of 39.09%. The farmers, while contributing to the degradation of agricultural soil quality through their land management decisions primarily based on experience, also demonstrate the changes in soil quality due to different management systems and crop selection (Jian et al., 2020; Ruf et al., 2018; Yadav et al., 2022).

In India, various studies have been conducted on soil quality assessment, including evaluating soil quality near municipal waste dumping sites (Uma et al., 2016; Deshmukh & Aher, 2017; Choudhury et al., 2022), examining the relationship between soil quality and crop productivity (Ghosh et al., 2014; Singh et al., 2020; Vasu et al., 2016), analysing the effects of land-use changes on soil quality (Abdoalmohamdi et al., 2021; De et al., 2022; Masto et al., 2008), investigating the impact of agroforestry on soil quality (Fahad et al., 2022; Meetei et al., 2020; Prasad et al., 2017) and exploring the connection between cropping systems and soil quality (Sinha et al., 2014; Dhanda et al., 2022) etc. Most of the studies focus on computing the SQI and interpreting it. In contrast, minimal studies, particularly in India, attempt to assess the spatial variability of SQI and identify site-specific fertiliser management systems with crop combination and sustainable yield in a holistic way in a particular area.

The primary objectives of this study are (1) to determine and evaluate 13 soil parameters, including five physical parameters (bulk density, soil porosity, soil aggregate stability, water holding capacity, and infiltration rate), six chemical parameters (available nitrogen, available phosphorous and available potassium, soil pH, soil organic carbon, and electrical conductivity), and two biological parameters

(soil respiration and microbial biomass carbon), (2) to compare spatial variability of the agricultural soil quality in two distinct, in terms of soil inherent and dynamics characteristics, C.D. Blocks, Ausgram-II and Memari-II using Inverse Distance Weighting (IDW) technique. (3) to validate the SQI using appropriate methods such as Sensitivity Index (SI), Efficiency Ratio (ER), and Sustainable Yield Index (SYI), and (4) to understand the underlying reason for the spatial variation of soil quality through a view of fertiliser management practices. It is hypothesised that there will be a significant difference in the spatial variation of SQI between the two Blocks. Eventually, crop selection leads to fertiliser management practices effectively impacting spatial variation of soil quality in this study area. The novelty of the work lies in identifying spatial variation of SQIs and understanding the site-specific fertiliser management system with distinct crop combinations. It also focuses on the sustainable fertiliser management practices in these two intensive agro-based C.D. Blocks.

Description of the study area

The eastern part of the erstwhile undivided Bardhaman District was known as the ‘rice bowl of Bengal’ due to the high production of rice. In 2017, the District was divided into Purba Bardhaman (East Bardhaman) and Paschim Bardhaman (West Bardhaman). However, currently, the rice bowl region falls under Purba Bardhaman District. Among the 23 C.D. blocks of Purba Bardhaman, two C.D. Blocks, Memari-II and Ausgram-II, were chosen for the study. Memari-II is located between 23°11'59"N to 23°22'25"N and 88°1'24"E to 88°14'05"E, covering an area of 186 km². Ausgram-II, on the other hand, is situated between 23°23'55"N to 23°37'38"N and 87°27'44"E to 87°43'51"E, with a total area of 360 km². The geological formations of Memari-II consist of diara, paskura, and sijua, while Ausgram-II comprises paskura, sijua, and laterite. Ausgram II is higher in elevation (65 m) than Memari-II (25 m). The mean monthly high and low temperatures of the study area are 32 °C (April) and 18 °C (January), respectively, with an annual rainfall of 1350 mm. Most of the soil in Memari-II is entisols, while Ausgram-II primarily comprises alfisols and ultisols. The parent material in Ausgram-II is alluvium-granite gneiss

and gneiss-alluvium, while Memari-II has alluvium as its parent material. Based on five-year NPK data (2016–17 to 2020–21) of the 23 Blocks of the District, the authors calculated the imbalance index (FL_{ib}I) of the N-P-K level using the following formula (Eq. 1). Previously, numerous researchers have applied the imbalance index (FL_{ib}I) in their studies (Rajiv Mehta, 2007; Chand & Pandey, 2009; Bora, 2022). The value of FL_{ib}I away from zero measures the magnitude of the imbalance of fertiliser usage. If FL_{ib}I equals zero, it indicates a balanced fertiliser use, while a value of one indicates a situation of maximal imbalance. The data revealed that Memari-II is the highest in the imbalance index (FL_{ib}I=0.75). At the same time, Ausgram-II is identified as the lowest (FL_{ib}I=0.003) (Fig. 1). Also, the reason behind the selection of these Blocks is due to the difference in inherent and dynamic characteristics of agricultural soils.

$$FL_{ib}I = \sqrt{\{(Na - Nn)^2 + (Pa - Pn)^2 + (Ka - Kn)^2\}}/3 \quad (1)$$

where ‘FL_{ib}I’ denotes the imbalance index, ‘a’ refers to the actual dose of NPK and ‘n’ means the norm ratio of NPK (4:2:2). It is generally accepted that an NPK ratio of 4:2:2 (N: P₂O₅: K₂O) is suitable for macro-level monitoring of plant nutrient intake for West Bengal (NAAS, 2009).

Materials and methods

Collection and analysis of the soil samples

The stratified unaligned grid sampling method was used to select the soil sampling points (Wollenhaupt et al., 1994). Initially, the total area was divided into 1 × 1 km. Then a total of 104 soil samples were randomly collected during the dry season (November–December) from the agricultural lands of each C.D. Block with a confidence level of 95% (Fig. 2). The soil collection was carried out during the dry season due to less compaction of soil, reduction of risk of contamination (Leul et al., 2023) and primarily fields were crop free. Five soil samples (four corners and one centre point) were collected from each grid using an auger at the depth of 0–20 cm as this layer is the most nutrient-enriched, susceptible to land use changes and biologically well-active (Abegaz et al.,

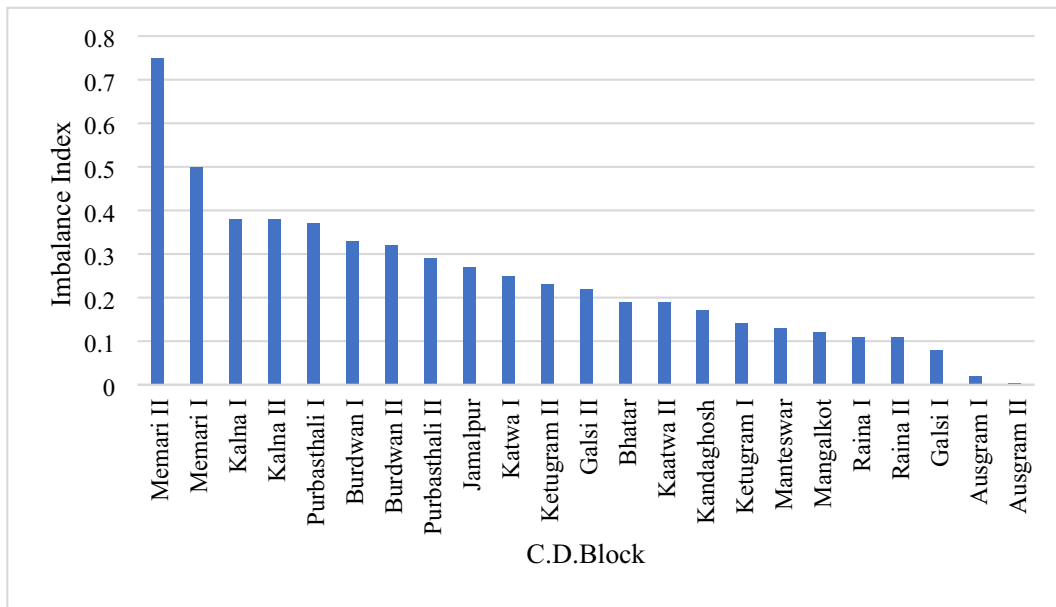


Fig. 1 Comparison of the imbalance index among the 23 C.D. Blocks of Purba Bardhaman District

2016; Leul et al., 2023). Then, samples were blended, and a considerable amount of soil was sealed in self-locking polythene bags marked with numbers and latitudinal and longitudinal extensions. In the laboratory, the samples were air-dried, ground and passed through a 2 mm size sieve for further analysis. Each sample was tested for thirteen soil properties, viz. five physical (bulk density, soil porosity, soil aggregate stability, water holding capacity, and infiltration rate), six chemical (available nitrogen, available phosphorous and available potassium, soil pH, soil organic carbon and electrical conductivity) and two biological (soil respiration and microbial biomass carbon).

Physical properties

A core cutter technique was applied to assess the dry bulk density (BD) (Blake & Hartge, 1986). A cylinder-shaped iron ring with a radius (r) of 2.25 cm and a height of 7.8 cm was used to measure the volume of the soil core. To determine BD, the weight of the dry soil core was divided by the volume of the soil core. Soil porosity (SP) was derived from the BD value using the formula $SP = 1 - (BD \div 2.65)$. The default value of 2.65 is used as a rule of thumb based on the average bulk density of rock (USDA-NRCS, 2019). Soil Aggregate Stability (SAS) was determined by

the wet sieving or wet aggregates method (Kemper & Rosenau, 1986). Following Kemper et al., (1985) to determine the wetting rates and stability of the samples to standardise the method. Water Holding Capacity (WHC) and Infiltration Rate (IR) were measured by the keen box method (Piper, 1966) and single ring infiltrometer (Tricker, 1978), respectively. Tricker, (1978) determined that a 15 cm diameter was the optimal measurement for infiltration, and a 50 cm ring height was utilised. Plastic was used to cover the open end of the ring and fill it with water to a depth of 5 cm. The ring was then driven 5 cm into the soil, and the plastic was removed from the mouth to measure the infiltration rate at 5-min intervals for 2 h (Tricker, 1978; Johnson, 1963).

Chemical properties

Available nitrogen (available N) was analysed using the Kjeldahl method (Kjeldahl, 1883). Available phosphorus (available P) and available potassium (available K) were determined by Olsen’s method (Olsen et al., 1954) and Flame photometer (Jackson, 1973), respectively. The wet digestion method (Walkley and Black, 1934) and the 1:2 soil/water method (Thomas, 1996) were used to measure Soil Organic Carbon (SOC)

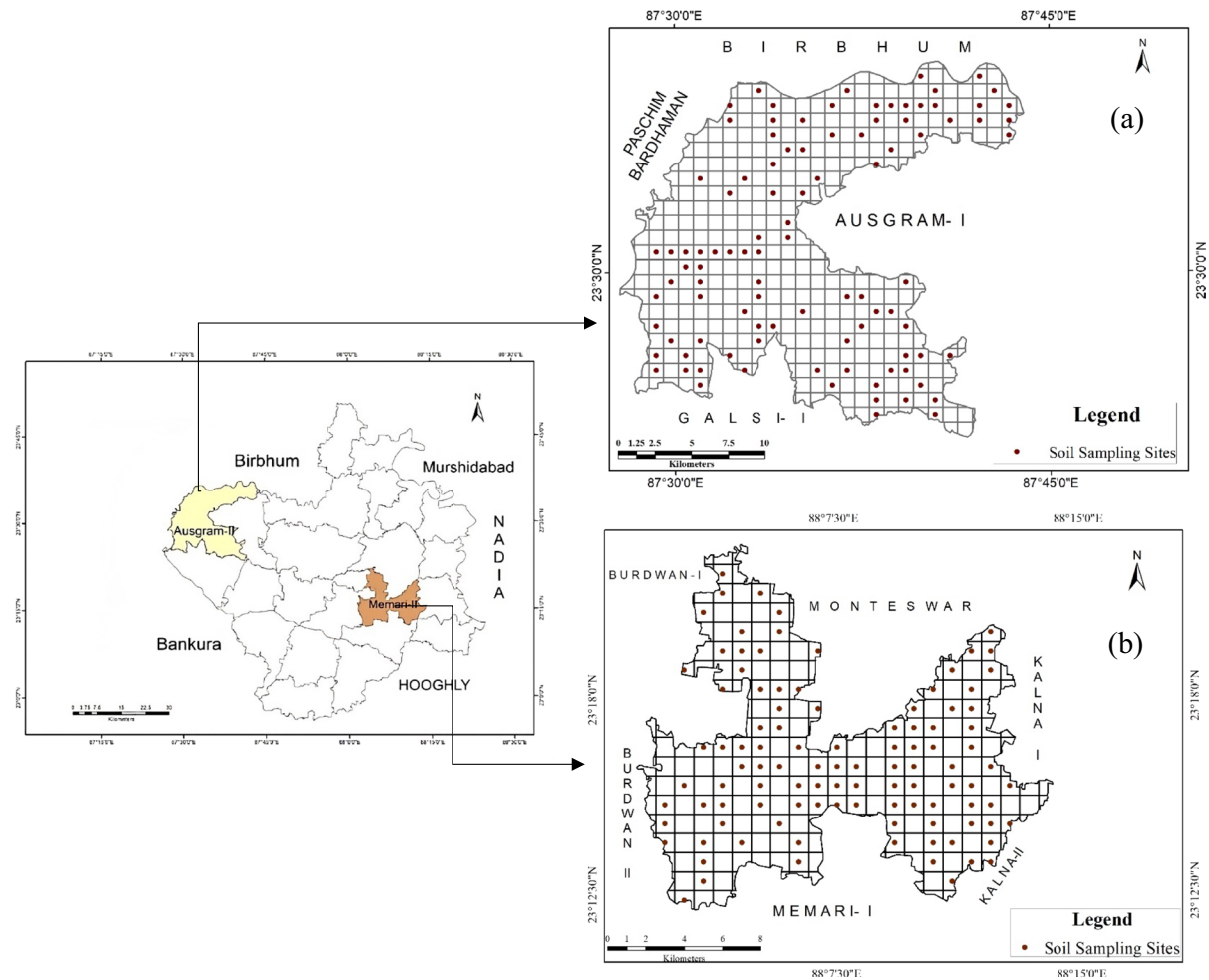


Fig. 2 Soil sampling sites of the case studied C.D. Blocks of Purba Bardhaman District, (a) Ausgram-II C. D. Block and (b) Meamri-II C.D. Block

and soil pH, respectively. Electrical Conductivity (EC) was measured by EC-meter (Fritz et al., 1999).

Biological properties

Microbial Biomass Carbon (MBC) was measured by chloroform fumigation-extraction (Vance et al., 1987) and Soil Respiration (SR) was analysed by the alkali trap method (Page, 1982).

Modelling of soil quality index

The Soil Quality Index (SQI) is determined through three steps: (1) selecting MDS from TDS by PCA,

(2) scoring the selected MDS, for this purpose, linear and non-linear scoring techniques are applied, and (3) integrating the score and selected MDS in a quantitative value (Andrews et al., 2002; Bel-Lahbib et al., 2023; Mastro et al., 2008).

Selection of MDS

PCA was used for data redundancy or retention of MDS from TDS (Doran & Parkin, 1994; Qi et al., 2009). PCs with eigenvalue ≥ 1 and cumulatively explained $\geq 70\%$ of the total variance were the criteria for selecting high-loading indicators (Kaiser, 1960; Andrews et al., 2002; Chandel et al., 2018). In each PC, soil parameters are represented with some

loading value to show their contribution in a respective PC. The absolute values that fall within 10% of the highest loading factor of the same PC were considered for MDS (Wander and Bollero, 1999; Rahmanipour et al., 2014). Pearson’s correlation coefficient was used to eliminate the redundancy of multiple highly weighted indicators. Regarding the correlated values between the two indicators, the soil property with a highly weighted value was considered MDS. However, if the highly loaded indicators were not correlated, both values were retained as MDS. The loading value of MDS is also known as the commonality of the factors, which represents their contribution to explained variance (Johnson & Wichern, 2002). To obtain the weighted value of PCs, the explained variance has been divided by the total cumulative variance (Andrews et al., 2002). From the MDS, the indicators were assigned by non-linear scoring according to their functions (Dadhwal et al., 2011).

Scoring function

The non-linear scoring method was employed to score the MDS. The scoring curve has a scale of 0 to 1 (Karlen & Stott, 1994; Qi et al., 2009). There are three types of curves; firstly, a sigmoid curve with an upper asymptote or ‘more is better’, where the indicators are scored highest (1) in its higher threshold value and other values are determined according to their obtained level. Secondly, the sigmoid curve with lower asymptote or ‘less is better’, where the indicators are scored high in its lowest threshold value, and thirdly, the bell-shaped curve or optimum value is better (Liebig et al., 2001; Andrews & Carroll, 2001 and Karlen et al., 1994). For example, available N is assigned as upper asymptote or ‘more is better’, BD as lower asymptote or ‘less is better’, and soil pH as optimum is better. In this study, IQI has been employed using a weighted additive index. In an unequal number of parameters, the weighted additive index is more suitable (Cherubin et al., 2016). Finally, the SQIs are computed using the following formula (Eq. 2). The entire methodological framework is shown in Fig. 3.

$$SQI = \sum_{i=1}^n Wi \times Si \tag{2}$$

where, ‘ Wi ’ is assigned as the weight of the indicators extracted from PCA, ‘ Si ’ refers to the indicator score and ‘ n ’ represents the number of indicators.

Methods of evaluating indices for SQI

Sensitivity index (SI)

After calculating the SQI, it is crucial to assess its efficacy (Zhou et al., 2022). The Sensitivity Index (SI) determines the existing quality of the soil. A higher value of SI indicates that the soil is more prone to soil management practices or external disturbances (Masto et al., 2008). It also shows the potential variability of the SQIs in the data set (Sheidai Karkaj et al., 2019). The following formula (Eq. 3) was applied to calculate the sensitivity of the soil.

$$SI = SQI_{(max)}/SQI_{(min)} \tag{3}$$

SI is a ratio of the maximum ($SQI_{(max)}$) and minimum ($SQI_{(min)}$) SQIs observed under each indexing procedure.

Efficiency ratio (ER)

ER indicates the efficiency level of SQI, or it determines how reliable the SQI value is (Sheidai Karkaj et al., 2019). ER is obtained by simply dividing the number of highly correlated values by the number of feasible indicators (Eq. 4). Higher ER explains the reliable value of SQI.

$$ER = \frac{K}{N} * 100 \tag{4}$$

‘ K ’ is the number of correlated indicators in a specific SQI, and ‘ N ’ is the number of feasible parameters or MDS.

Sustainable yield index (SYI)

A sustainable agricultural system aims to preserve soil quality and land productivity over time (Kanwar, 1994). SYI is an essential quantitative measurement that includes long-term cultivable fields with similar land management practices (Singh et al., 1990). The

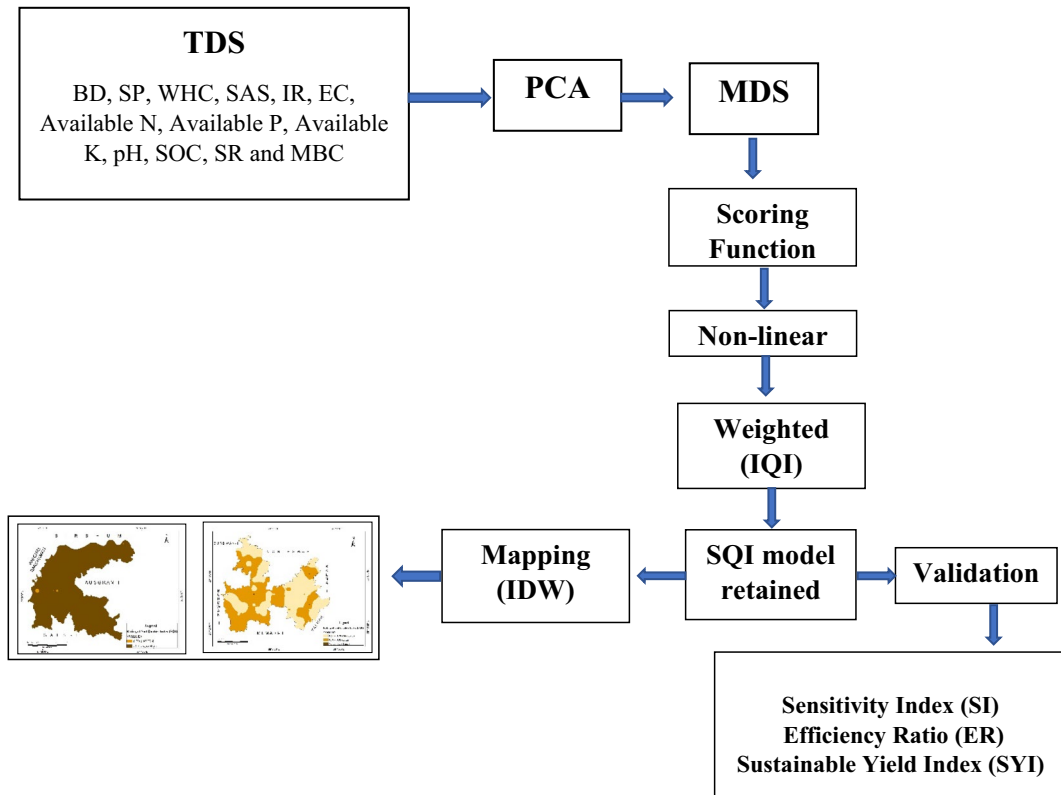


Fig. 3 Methodological flow chart for computation of SQI

following formula (Eq. 5) has been used to calculate the SYI.

$$SYI = \frac{\bar{Y} - \sigma}{Y_{max}} \tag{5}$$

where ‘ \bar{Y} ’ indicates the mean yield of a treatment of a particular crop, ‘ σ ’ means the standard deviation of that treatment, and ‘ Y_{max} ’ is the maximum yield of a particular crop within the treatment tenure.

Statistical technique and software

Maximum, minimum, mean, coefficient of variation (CV), kurtosis, and skewness of the soil parameters were included in the descriptive data set. Principal Component Analysis (PCA) was applied to select the MDS from the TDS. Pearson’s correlation coefficient was used to find the correlated indicators for dimension reduction. MS Excel 2016 and IBM SPSS Statistics V25 were used to compute the descriptive statistics.

Spatial variability technique

Inverse Distance Weighting (IDW) assumes the value of unvisited points through the assigned known points (Eq. 6). IDW, a suitable interpolation method, was applied to present the spatial variation of the soil parameters, including SQI. IDW is used to estimate the value of the attribute at unvisited locations based on the data points within a neighbourhood or window surrounding the unvisited point (Bhunja et al., 2018). To run the IDW, ArcMap 10.6 has been used.

$$z(x_0) = \frac{\sum_{i=1}^n \frac{x_i}{h_{ij}^\beta}}{\sum_{i=1}^n \frac{1}{h_{ij}^\beta}} \tag{6}$$

z is the interpolated value at the location x_0 ; n indicates the total number of sample points; β denotes the weighting power ($\beta=2$); x_i is the measured value, and h_{ij} is the separation distance between the interpolated value and the measured value.

Result

Statistical description of the soil parameters

The essential descriptive statistics such as minimum, maximum, mean, standard deviation (SD), skewness, kurtosis and coefficient of variance (CV) of the selected 13 soil parameters are properly presented (Table 1). Skewness, kurtosis, and CV are crucial statistical techniques for evaluating data normality. The threshold values for skewness and kurtosis are -2.0 to +2.0 and -7.0 to +7.0, respectively (Hair et al., 2010; Byrne, 2010). The analysed data fall within the specified thresholds for skewness and kurtosis. In terms of CV, some researchers classified the

ranges into three categories: low (<10%), moderate (10–100%), and high (>100%) (Nielsen and Bouma, 1985; Behera and Shukla, 2015). It is widely accepted that CV <10% indicates very good, 10–20% denotes good, 20–30% is acceptable and CV >30% means not acceptable (Sedivy et al., 2021; Doan & Hassell, 2023). In Ausgram-II C.D Block, soil respiration (29.03%) and soil pH (5.44%) are the highest and lowest CV, respectively. In the Memari-II Block, soil respiration is the lowest CV (16.64%), and available N is the highest (2.94%) (Table 1). The BD ranges from 1.06 to 1.62 g/cm³ (mean 1.30 g/cm³) and 1.14 to 1.65 g/cm³ (mean 1.41 g/cm³) in Ausgram-II and Memari-II Block, respectively. While SP also varies from 38 at 57% (average 46.92%) in Memari-II

Table 1 Descriptive statistics of the soil parameters in Ausgram-II and Memari-II C.D. Block (n = 104)

Soil Parameter	Unit	C.D.Block	Min	Max	Mean	SD	Skewness	Kurtosis	CV (%)
BD	g/cm ³	Ausgram-II	1.06	1.62	1.30	0.11	0.23	0.32	8.75
		Memari-II	1.14	1.65	1.41	0.11	-0.35	-0.005	6.86
SP	%	Ausgram-II	60	39	50.66	4.30	-0.14	0.33	8.49
		Memari-II	38	57	46.92	4.24	0.40	0.02	7.44
WHC	%	Ausgram-II	25	49	30.51	4.83	1.60	2.42	15.91
		Memari-II	26	52	36.71	7.33	0.47	-0.91	14.10
IR	mm/hr	Ausgram-II	10	29	22.19	4.80	-1.20	0.76	21.63
		Memari-II	2	7	4.05	0.99	0.26	-0.11	14.27
SAS	%	Ausgram-II	32	51	40.02	4.38	0.58	-0.06	10.93
		Memari-II	34	55	45.14	4.97	-0.19	-0.76	9.04
EC	dS/m	Ausgram-II	0.2	0.7	0.43	0.12	-0.13	-0.74	29.07
		Memari-II	0.1	1.4	0.50	0.22	1.58	4.22	16.06
pH	-	Ausgram-II	6.12	7.34	6.57	0.36	0.87	-0.34	5.44
		Memari-II	5.12	7.65	6.00	0.59	0.22	-0.42	7.73
SOC	%	Ausgram-II	0.52	0.88	0.72	0.10	-0.14	-1.05	12.57
		Memari-II	0.28	0.69	0.48	0.1	-0.06	-0.01	12.12
Available N	kg/ha	Ausgram-II	225	454	353.87	67.84	-0.16	-1.25	19.17
		Memari-II	415	481	451.19	14.15	-0.14	-0.48	2.94
Available P	kg/ha	Ausgram-II	41	95	66.58	17.83	-0.09	-1.48	26.79
		Memari-II	64	112	93.04	10.88	-0.66	-0.43	9.71
Available K	kg/ha	Ausgram-II	148	285	215.83	37.22	-0.09	-1.12	17.25
		Memari-II	234	296	281.76	10.45	-1.53	4.21	3.53
SR	CO ₂ -C lbs/acre-3"/day	Ausgram-II	21	61	38.87	12.41	0.36	-1.31	29.03
		Memari-II	14	37	22.31	6.16	0.53	-0.84	16.64
MBC	µg/g	Ausgram-II	284	289	258.75	14.58	-0.13	-1.16	5.64
		Memari-II	214	262	228.15	10.78	0.94	0.20	4.11

Min: Minimum; Max: Maximum; SD: Standard Deviation; CV: Coefficient of variance; BD: Bulk Density; SP: Soil Porosity; WHC: Water Holding Capacity; IR: Infiltration Rate; SAS: Soil Aggregate Stability; EC: Electrical Conductivity; SOC: Soil Organic Carbon; Available N: Available Nitrogen; Available P: Available Phosphorous; Available K: Available Potassium; SR: Soil Respiration; MBC: Microbial Biomass Carbon.

compared to ranges of 39 to 60% (average 50.66%) in Ausgram-II Block. BD and SP are recognised as negatively correlated to each other. The infiltration rate of Ausgram-II ranges from 10 to 29 mm/hr (Mean 22.19 mm/hr), whereas Memari-II ranges from 2 to 7 mm/hr (Mean 4.05 mm/hr). The mean SAS in Memari-II Block is 45.14% (34–55%), higher than Ausgram-II with a mean of 40.02% (32–51%). WHC varies from 25 to 49% (Mean 30.51%) in Ausgram-II and ranges from 26 to 52% (mean 36.71%) in Memari-II Block, which is slightly higher than Ausgram-II. The Average value of EC has been observed at 0.43 dS/m (ranges 0.2–0.7 dS/m) in Ausgram-II Block compared to 0.5 dS/m (range 0.1–1.4 dS/m) in Memari-II. The soil pH is neutral for Ausgram-II, having a mean of 6.57 (range of 6.12–7.34), and Memari-II, having a mean of 6.00 (range of 5.12–7.65). Regarding SOC, it is found to be slightly better for Ausgram-II with a mean of 0.72% (range of 52–88%) compared to Memari-II, 0.50% (range of 28–69%). Available N, P and K are relatively high in Memari-II with the mean of 451.19 kg/ha (range of 415–481 kg/ha), 93.04 kg/ha (range of 64–112 kg/ha) and 281.76 kg/ha (range of 234–296 kg/ha), respectively. In contrast, in Ausgram-II, the mean of available N, P and K are found to be 353.87 kg/ha (range of 225–454 kg/ha), 66.58 kg/ha (range of 41–95 kg/ha) and 215.83 kg/ha (range of 148–285 kg/ha), respectively. In Memari-II, SP varies from 14 to 37 CO₂-C lbs/acre-3"/day (Mean 22.13 CO₂-C lbs/acre-3"/day) compared to a range of 21 to 61 CO₂-C lbs/

acre-3"/day (mean 38.87 CO₂-C lbs/acre-3"/day) for Ausgram-II. Lastly, the MBC shows also better in Ausgram-II with an average of 258.75 µg C/g (range of 284–289 µg C/g) in contrast, Memari-II with 228.15 µg C/g⁻¹ (ranges 214–262 µg C/g). The differences between Ausgram-II and Memari-II Block are evident in various soil properties.

Spatial distribution of the soil parameters

Spatial distribution of the soil data was used to understand the space-specific variability of soil health and estimate associated soil management practices. IDW, a reliable and suitable method, was used to produce the distribution of soil properties by estimating non-sampled points from the known points. The Blocks are distinct textural classes due to their unique geological formation, climate and other physical factors. The soil of Ausgram-II is predominantly sandy loamy and sandy clay loamy (Fig. 4a), whereas Memari-II has a clay loam and silty clay-type texture (Fig. 4b). For Ausgram-II, the Ideal BD (<1.40 g/cm³) for sandy loamy and sandy clay loamy soil are covered almost 94% of area (Fig. 5a), while predominate BD (<1.49 g/cm³) shows that 88% of area for Memari-II Block (Fig. 6a), though the ideal BD found <1.10 for clay loam and silty clay soil. In Ausgram-II, 67.40% (<50%), 16.68% (50%) 15.91% (>50%) of the area are covered as low, medium or ideal and high SP (Fig. 5b). Whereas, for Memari-II, it shows 83% of the area is dominated by low porosity, 5% ideal, and

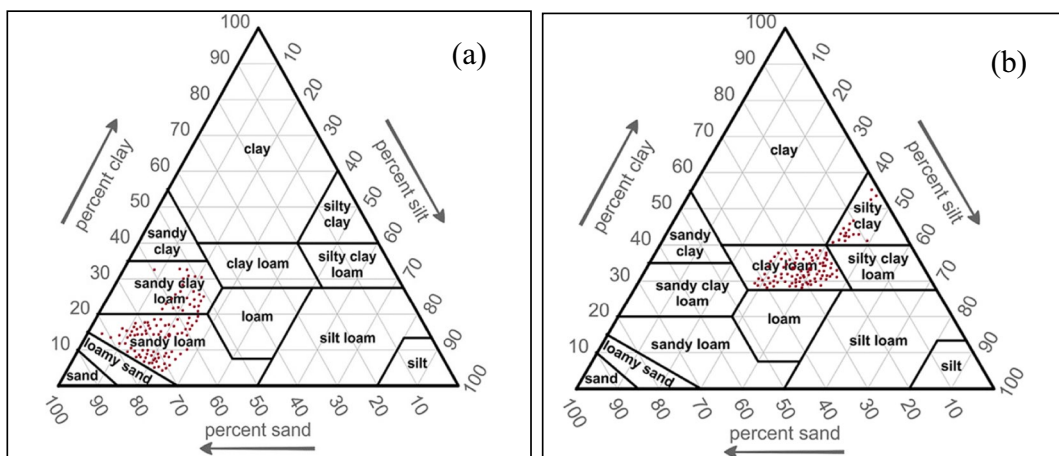


Fig. 4 Soil Textural classes of the studied Blocks, (a) Ausgram-II and (b) Memari-II

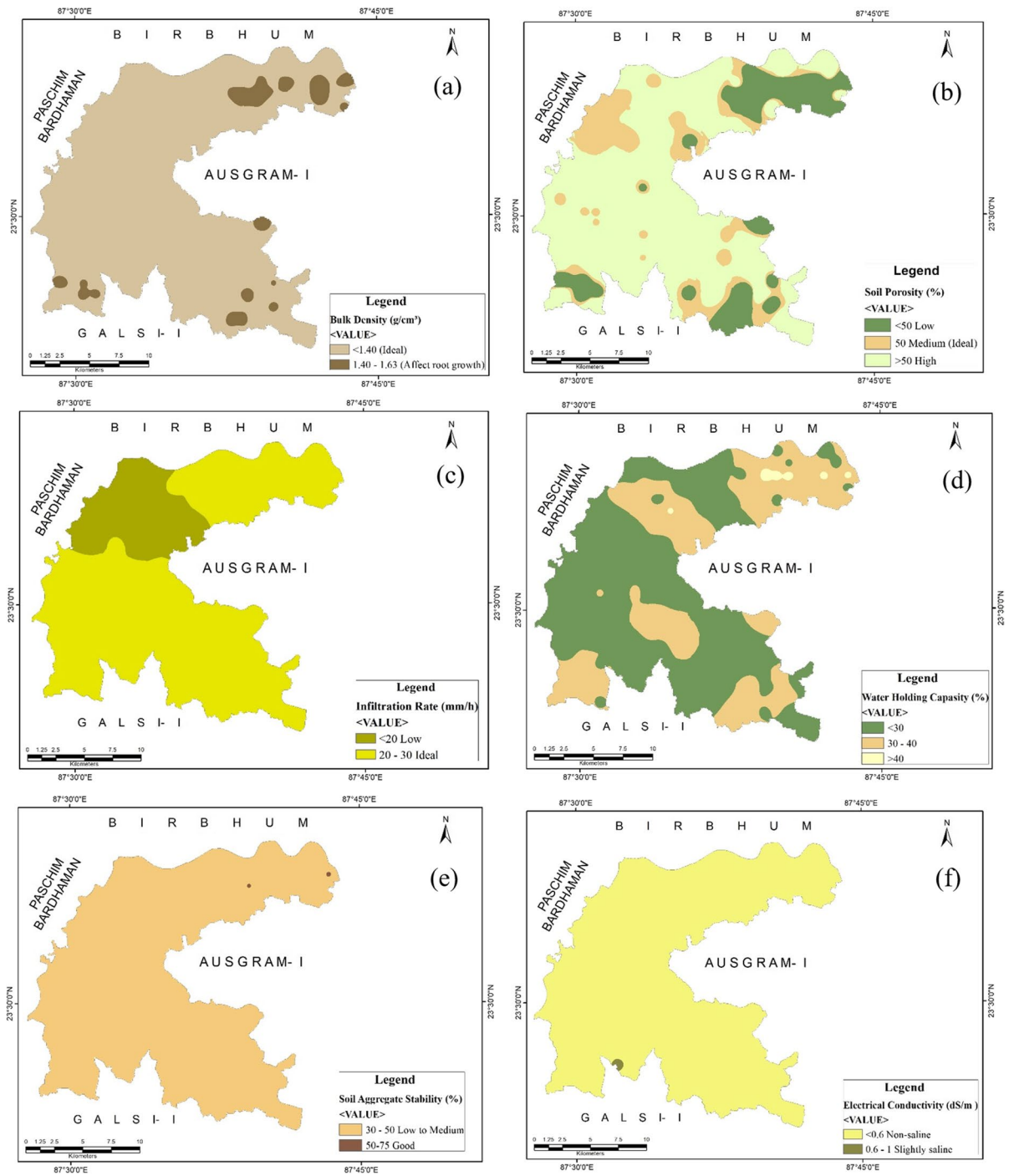


Fig. 5 Spatial distribution of (a) BD, (b) SP, (c) IR, (d) WHC (e) SAS, (f) EC, (g) Available N, (h) Available P, (i) Available K, (j) Soil pH, (k) SOC, (l) SR and (m) MBC by IDW in Ausgram-II C.D. Block

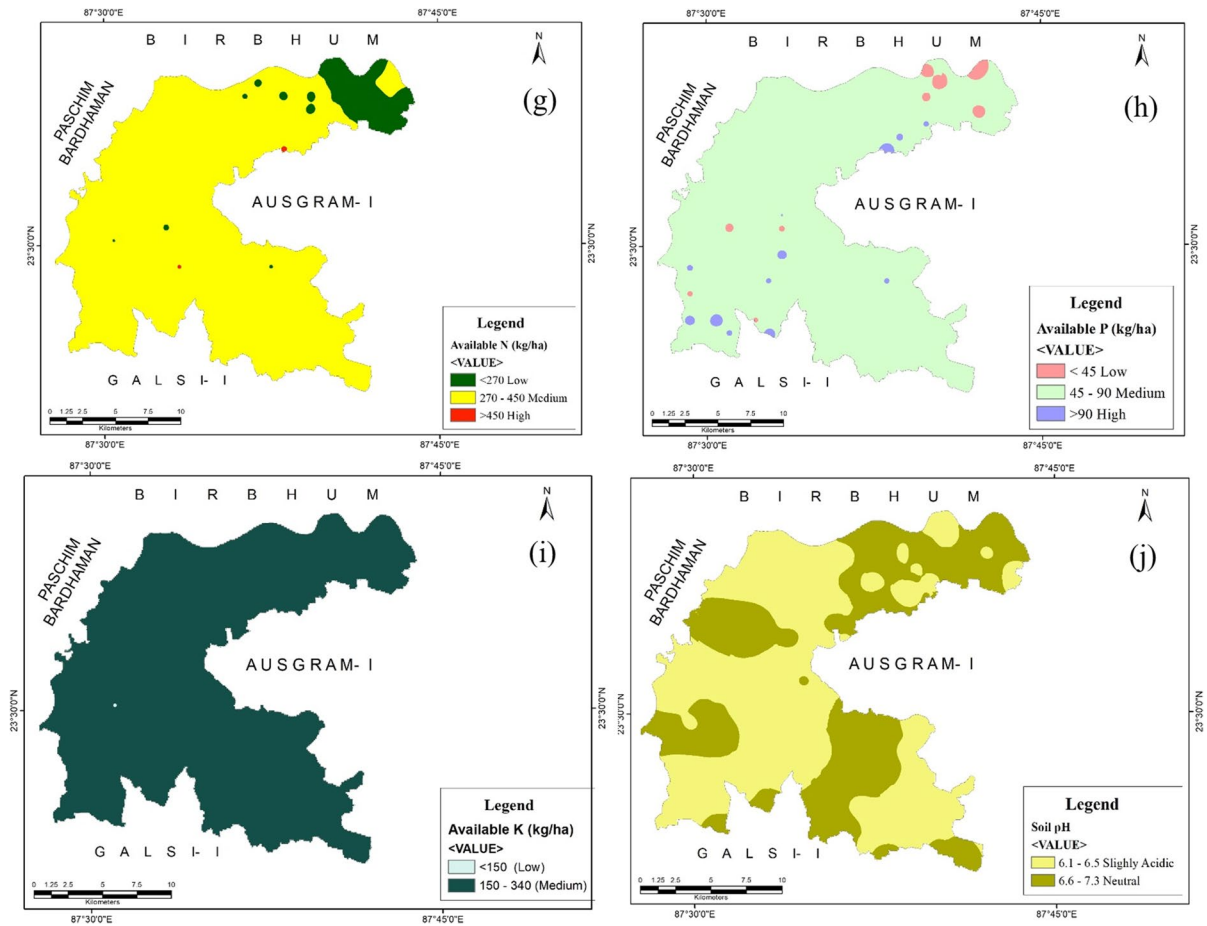


Fig. 5 (continued)

12% high porosity (Fig. 6b). In case of IR, the ideal IR (20–30 mm/hr) is observed 80.56% of northern part and southern part of Ausgram-II Block (Fig. 5c) compared to almost entire of area (96%) is covered with low IR and remaining only 4% of area shows ideal IR for Memari-II Block (Fig. 6c). WHC is observed 62.28% (<30%), 36.53% (30–40%) and 0.81% (>40%) for Ausgram-II (Fig. 5d) and 3% (<30%), 74% (30–40%) and 23% (>40%) for Memari-II (Fig. 6d). For SAS, low to medium (99.93%) is predominated for Ausgram-II (Fig. 5e) while 95% of the lands of Memari-II is covered by low to medium and 5% shows good (Fig. 6e). In terms of EC, Fig. 5f shows that 99% of the lands of Ausgram-II is covered with non-saline soil (<0.6 dS/m). For Meamri-II, Fig. 6f shows 87% of the area is dominated by non-saline (<0.6 dS/m), and the remaining lands, mostly the north-eastern corner part, is covered by slightly saline (0.6–1 dS/m) and

moderately saline soil (1–2 dS/m). The spatial variation map (Fig. 5g) of available N shows that 6.90% are low (<270 kg/ha), observed in the north-eastern portion, 93.03% are medium (270–450 kg/ha), and 0.07% (>450 kg/ha) are high in Ausgram-II. In comparison, 36.38% are medium (270–450 kg/ha), observed mostly south-eastern part, and 63.62% are high (>450 kg/ha), the remaining entire area of Memari-II (Fig. 6g). Figure 5h shows 1.46% of low (<45 kg/ha), mostly observed in the north-eastern part, 97.59% are medium (45–90 kg/ha), and 0.95% are high (>90 kg/ha), available P of Ausgram-II Block compare to Fig. 6h shows that 26% is identified as medium (45–90 kg/ha) and 74% are high (>90 kg/ha) in Memari-II Block. In both Blocks, a medium amount (150–340 kg/ha) of available K dominates the entire area (Fig. 5 i and 6i). In terms of soil pH, some scatter portion (57.05%) of the north centre and southern part of Ausgram-II is

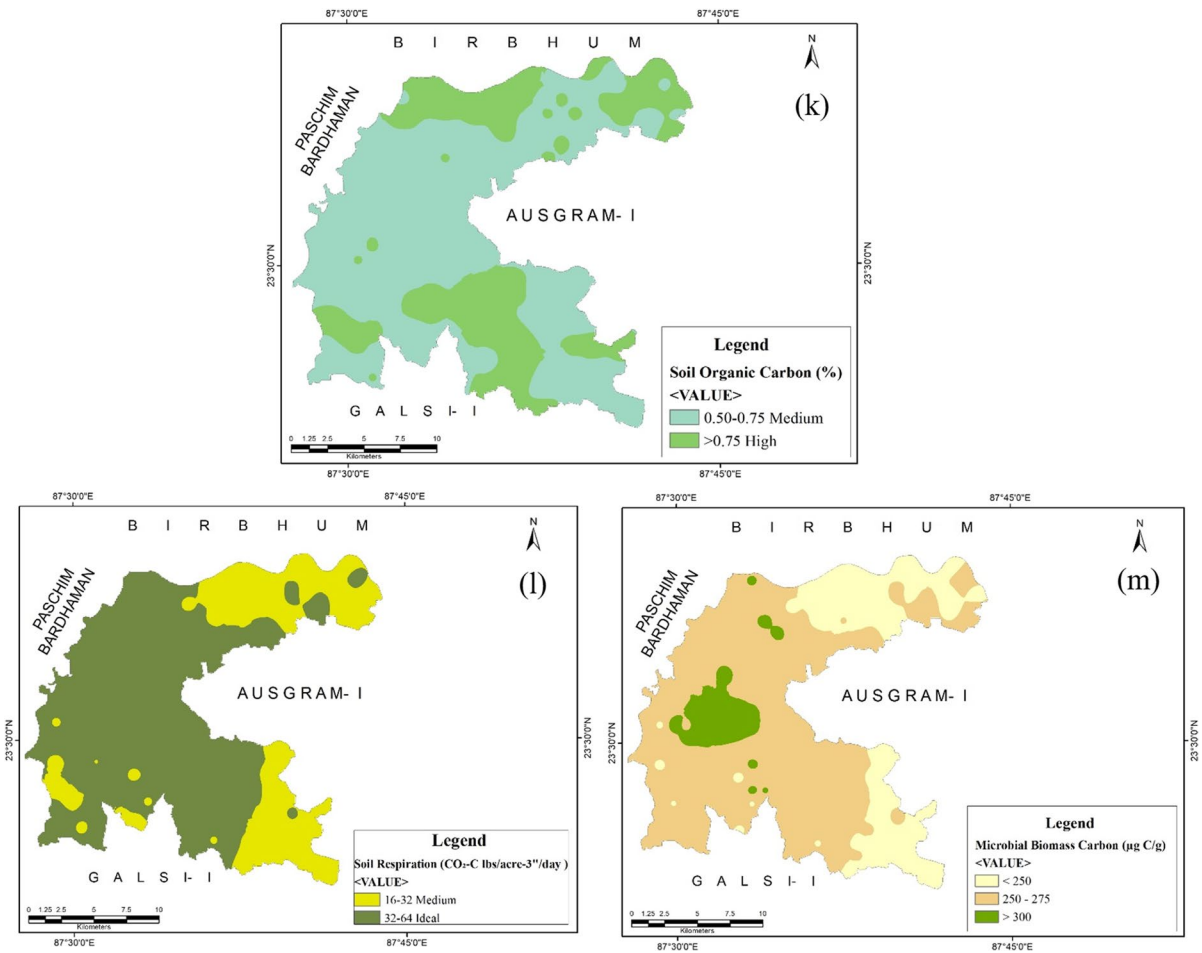


Fig. 5 (continued)

covered by neutral (pH=6.6–7.3), and the remaining 42.95% of the area is observed as slightly acidic soil (pH=6.1–6.5) (Fig. 5j). In Memari-II, Fig. 6j shows 11% strongly acidic (pH=5.1–5.5), 31% moderately acidic (pH=5.6–6.0), 41% slightly acidic (pH=6.1–6.5), 15% neutral and 0.56% (pH=6.6–7.3), and slightly alkaline soil (pH=7.4–7.8). For SOC, Fig. 5k shows 68.28% are medium (0.50–0.75%), and 31.72% are high (>0.75%), while Fig. 6k shows 57% are low (<0.50) and 43% are medium (0.50–0.75%) in Ausgram-II and Memari-II, respectively. SR is mostly dominated by ideal (32–64 CO₂-C lbs/acre-3"/day) with 69% of the area of Ausgram-II and remaining 29% shows medium (16–32 CO₂-C lbs/acre-3"/day) in the northern and southern part of the Block (Fig. 5l). In comparison, it is observed in the Fig. 6l that 2% of the area are low (9.5–16 CO₂-C lbs/acre-3"/day), 96.04%

are medium (16–32 CO₂-C lbs/acre-3"/day) and 2% are ideal (32–64 CO₂-C lbs/acre-3"/day) in Memari-II. For MBC, about 70% of the area of Ausgram-II is covered with medium (250–275 µg/g) (Fig. 5m) and about 82% of the area of Memari-II is dominated by medium class (220–240 µg/g) (Fig. 6m).

Soil quality index (SQI)

Selection of minimum data set (MDS)

In the Blocks Ausgram-II and Memari-II, up to five PCs are extended to fulfil the above-mentioned principle. In the case of Ausgram-II, PC1 explains the highest variance (26.71%), followed by PC2 (19.77%), PC3 (10.28%), PC4 (9.39%) and PC5 (8.38%). PC1 is represented by SAS (0.806), SR

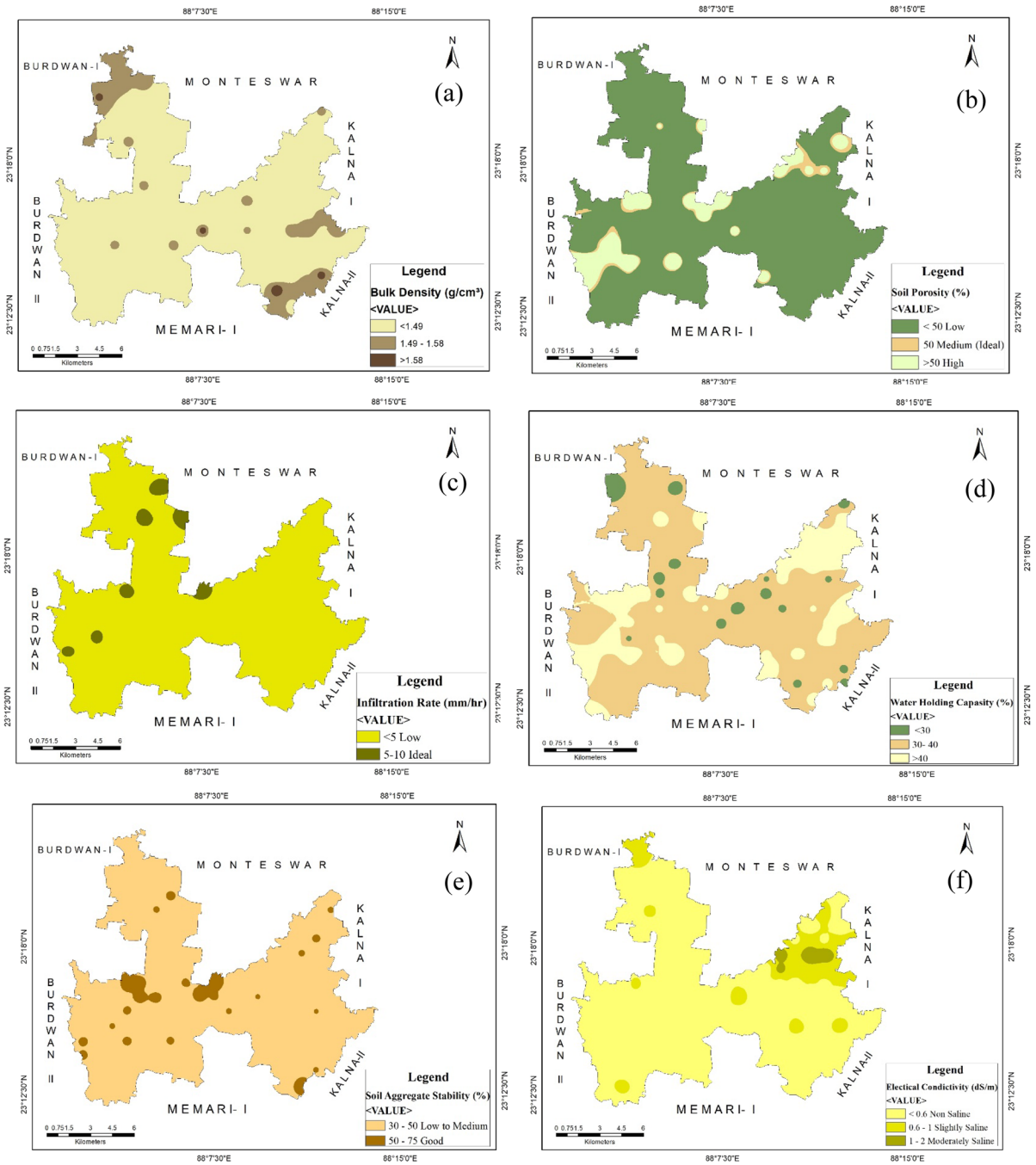


Fig. 6 Spatial distribution of (a) BD, (b) SP, (c) IR, (d) WHC (e) SAS, (f) EC, (g) Available N, (h) Available P, (i) Available K, (j) Soil pH, (k) SOC, (l) SR and (m) MBC by IDW in Memari-II C.D. Block

(0.803) and MBC (0.782). In PC2, BD is the highest negatively correlated value (-0.836), followed by SP (0.835), and available K (0.762). PC3, PC4, and PC5 are represented by highly loaded values of

soil pH (-0.754), available N (0.529), and available P (0.715), respectively (Table 2).

For Memari-II, cumulative variance accounts for 80.36% of the five PCs (Table 3). The highest value

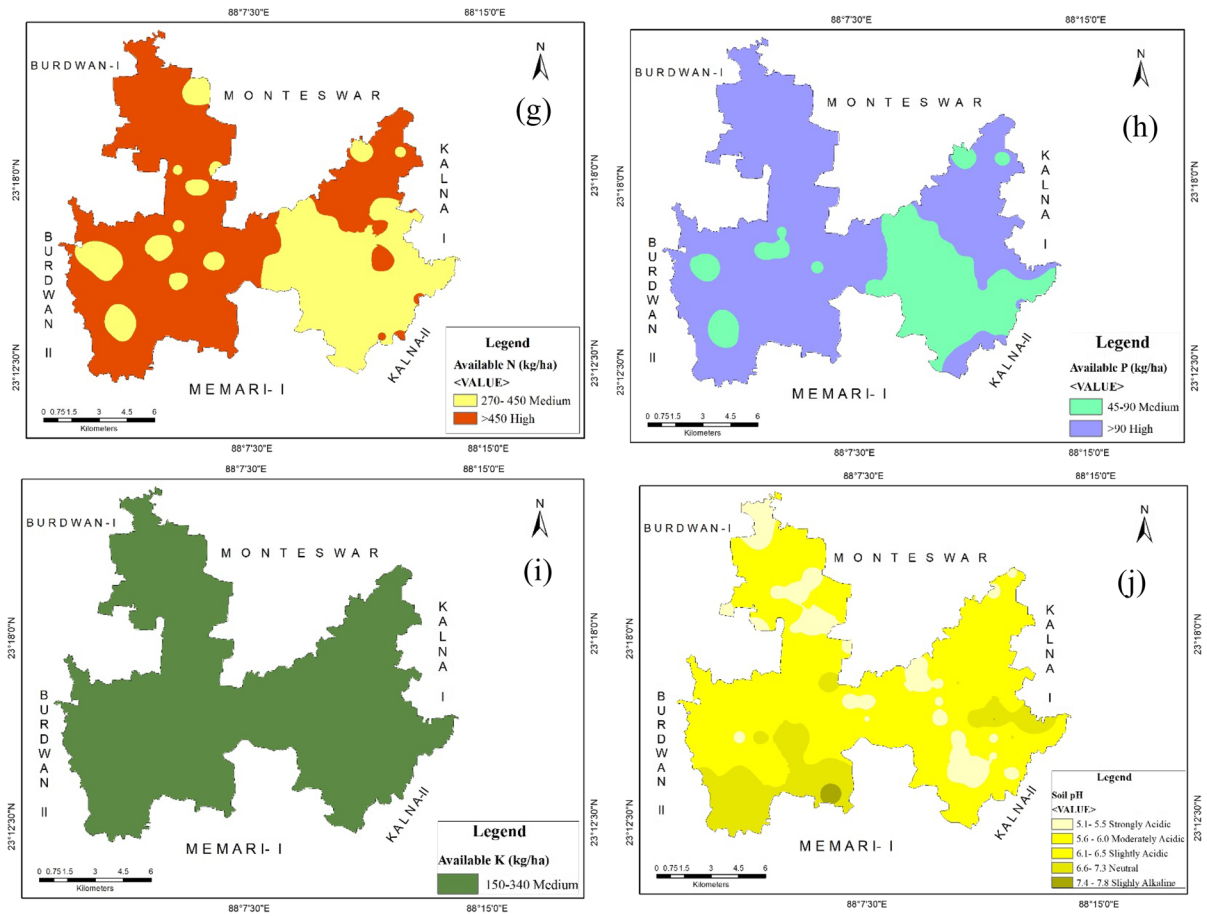


Fig. 6 (continued)

is explained by PC1 (29.145%), followed by PC2 (16.78%), PC3 (13.940%), PC4 (22.935%) and PC5 (8.565%). In PC1, WHC has the highest positive loading value (0.907), followed by BD (-0.837), SP (0.832), and IR (-0.825). PC2 is represented by SR (0.889) and MBC (0.843). Available N (-0.821) is the highest negative loading in PC3, followed by available P (-0.739). PC4 is represented by SOC (0.663) and Soil pH (0.632). While PC5 is represented only by SAS (0.511).

Data redundancy and retention of MDS

For Ausgram-II Block, from the PC1, only SAS is selected as representative as it is correlated with SR and MBC. In PC2, BD is correlated with SP. Thus,

BD and available K are taken as representative as they are both highly loaded but not correlated to each other (Fig. 7). Soil pH, available N and available P are selected for PC3, PC4 and PC5, respectively, as they are only representative of respective PCs. In Memari-II, PC1 is represented by WHC, BD, SP and IR. WHC has been taken for further calculation as WHC is correlated to remaining soil parameters. While SR and MBC represent PC2, and as they are correlated, highly loading SR has been selected as MDS. Similarly, in PC3 and PC4, available N and pH have been taken in MDS, as both parameters correlated to the rest of the highly loading parameters (Fig. 8). SAS is the only representative for PC5, so it has been selected for further computation.

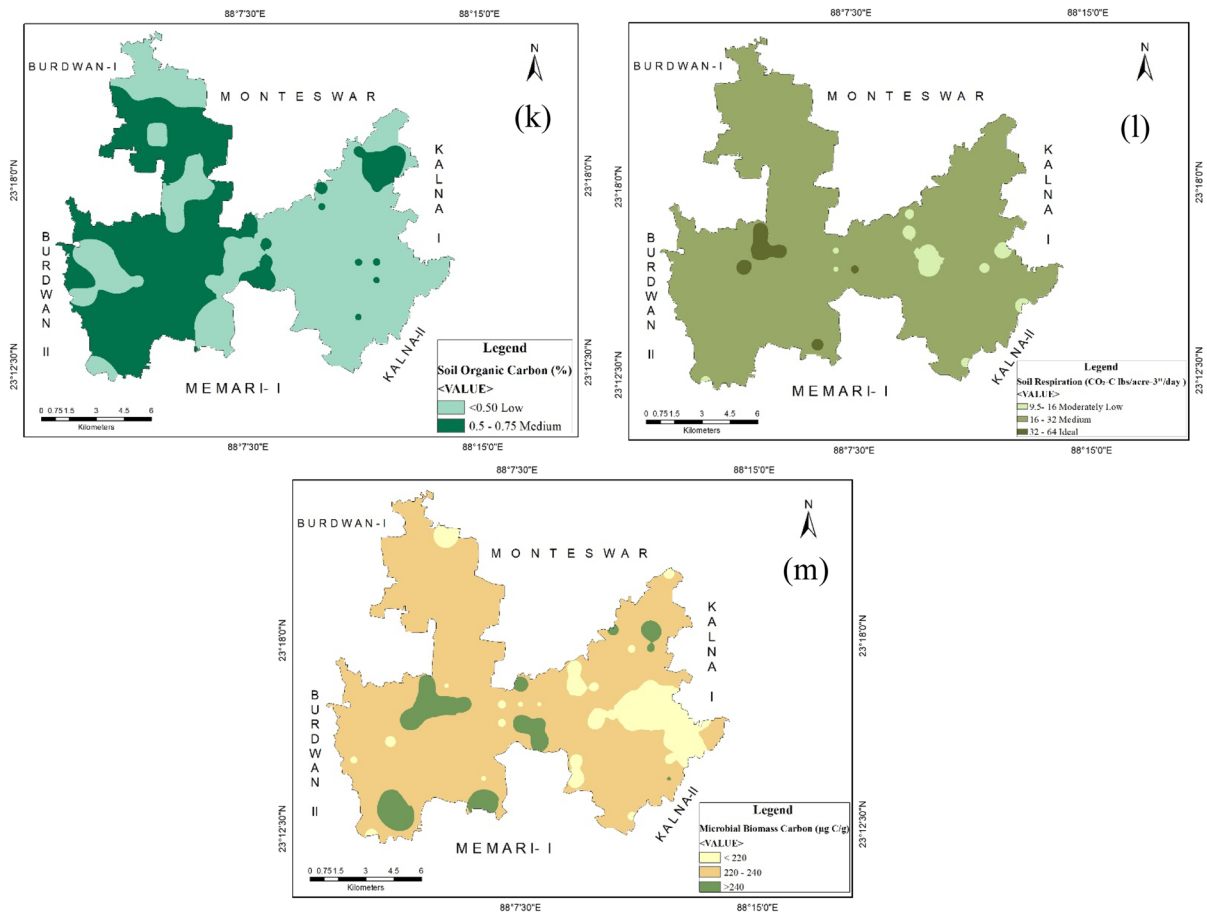


Fig. 6 (continued)

Scoring of MDS

For Ausgram-II Block, SAS, BD, available K, pH and available P have been retained as highly loading components. In contrast, WHC, SR, available N, pH, and SAS have been considered for calculating the SQI for Memari-II. Now, it is necessary to assign a score to the retained components (Tables 4 and 5). SAS, available K and available N have been assigned the score as ‘more is better’, whereas BD and pH have been scored as ‘less is better’ and ‘optimum is better’ (Table 4). In Memari-II, apart from pH, WHC, SR, available N, and SAS have been assigned as ‘more is better’ while pH has been assigned as ‘optimum is better’ (Table 5). To calculate the weight of each parameter, extracted individual variance has been divided by cumulative variance (Andrews et al., 2001; Bhardwaj et al., 2011). For Ausgram-II Block, the SAS (26.71%) shows the highest contribution

to SQI followed by BD (19.77%), available K (19.77%), pH (10.28%) available N (9.39%) (Fig. 9a). Weight of the retained components have been given as $0.36 > 0.27 > 0.27 > 0.14 > 0.13 > 0.11$.

Among the retained components, WHC (29.15%) contributes the highest contribution to SQI, followed by SR (16.78%), available N (13.94%), pH (11.94%), and SAS (8.57%) in Memari-II Block (Fig. 9b). The weight of the retained components has been given as $0.36 > 0.21 > 0.17 > 0.15 > 0.11$.

Compare the SQI between two C.D. Blocks

The ideal indicator of soil quality would be an index that considers multiple highly loaded soil properties, as individual soil attributes do not accurately reflect the overall health of the soil. In this study, the SQI represents the soil health of each Block, and the

Table 2 Principal components, eigenvalues and component matrix of soil parameters of Ausgram-II Block

PCs Parameter	Component				
	PC1	PC2	PC3	PC4	PC5
Eigenvalues	3.472	2.570	1.336	1.220	1.089
Variance Explained (%)	26.709	19.766	10.281	9.387	8.375
Cumulative Variance Explained (%)	26.709	46.475	56.756	66.142	74.518
Soil Parameter	Factor Loadings				
BD	-0.254	-0.836	0.328	0.220	-0.245
SP	0.268	0.835	-0.323	-0.214	0.239
WHC	0.671	0.374	0.260	-0.124	-0.295
IR	-0.679	-0.074	-0.134	0.380	0.355
SAS	0.806	-0.061	0.160	0.047	0.195
pH	-0.226	0.009	-0.754	0.268	-0.060
SOC	-0.363	-0.177	-0.113	-0.410	0.316
EC	-0.365	0.216	0.324	-0.433	0.107
Available N	0.258	0.510	0.171	0.529	-0.093
Available P	0.033	0.062	0.438	0.288	0.715
Available K	-0.365	0.762	0.155	0.381	-0.198
SR	0.803	-0.454	-0.172	0.041	0.092
MBC	0.782	-0.320	-0.232	0.165	0.192

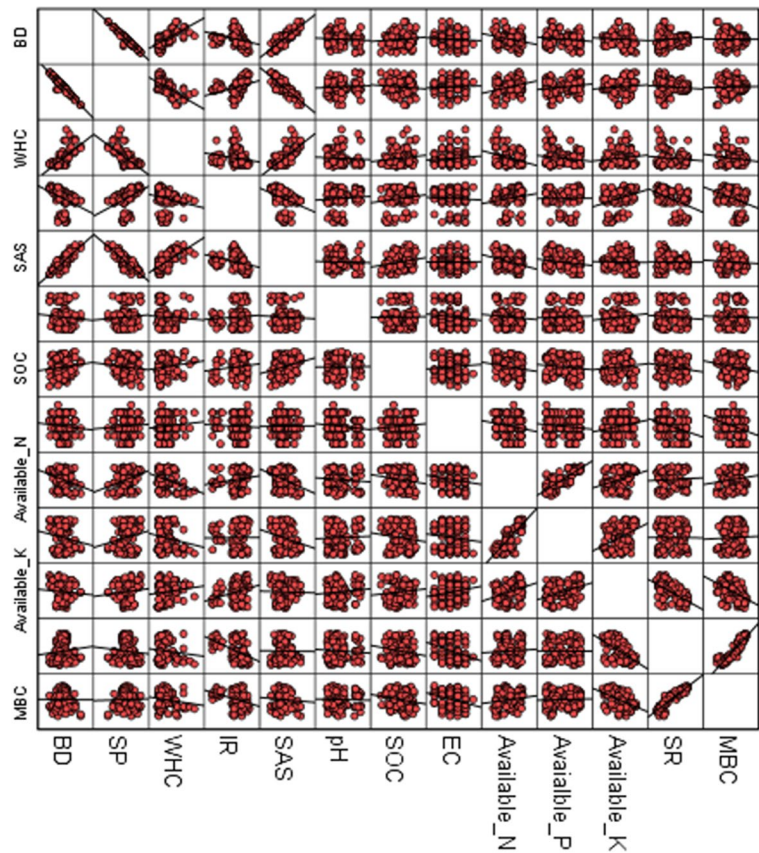
BD: Bulk Density; SP: Soil Porosity; WHC: Water Holding Capacity; IR: Infiltration Rate; SAS: Soil Aggregate Stability; EC: Electrical Conductivity; SOC: Soil Organic Carbon; Available N: Available Nitrogen; Available P: Available Phosphorous; Available K: Available Potassium; SR: Soil Respiration; MBC: Microbial Biomass Carbon.

Table 3 Principal components, eigenvalues and component matrix of soil parameters of Memari-II Block

PCs Parameter	Component				
	PC1	PC2	PC3	PC4	PC5
Eigenvalues	3.789	2.181	1.812	1.552	1.113
Variance Explained (%)	26.145	16.778	13.940	11.935	8.565
Cumulative Variance Explained (%)	29.145	45.923	59.863	71.798	80.363
Soil Parameter	Factor Loadings				
BD	-0.837	0.114	0.044	-0.177	0.406
SP	0.832	-0.117	-0.053	0.174	-0.405
WHC	0.907	-0.111	0.022	-0.101	0.275
IR	-0.825	-0.121	-0.044	0.186	-0.344
SAS	0.717	0.006	0.087	-0.252	0.511
pH	0.250	0.436	0.281	0.662	-0.144
SOC	0.166	0.157	0.427	0.612	0.221
EC	-0.347	-0.025	0.361	-0.040	0.156
Available N	-0.096	0.269	-0.821	0.199	0.235
Available P	0.226	0.478	-0.739	0.197	-0.017
Available K	-0.319	0.334	0.003	0.439	0.382
SR	0.010	0.889	0.172	-0.294	-0.219
MBC	0.072	0.843	0.248	-0.427	-0.076

BD Bulk Density, SP Soil Porosity, WHC Water Holding Capacity, IR Infiltration Rate, SAS Soil Aggregate Stability, EC Electrical Conductivity, SOC Soil Organic Carbon, Available N Available Nitrogen, Available P Available Phosphorous, Available K Available Potassium, SR Soil Respiration, MBC, Microbial Biomass Carbon

Fig. 7 Correlation matrix of the soil indicators of Ausgram-II Block



results show that the SQIs of the Blocks vary significantly. The mean SQI value of Memari-II is 0.69 (ranges 0.57–0.86) compared to the mean value of 0.97 (ranges 0.83–1.08) of Ausgram-II (Fig. 10). Although the SD for both the Blocks is found to same (SD=0.06) and CV is also very minimal differences (1.37%) (Table 6).

SQI ranges could be divided into five grades (Table 7). The spatial distribution shows that the SQI of Memari-II is observed mostly moderate to high (Grades III and IV), while in Ausgram-II Block, it is very high (Grade I). Understanding the spatial variability of SQI is important because it indicates the extent of land affected by poor soil management systems. In Ausgram-II, 99.72% of the area is classified as very high SQI with grade I, while the remaining 0.28% is classified as high SQI with grade II (Fig. 11a). On the other hand, moderate (Grade III), high (Grade II), and very high (Grade I) SQI values cover the land of 49.95%, 49.90%, and 0.16% of Memari-II, respectively (Fig. 11b). Moderate SQI is

dominated on the eastern side and some patches in the western side. In contrast, high grade is dominated mostly on the western side of the Block.

Evaluation of SQI

Sensitivity index (SI) and efficiency ratio (ER)

For SI, the soil of the Memari-II Block (SI=1.53) is more sensitive than Ausgram-II (SI=1.30), which indicates higher external disturbances or human interventions to the soil. In the case of ER, out of 12 highly loaded parameters, Ausgram-II has 6, and Memari-II has 5 parameters selected for MDS. Therefore, Ausgram-II (ER=50%) has a slightly higher ER value than Memari-II Block (ER=42%).

Validation of SQI by sustainable yield index (SYI)

The study also attempts to understand the relationship between SQI and SYI. Singh et al., 1990 introduced

Fig. 8 Correlation matrix of the soil indicators of Memari-II Block

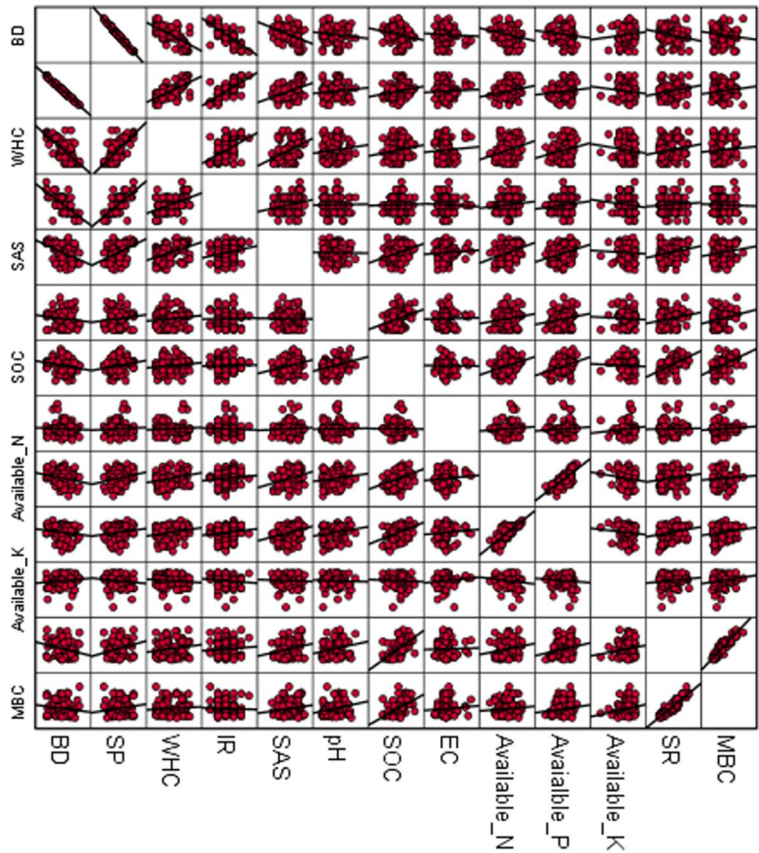


Table 4 Assigned score and weight of retained component of Ausgram-II Block

Retained Component	Scoring Curve	Min	Max	Weight	Contribution to SQI (%)	Associated Sol function
SAS	More is better	32	51	0.36	26.71	Control the movement of water and air
BD	Less is better	1.06	1.62	0.27	19.77	Regulate the infiltration of water
available K	More is better	148	285	0.27	19.77	Supply nutrients to soil and plants
pH	Optimum is better	6.12	7.34	0.14	10.28	Control the availability of nutrients to plants
available N	More is better	225	454	0.13	9.39	Supply nutrients to soil and plants
available P	More is better	41	95	0.11	8.38	Supply nutrients to soil and plants

BD Bulk Density, *SAS* Soil Aggregate Stability, *Available N* Available Nitrogen, *Available P* Available Phosphorous, *Available K* Available Potassium

a quantitative formula for SYI, which requires mean, SD, and maximum crop production. SYI ranges from 0 to 1, with high yielding and low SD resulting in higher SYI. A stable management with low SD and high mean provides the best feasible SYI (Wanjari et al., 2004).

The selected Blocks are identified as intensive agro-based. Seven years of annual data (District

Statistical Handbook, 2010–11 to 2017–18) have been considered for assessing crop productivity. In Ausgram-II, the highest average yield is found in potatoes, followed by paddy, wheat, mustard, sesame and lentils. A similar sequence of productivity has been seen in Memari-II. However, the cultivated lands are seen differently. In Augram-II, paddy is cultivated in the maximum lands (96%) of total cultivated lands

Table 5 Assigned score and weight of retained component for Memari-II Block

Retained Component	Scoring Curve	Min	Max	Weight	Contribution to SQI (%)	Associated Sol function
WHC	More is better	26	52	0.36	29.15	To store water and supply to plant
SR	More is better	14	37	0.21	16.78	Balance the carbon cycle
available N	More is better	415	481	0.17	13.94	Supply nutrients to soil and plants
pH	Optimum is better	5.12	7.65	0.15	11.94	Control the availability of nutrients to plants
SAS	More is better	34	55	0.11	8.57	Control the movement of water and air

WHC Water Holding Capacity, SAS Soil Aggregate Stability, Available N Available Nitrogen, SR Soil Respiration

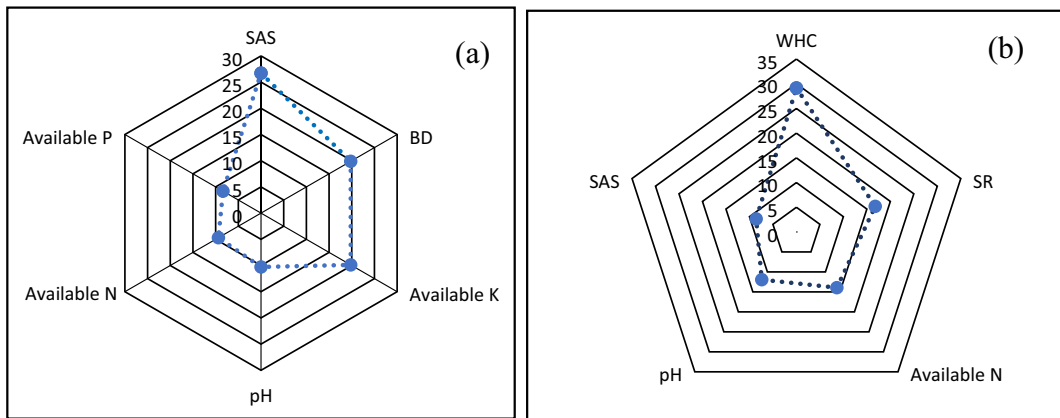


Fig. 9 Percentage of the contribution of the retained MDS to the SQIs of (a) Ausgram-II and (b) Memari-II C.D. Block

Fig. 10 Ranges, mean, median and quartiles of SQIs of the Blocks

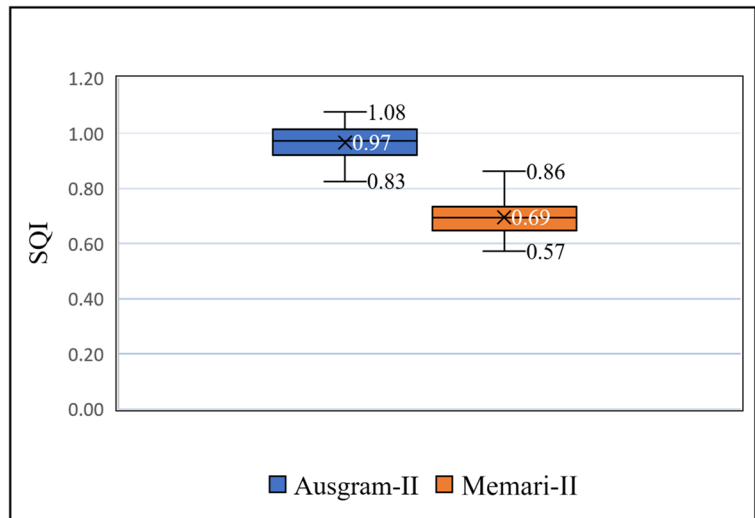


Table 6 Descriptive statistics of SQIs in the studied Blocks

C.D. Blocks	Min	Max	Mean	SD	CV (%)
Ausgram-II	0.83	1.08	0.97	0.06	6.25
Memari-II	0.57	0.86	0.69	0.06	8.62

Min Minimum, *Max* Maximum, *SD* Standard Deviation, *CV* Coefficient of variance

in the respective growing season, followed by potato (65%), mustard (45%), wheat (42%), sesame (32%), and lentils (24%). Whereas, in Meamri-II, paddy (94%) and potato (91%) dominate most of the area in their respective growing season, followed by mustard (20%), wheat (15%), sesame (8%), lentils (6%).

The mean of SYI for Ausgram-II is higher (0.51) than Memari-II (0.43) for the overall period, but

Table 7 Rating of SQI with the association of respective grades and description (Bel-Lahbib et al., 2023)

Grade	SQI	Rating of SQI	Description	Reference
I	>0.85	Very High	Most suitable for plant growth	Qi et al., 2009; Marzaioli et al., 2010;Huang et al., 2021
II	0.7–0.85	High	Suitable for plant growth	
III	0.55–0.7	Moderate	Suitable with limitations	
IV	0.40–0.55	Low	More serious than grade III	
V	<0.40	Very Low	Most severe restrictions	

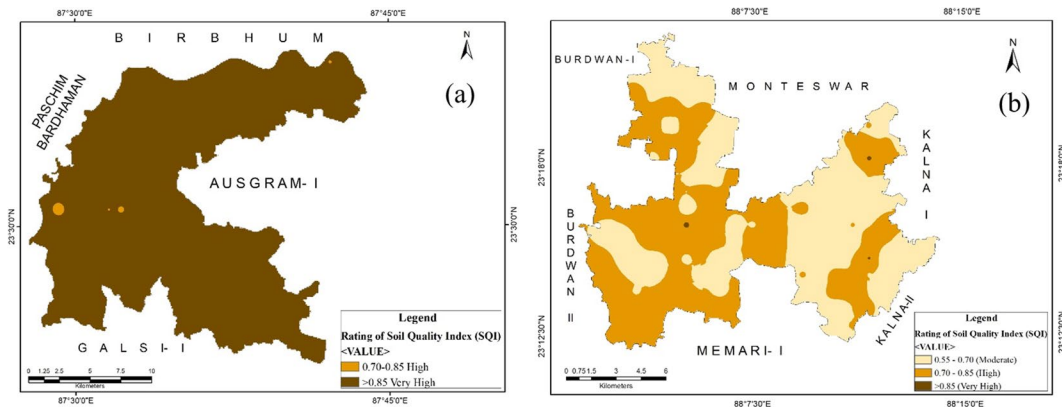


Fig. 11 Spatial variability of SQIs in the Blocks, (a) Ausgram-II and (b) Memari-II

Fig. 12 Comparison of Sustainable Yield Index (SYI) among the cultivated crops

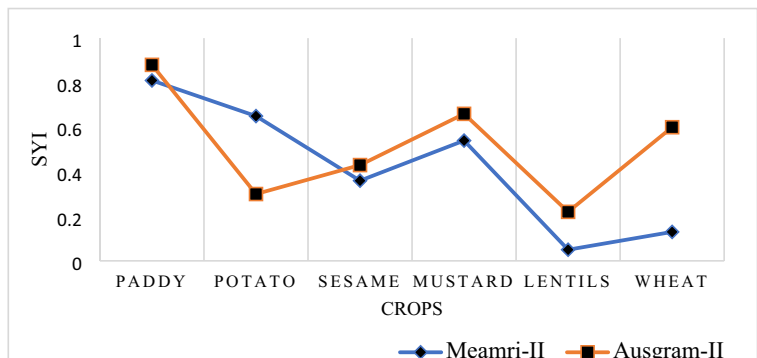


Table 8 Inter-relation between SQI and SYI in the Studied C.D. Blocks

C.D. Block	Crop	Cultivated area (%) to Total arable land	Average Yield (kg/ha)	SD	SYI	Average (SYI)	Average (SQI)	R ^{2*}
Ausgram-II	Paddy	96%	3186	269	0.88	0.51	0.97	0.82
	Potato	65%	25,750	11,248	0.30			0.71
	Wheat	42%	2544	566	0.60			0.65
	Mustard	45%	939	180	0.66			0.68
	Lentils	24%	764	503	0.22			0.55
	Sesame	32%	813	286	0.43			0.65
Memari-II	Paddy	94%	3052	205	0.81	0.43	0.69	0.72
	Potato	91%	36,134	8536	0.65			0.78
	Wheat	15%	1702	1329	0.13			0.61
	Masturd	20%	864	229	0.54			0.67
	Lentils	6%	399	447	0.05			0.51
	Sesame	8%	603	257	0.36			0.55

*Correlation between SQI and Crop yield ($p < 0.01$)

Memari-II has a better SYI value for only potato yield (0.65). Ausgram-II has better SYI values for the remaining five crops: paddy (0.88), wheat (0.60), mustard (0.66), lentils (0.22), and sesame (0.43) (Fig. 12). The SQI and SYI have found lower value in Memari-II than Ausgram-II (Table 8). All the crop yields are positively correlated with SQIs in both Blocks. In Ausgram-II, paddy ($R^2=0.82$) and Potato ($R^2=0.71$) are found to be highly positively correlated, while mustard ($R^2=0.68$), wheat ($R^2=0.65$), sesame ($R^2=0.65$), and lentils ($R^2=0.55$) are moderately correlated. In Memari-II, Potato ($R^2=0.78$) and paddy ($R^2=0.72$) are highly positively correlated, followed by mustard ($R^2=0.67$), wheat ($R^2=0.61$), sesame ($R^2=0.55$), and lentils ($R^2=0.51$), respectively (Table 8).

Discussion

Explanation of the classes of soil indicators

In Ausgram-II, BD is lower than the threshold value for sandy loamy and sandy clay loamy soils (1.40 g/cm^3) compared to Memari-II; it is slightly above the recommended range ($< 1.10 \text{ g/cm}^3$) for silty clay and clay loamy soil as per the USDA-NRCS (2019). Numerous studies consider that a porosity of about 50% is appropriate for soil productivity (Klopp &

Bly, 2023). So, a soil porosity of 50% is considered as ideal. The infiltration rate is optimum for soil texture for both Blocks, as per the Food and Agricultural Organization (FAO, 1990). For WHC, both the Blocks fall above the threshold value ($> 18\text{--}20\%$) (NRCCA, 2010). Soil with less than 2 dS/m is classified as non-saline (USDA-NRCS, 2011). It is also stated that when the EC level exceeds 2.1 dS/m, 12% of the paddy production would decline (USDA-NRCS, 2011). Durand (1983) classified $\leq 0.6 \text{ dS/m}$ as non-saline, $> 0.6 \text{ EC} \leq 1$ as slightly saline, and $> 1 \text{ EC} \leq 2$ as moderately saline soil. More than 50–75% of SAS have been considered as medium to good physical quality (Shadekar, 2018) and $> 75\%$ as structural integrity (USDA-NRCS, 2001). As per the standard classification of soil pH (USDA-NRCS, 1998), mostly neutral and slightly acidic soil is found in Ausgram-II and Memari-II C.D.Block, respectively. The low, medium and high SOC are $< 0.50\%$, $0.5\text{--}0.75\%$ and $> 0.75\%$, respectively. Optimum ranges of available N, P and K are $< 270\text{--}450 > \text{kg/ha}$, $< 45\text{--}90 > \text{kg/ha}$ and $< 150\text{--}340 > \text{kg/ha}$, respectively, in agricultural land (CDAP, Purba Bardhaman 2017–20). Therefore, in Memari-II, available N and available P are slightly excessive than the optimum level. In contrast, the analysed data of N, P and K in Ausgram-II fall below the threshold ranges. USDA-NRCS (2014) defines high SR as $32\text{--}64 \text{ CO}_2\text{-C lbs/acre-3"/day}$ and moderate SR as $16\text{--}32 \text{ CO}_2\text{-C lbs/acre-3"/day}$.

Evaluation of retained MDS

Among the total 13 parameters, 5 parameters were retained as MDS using PCA for both the Blocks. MDS is one of the most efficient methods for determining SQI as it reduces the variables, avoids data redundancy and retains the specific and effective variables (Huang et al., 2021; Nabiollahi et al., 2017). This study identified the highest loading factor for SQI in Ausgram-II and Memari-II Block as SAS, contributing 26.71%, and WHC, contributing 29.15 to SQI, respectively. A positive correlation ($r=0.58$) between SAS and SOC may be attributed to the high use of organic matter. It was the prime observation of some previous works (Mustafa et al., 2020; Wolschick et al., 2018). Wolschick et al., (2018) showed that the tillage system also influences the SAS. On the other hand, WHC is the highest loading factor and serves as the primary physical parameter. WHC has a positive correlation with SAS ($r=0.75$) and a negative correlation with BD ($r=-0.62$) and IR ($r=-0.86$). According to Nath, (2014), soil texture significantly impacts WHC in an experimental investigation conducted in Assam, India. The study finds that the WHC positively correlates with clay content ($r=0.80$) as opposed to sandy content ($r=-0.78$), indicating that clay texture enhances WHC. The textural class of Memari-II Block is predominantly clay loam and silty clay-type, which may explain why WHC is higher in this area. However, WHC could be improved using manure, inorganic, and bio-fertiliser (Datt et al., 2013). Shah et al., (2022) showed that both the plots practised with inorganic and organic fertiliser received higher WHC. Available N and soil pH have been retained as MDS for both Blocks, indicating that both indicators influence soil quality. The amount of N-content appears to impact soil pH, with a negative correlation observed for both Blocks. This could be attributed to the acidifying effect of excessive N-fertilisation. In Memari-II, the soil pH is slightly below the neutral level ($\text{pH}=7$) due to the high N-fertilisation, while the opposite finding is observed in Ausgram-II. Findings that align with the current results suggest that soil pH decreases linearly with increasing N-content in soils. Urea and NH_4NO_3 were found to be more responsible for acidification than NH_4 fertilizer (Tian & Niu, 2015). In this study, urea was one of the primary fertilisers used as a nitrogen source in the soil. Available N

contributed 13.94% and 9.31% to SQI of Memari-II and Ausgram-II, respectively. The reason may be the excessive usage of urea (46%N) and Di-ammonium Phosphate (18%N) in the Memari-II Block. Cattle manure contributes very slowly to the nitrogen in the soil. Sharma et al., (2008) found available N as a key indicator of SQI. They reported that nitrogen plays an important role in improving biomass and crop productivity above the soil and below the soil. Available K, the second most important indicator along with BD, contributes 19.77% to the SQI of Ausgram-II Block. Zero tillage sometimes lowers the available K as a minimum, or zero tillage increases bulk density (Sharma et al., 2005; Tisdale et al., 1985). However, BD was also found ideal, contributing 19.77% towards the SQI of Ausgram-II. This means tillage is regular and does not affect the available K. Available K controls the osmotic pull that draws water from the soil into plant roots (Sharma et al., 2005).

Effects of fertiliser management practices on soil properties and SQI

In Ausgram-II, 99.72% of the area is classified as very high SQI with grade I, while the remaining 0.28% is classified as high SQI with grade II. On the other hand, moderate (Grade III), high (Grade II), and very high (Grade I) SQI values cover 49.95%, 49.90%, and 0.16% of Memari-II, respectively. Nguemezi et al. (2020) attempted to investigate land management practices, showing that most lands are identified as having average fertility (46.49%) followed by good fertility (29.04%), poor fertility (21.46%) and very good fertility (3.79%) in sub-Saharan Africa. The major reason they noticed good to very good fertility was high organic matter, and poor fertility was related to severe limitation of physical parameters. A similar study was conducted in China's humid monsoon climatic sub-tropical region (Qi et al., 2009). They found that 90% of the area was covered by moderate soil quality (grade II and III), and the remaining 10% was shared by very high (grade I) and poor soil quality (grade II). Sandy-loamy soil is found to have low soil quality with low SOC and alkaline soil, while clay loamy is quite healthy with high SOC and is nutrient-rich. Although the findings contradict the present study, this may be the reason for differentiated land management systems that make a difference in soil quality. Similarly, Maleki et al., (2022) found

that the most dominant soil quality is moderate (grade II and III) due to topographical attributes and irrigation from poor-quality groundwater. They addressed the sustainable and appropriate land management to mitigate soil degradation. A study demonstrates that the highest Soil Quality Index (SQI) is achieved at the optimal NPK fertiliser level (0.90), followed by the intermediate (0.86) and no fertilizer (0.78) levels in the Mediterranean environment (Armenise et al., 2013).

Farmers of Memari-II Block prefer farming with alone inorganic fertiliser, a certain amount of bio-fertiliser, and nearly no organic fertiliser. The common combinations are NPK and NPK+bio-fertiliser. In Ausgram-II Block, major combinations of fertiliser inputs NPK+cattle manure, NPK+cattle manure+bio-fertiliser and NPK+cattle manure+bio-fertiliser+rice husk ash. Studies have shown that high-quality cow dung contains important nutrients such as N (1.44–2.10%), P (48–80%), and K (1.74%) (Ewusi-Mensah et al., 2015). Additionally, cow dung with chicken manure can improve soil health by enhancing pH, SOC, exchangeable Ca, total N, and available P while reducing BD (Van Dang et al., 2021). Rice husk ash also benefits soil health and land productivity, as it contains biomaterials (Kordi et al., 2023). Another study found that combining rice husk biochar and fly ash with inorganic fertilisers can improve soil pH, SOC, CEC, available NPK, and EC, and even using 50% N content with rice ash biochar and fly ash can produce the same yield as 100% of the recommended dose (Munda et al., 2016). Matching with the findings of the present study, Sharma et al., (2010) proved that fertiliser practice with 100% organic (SQI=2.62) improves soil quality more than 50% organic+50% inorganic (SQI=2.35) in rainfed alfisols. Ram et al., (2016) conducted a study on the effect of integrated nutrient management and revealed that continuous use of FYM improved the most to SQI (0.94). Applying the SQI method to 9 different fertiliser treatments, Li et al., (2020) highlighted that vermicompost and pig manure had significantly higher SQI, followed by straw, biochar and single chemical fertiliser. Eventually, to improve the soil health, they suggested applying a combination of chemicals with organic fertiliser. Rezaee et al., (2020) have studied paddy fields in Iran and identified poor soil quality (SQI<0.58). The primary reason is that rice cultivation does not use

optimum phosphorous and potassium-based fertiliser. Dengiz (2020) stated that SQI was dominated by moderate (36.8%) followed by high quality (36.1%), very low (22.5%) and low (4.5%) in Çarsamba Deltaic Plain in Turkey for rice cultivation. Excess slope, low clay content, salinity and water holding capacity have been found as reasons why 25.9% of the study area is unsuitable for rice cultivation.

In recent times, human activities have become more common than natural disturbances when it comes to changes in soil quality. SOC is a crucial indicator of soil quality because it can increase crop productivity and improve yield stability. The present study found that applying chemical fertilisers with manure can yield soil quality that matches previous findings (Han et al., 2016; Zhengchao et al., 2013). Han et al., (2016) found that unbalanced chemical fertilisers had the lowest SOC (0.10) and that chemical fertilisers combined with manure had the highest (0.31). In the present study, SOC was found to be low to moderate due to the excessive use of chemical fertilisers, while it was moderate to high when chemical fertilisers were combined with manure. Additionally, excessive usage of N-fertiliser has been found to reduce soil pH, as demonstrated by extensive research in China over the past 30 years (1980–2010) (Guo et al., 2018). The amount of organic matter has a significant impact on BD. Studies have shown that organic matter generally reduces BD and increases soil aggregate stability (SAS) (Biswas et al., 2023; Ekwue, 1990; Keller & Håkansson, 2010). In the present study, the use of organic fertilisers improved SAS in the study area. While WHC found the highest loading for Memari-II, this may be due to the higher percentages of clay contents in soils (Franzluebbbers, 2020) Furthermore, there was a highly positive correlation between SR and MBC for both the Blocks. The presence of organic matter improves SR and, in turn, enhances microbial activities in the soil. MBC was higher in no-tillage systems due to the high percentage of organic matter, while pasture land with no organic matter showed a reduction in MBC (Valpasos et al., 2001).

Association of SQI with crop combination

Armenise et al., (2013) revealed that double cropping of wheat and dry beans has a higher SQI than other crop combinations. In North-West India, the

rice–wheat-mungbean crop combination has the highest SQI (0.91) compared to the lowest SQI (0.65) of rice and wheat (Roy et al., 2022). The current study shows that the crop combination of paddy during the *kharif* season (rainy) and potato, wheat, and mustard during the *rabi* season (winter) is better than the paddy-potato cropping system. This finding is consistent with Saurabh et al., (2021), who reported that the paddy-wheat and green-gram crop combination had the highest SQI and crop yield. In the present study, paddy with potato, wheat, mustard, sesame, and lentils improved SYI and SQI. The diverse crop rotation leads to improving soil health through balancing the nutrient cycle (Amorim et al., 2020; Lal, 2015; McDaniel et al., 2014). In the present study, dominant SQI grades are moderate to very high for Memari-II and high to very high for Ausgram-II Block. Previous studies found the dominant grades to be II and III, covering 58% of corn belt croplands in northern China (Li et al., 2018). In Qazvan Province, Iran, 54.44% of the area was found to have moderate (Grade-III) agricultural soil quality (Rahmanipour et al., 2014). Similar results were reported by Nabiollahi et al., 2018. In Memari-II, Potato is the primary crop, followed by paddy and insignificant cultivated lands of other crops (mustard, wheat, lentils, and sesame). In contrast, in Ausgram-II, farmers cultivated mustard, wheat, lentils, and sesame alongside paddy and potato as main crops. The diverse crop rotation leads to improving soil health through balancing the nutrient cycle (Amorim et al., 2020; Lal, 2015; McDaniel et al., 2014). While continuous paddy cultivation significantly decreased soil pH, SOC, available P and available K (Ren et al., 2020). Singh et al., (2020) identified that potato-green gram-rice would be the best crop combination in crop production. However, the rice-lentils combination mostly improves the soil quality in the Indo-Gangetic Plains of India. This finding matches the present study, which found that intensive paddy and potato combination increases crop yield but not soil quality, which is used to cultivate in Memari-II. Ghorai et al. (2023) proved that rice-mustard-sesame for 22 years fields responded positively towards soil quality with farm yard manure in lower Indo-Gangetic Plains. The present study shows that rice-mustard-sesame, a common crop combination, was used to cultivate

in Ausgram-II C.D.Block. Xing et al., (2021) found that very low SQI (ranges from 0.06–0.46) in potato fields in the loess plateau region suggested using organic fertiliser and reasonable use of NPK. As a principal crop of Memari-II is potato, both suggestions are useful for this area. The nutrient (NPK) ratio of Memari-II (5:3:2.5) is found to be comparably higher than Ausgram-II (4:2.1:2). It is generally accepted that an NPK ratio of 4:2:1 (N: P₂O₅: K₂O) is suitable for macro-level monitoring of plant nutrient intake for India as a whole and 4:2:2 for West Bengal in specific (NAAS, 2009). The study reveals a significant variation in the spatiality of SQI between two Blocks, and poor nutrient management is the principal cause of low soil quality.

Explanation of SQI validation

The SI value of the present finding (1.30 & 1.53) is lower than in the previous study (2.268) (Sheidai Karkaj et al., 2019). However, another study showed that the sensitivity of three different SQI approaches was 1.43, 1.48 and 1.52 (Masto et al., 2007). Which is higher than the Ausgram-II Block (1.30) but lesser than the Memari-II Block (1.53). In the weighted additive method of MDS, the value of ER was observed to be low at 71.43% (Sheidai Karkaj et al., 2019), which is relatively higher than the present study. Not all TDS parameters are highly loaded in PCA during MDS selection. For SYI, Previous studies showed that the highest SYI was found in NPK + FYM (0.35–0.62), followed by N-fertilizer without manure (0–0.07). SYI can determine the recommended fertiliser dose. Liu et al., (2017) found that the recommended doses of N, P₂O₅ and K₂O fertilisation rates for rice in southeast China were 186, 60, and 96 kg/ha, respectively. The study revealed a positive linear relationship between the recommended dose and SYI. A similar study showed that the highest SYI was achieved with 100% NPK + FYM at 15 t ha⁻¹, which improved soil organic carbon rapidly. However, SYI values were more sustainable for wheat than rice yield (Ram et al., 2016). The present findings show higher SYI in various crop rotation (paddy, paddy, wheat, mustard, sesame and lentils) fields with a fertiliser combination of NPK + Organic manure + Bio-fertiliser + Rice husk ash. In comparison, it is found to be low when NPK is used solely in paddy-potato fields.

Conclusions

The study attempted to compare the two distinct soil inherent and dynamics characterised C.D. Blocks, Ausgram-II and Memari-II, using the SQI model to understand the spatial variation of soil quality and unveil the underlying reasons. Among the thirteen soil indicators, PCA showed that SAS, BD, available K, pH, available N, and available P were the most significant factors contributing to the SQI in Ausgram-II. Similarly, in Memari-II, WHC, SR, available N, pH, and SAS were the highest contributing parameters. The average SQI value is significantly higher in Ausgram-II (0.97), with 99.72% of the area having a very high SQI (Grade-I) compared to Memari-II (0.69) with 49.95% of the area bearing moderate SQI (Grade-II) and 49.90% shown a high SQI (Grade-III). SYI was relatively higher in Ausgram-II Block (0.51) than Memari-II (0.43). The results have shown that the Agricultural lands of Memari-II were identified as more sensitive (SI=1.53) to external disturbances or land management systems than Ausgram-II (SI=1.30). Differentiated fertiliser management systems, nutrient ratio and crop selection mostly cause the disparity in SQIs. Most importantly, the nutrient ratio is much higher than the recommended ratio in Memari-II C.D.Block compared to Ausgram-II C.D.Block, which is a serious concern. The study found that the combination of fertiliser management practices in Memari-II is predominantly NPK and NPK + bio-fertiliser. In contrast, it is completely different in Ausgram-II, with NPK + organic fertiliser (cattle manure) + bio-fertiliser + rice husk ash. A strong positive correlation was observed between SQI and paddy ($R^2=0.82$ & 0.72) and potato yield ($R^2=0.71$ & 0.78). The study focuses on space-specific variations in soil health and identifies faulty fertiliser management practices to enhance sustainable crop productivity. In the future, regions such as the agro-based Indian subcontinent should prioritise similar studies to improve crop yields with appropriate agricultural practices.

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Corresponding author, Piyush Maji took the lead in writing the manuscript, data collection, performed the analytical calculation, interpreted the results and designed the model.

All the authors provided critical feedback and helped to shape the research, analysis and manuscript. All authors read and approved the final manuscript.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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Research involving Human Participants and/or Animals This article does not contain any studies with human participants or animals performed by any of the authors.

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