Nutrient index, microbial activity and soil quality depleted under sugarcane mono-sequencing in Indian subtropics

S. R. Singh¹, S. Singh², Tapendra Srivastava³, M. Tripathi², R. Dohare², Ram Verma⁴, Poonam Yadav², and R. Singh²

¹ICAR-Indian Institute of Sugarcane Research, Lucknow

²Indian Institute of Sugarcane Research

³ICAR- Indian Institute of Sugarcane Research, P.O. Dilkusha, Raebareli Road, Lucknow 226 002, India

⁴Indian Institute of Sugarcane Research, Lucknow - 226 002, Uttar Pradesh, India

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Abstract

Sugarcane mono-sequencing is one of the prominent systems of Uttar Pradesh but wide variations in cane yields are the main cause of concern across the cane producing zones. Hence, 131, 198 and 122 composite soil samples (0-20 cm depth) were taken from cane producing Eastern zone (EZ), Central zone (CZ) and Western zone (WZ) of Uttar Pradesh, respectively to assess the causes of yield variations and impact of sugarcane mono-sequencing on nutrient index (NI), microbial activity and soil quality. Sugarcane mono-sequencing depleted soil organic carbon (SOC), available nitrogen (Na), potassium (Ka), sulphur (Sa) and Zn as 48.9, 98.2, 39.0, 43.3 and 26.4% soil samples falls in low categories, respectively. However, soil degradation aggregated more in EZ soils due to acute deficiency of macro-nutrients as well as high content of Cu, Fe and Mn in low-lying areas. Total microbial counts, microbial biomass of C and N, basal soil respiration, acid and alkaline phosphatase were highest in WZ, but Na, Pa, Ka, Sa, FDA, β -glucosidase and urease activity was greater in CZ soils. As a result, NI was greater in CZ (2.19) followed EZ (1.98) and WZ (1.97), but soil quality index (SQI) was found in the order of CZ (0.795) > WZ (0.785) > EZ (0.708). The sensitivity index (S) was lowest in CZ soils (1.420) indicated that WZ (1.810) and EZ (1.915) soils are more preferable and sensitive to perturbations and management practices. Na was the most vital indicator for sugarcane production followed by SOC, AZO and Sa.

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Indian Institute of Sugarcane Research Lucknow, India-226002

Abstract

Sugarcane mono-sequencing is one of the prominent systems of Uttar Pradesh but wide variations in cane yields are the main cause of concern across the cane producing zones. Hence, this study was undertaken to assess the causes of yield variations and impact of long-term sugarcane mono-sequencing on nutrient index (NI), microbial activity and soil quality. About 131, 198 and 122 composite soil samples (0-20 cm depth) were taken from cane producing Eastern zone (EZ), Central zone (CZ) and Western zone (WZ) of Uttar Pradesh, respectively and analyzed. Long-term sugarcane mono-sequencing depleted soil organic carbon (SOC), available nitrogen (N_a), potassium (K_a), sulphur (S_a) and Zn as 48.9, 98.2, 39.0, 43.3 and 26.4%

soil samples falls in low categories, respectively. However, soil degradation aggregated more in EZ soils due to acute deficiency of macro-nutrients as well as high content of Cu, Fe and Mn in low-lying areas. Total microbial counts (TCB, TCA, AZO), microbial biomass of carbon and nitrogen, basal soil respiration, acid and alkaline phosphatase were highest in WZ but N_a , P_a , K_a , S_a , FDA, β -glucosidase and urease activity was greater in CZ soils. As a result, NI was more in CZ (2.19) followed EZ (1.98) and WZ (1.97), but soil quality index (SQI) was found in the order of CZ (0.795) > WZ (0.785) > EZ (0.708). The sensitivity index was lowest in CZ soils (1.420) followed by WZ (1.810) and EZ (1.915) indicated that WZ and EZ soils are more preferable and sensitive to perturbations and management practices. N_a was the most vital soil quality indicator (contributed 25.7, 26.9 and 23.7% towards SQI development in EZ, CZ and WZ, respectively) followed by SOC, AZO and S_a . Under nutrient deficient zone, targeted yield equations may be useful for improving NI, SQI and sensitivity index to achieve sustainable cane productivity and soil quality.

Key words: Sugarcane monocropping, Nutrient index, Microbial activity, Minimum data set, Soil quality index.

Abbreviations:

ACP: acid phosphatase activity, ALP: alkaline phosphatase activity, AZO-*Azotobacter* counts, N_a : available nitrogen, P_a : available phosphorus, K_a : available K, S_a : available sulphur, β -glu: β -glucosidase, BSR: basal soil respiration. CZ: central zone, DAP: diammonium phosphate, DHA: dehydrogenase activity, EC: electrical conductivity, EZ: eastern zone, FDA: fluorescein diacetate hydrolytic activity, MBC: microbial biomass carbon, MBN: microbial biomass nitrogen, MDS: minimum data set, NI: Nutrient index, SOC: soil organic carbon, SQI: soil quality index, S : sensitivity index, TC: total carbon, TCA: total culturable actinomycetes counts, TCB: total culturable bacterial counts, TCF: total culturable fungal counts, TYE: targeted yield equations, WZ: western zone.

INTRODUCTION

India is the second largest sugarcane producer in the world with 18.7% of world's production during 2017 after Brazil, which is the largest (37.0%) producer of the world (FAO, 2019). The increasing demand of foodstuffs, animal feed, chemicals and industry are the major causes of sugarcane expansion. Lisboa et al. (2011) stated that increasing demand of bio-ethanol is the key driver of this quick increase. Since, it used as a sustainable bio-energy sources, reduces emission of greenhouse gases (GHGs), minimize unpredictability related to volatility of fossil fuel prices (Black et al., 2012), and endowing a fixed income source for farmers. Thus, sugarcane paramount a key role in Indian economy as 50 million farmers' and 5.0 lakhs skilled and unskilled workers are engaged in its production and processing (Krishnakant et al., 2015).

In India, sugarcane cultivated 45% and 55% of the total area in tropical and sub-tropical conditions, respectively but vice-versa in its production. Uttar Pradesh is the key sugarcane producing province under subtropics has largest area (2.234 m ha), production (177.06 m t) and average productivity (79.26 t ha⁻¹) during 2017-18 (Cooperative sugar, 2021). As many as 30 district, in which Muzaffarnagar, Meerut, Bijnor, Moradabad and Saharanpur, districts in western zone (WZ), Bareilly, Shahjahanpur, Lakhimpur-Kheri and Sitapur districts in central zone (CZ) and Kushinagar, Gonda, Balrampur, Basti, Bahraich and Maharajganj in eastern zone (EZ) are considered as the main cane producing district of Uttar Pradesh. WZ is considered as cane heart land of the state due to highest cane production in India. Though, wide yield variations existed across the cane production zones of Uttar Pradesh despite having similar soil type (alluvial soils) might be due to variations in nutrient management and edaphic factor. Rahman and Bee (2019) observed 82.9, 72.0 and 66.9 Mg ha⁻¹ and Cooperative sugar (2021) reported 90.7, 86.8 and 77.8 Mg ha⁻¹ cane productivity of Muzaffarnagar, Lakhimpur-kheri, and Kushinagar district during 2016-2017 and 2019-20, respectively. Indeed, cane productivity has been increased significantly during the decade due to inducing high yielding variety and advance management practices, but yield variation remains is the cause of concern in sub-tropical region (Uperti and Singh, 2017). Yet, the right causes of cane yield variations are not confirmed. Albeit, there are various reasons including increasing compactness, degrading soil structure, nutrient losses through erosion, declining SOC, and increasing multi-nutrient deficiency (Hartemink, 1998).

In addition, low-lying area affected with floods, surface runoff and water logging during monsoon can be a major cause to suffer production and productivity of sugarcane in EZ (Rahman and Bee, 2019). Imbalance fertilization over the years can be another factor for variations in cane yield, nutrient index and soil quality. Because, sugarcane is a heavy nutrient feeder crop required 150–350 kg N; 60–100 kg P_2O_5 , and 60–120 kg K_2O ha^{-1} annually depending upon planting time, growing condition and nutrient status in soil. However, sugarcane growers largely using 150:60:60 kg N, P_2O_5 and K_2O ha^{-1} year $^{-1}$ across the sub-tropical zone from the decades despite changes of fertility gradient (from medium to low or very low categories of nutrients). Contrary to that, sugarcane removed about 208, 53 and 280 kg N, P, and K ha^{-1} year $^{-1}$ for producing 100 Mg ha^{-1} cane yields (Shukla et al., 2017). Sugarcane mono-cropping over the years depleted 53, 56, 84 and 86% SOM, total N, Olsen P and exchangeable K, respectively than the virgin land (0-30 cm depth). Chi et al. (2017) also suggested that prolonged sugarcane cropping has detrimental effects on soil fertility, but deterioration depends on soil types, surface runoff and water logging (Satiro et al., 2017). Heavy mechanization in sugarcane also caused adverse impact on soil compaction notably in top soils. Consequently, reduce soil aeration, soil resistance and infiltration rates and increases runoff and soil erosion in Brazil (Macedo, 2007). Thus, cumulative effects of these factors affect microbial life in soils (i.e. bacterial, fungal, actinomycetes, and nematodes counts) (Hartemink, 2008). Holt & Mayer (1998) observed that long-term sugarcane cultivation had low enzymes' activity than natural habitats and pasture. Although, it varied with management practices such as unfertilized/fertilized, burnt/green harvesting, trash removal/trash mulching and tillage level employed (Yadav et al., 2009; Stirling et al., 2010; Castioni et al., 2018).

Soil quality may be defined as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994a). Recently, it utilized by various researchers as a tool for assessing the suitability of management practices implies in a soil, and indices have been developed to grade and compare soil conditions over time and or between different locations (Nortcliff, 2002). Various methods such as soil management assessment framework (Masto et al., 2007), Fuzzy association rule (Yue-Ju et al., 2010), dynamic variability of soil quality methods (Larson & Pierce, 1994), nutrient index (Amara et al., 2017), soil health cards and test kit (Ditzler & Tugei, 2002) have been employed by researchers for soil quality assessment. Among these methods, soil quality index has been most extensively applied due to its quantitative flexibility and suitability for different types of soil and its coordination among the physical, chemical and biological attributes. Hence, soil quality indices are using at large scale to assess the impact of long-term management practices in particular crop production on the soil at a district; regional and provincial scale (Gong et al., 2015). Soil quality markers are vital component that incorporate soil function, and reflect environmental differences at large scale liable to influence soil quality. Though, lacking in consensus on which soil marker is useful for soil quality monitoring. For instance, Rahmanipour et al. (2014) had chosen soil erodibility, chromium and cobalt contents as quality indicators to assess soil quality, but were not found in other research. Liu et al. (2015) included some biological indicators like as acid phosphatase, and total counts of bacteria and AM fungi in minimum data set. However, soil pH, P_a , K_a , soil structure and SOC were considered as ideal soil quality indicators for the sugarcane production in Brazil (Cherubin et al., 2016). deFreitas et al. (2018) also reported that total sand, clay, micro-porosity, magnesium, calcium, soil pH, and organic matter considered as a sensitive soil quality indicators for sugarcane and native forest grown in northeastern São Paulo state, Brazil.

Certain soil environments have been shown to produce ultra-high sugarcane yields (i.e., >100 t ha^{-1}). Although, it is unaware to which extent soil physical, chemical and biological properties contribute to create yield differences between the area under ultra-high yields and average yields within the same soil order (Binggott et al., 2019). Although, the study was meager to assess causes of yield variation and long-term impact of sugarcane mono-cropping on nutrient index, microbial activity and soil quality across the cane producing zones of Uttar Pradesh. Hence, this study was undertaken to (i) assess the chemical and biological properties of soil on different cane producing zones of Uttar Pradesh, (ii) evaluate the effects of soil attributes on nutrient index, soil quality and sensitivity measurement differ among the high, average and lower yielding areas and (iii) suggest the doses of balance fertilizer for different cane producing zones of Uttar Pradesh.

2. MATERIALS AND METHODS

2.1. Study site, soil sampling and nutrient analysis

The current study was undertaken in key cane producing districts of Kushinagar (Eastern zone-EZ), Sitapur and Lakhimpur-kheri (Central zone-CZ), and Muzaffarnagar (Western zone-WZ) of Uttar Pradesh Province, India. The study site comprises in alluvial soil (Inceptisol) covered about 10.7×10^4 km² (Fig. 1) which spreads across the subtropical zone with dry winter and hot summer. The average annual temperature and precipitation ranged from 24.2 to 31.0°C and 736 to 1000 mm, respectively (Table 1). About 131, 198 and 122 soil samples were taken through AMS auger (0-20 cm depth) on standing sugarcane crops from eastern zone (EZ), central zone (CZ) and western zone (WZ) during November-December, 2017, respectively (Table 1). Random sampling was followed, in which five samples were collected from one location, and pooled for making composite sample. Immediately after collection, moist samples were divided in two parts. In which, one parts packed separately in sterilized polythene bags and stored in ice-packed box, and finally stored in -20°C at laboratory for microbial study. Simultaneously, 100 g fresh moist samples were taken separately in moisture box for the determination of moisture content. The remaining portion of soil sample was packed in separate polythene bags, brought to the laboratory, and processed for analyzing physical and chemical attributes. Soil pH, EC, N_a, P_a, K_a and S_a were analyzed as per protocol proposed by Jackson (1973). The SOC was determined by TOC analyzers (Multi N/C-2100S-Analytic-Jena), while as Zn, Cu, Fe and Mn were through atomic absorption spectrophotometer (Z2300, Hitachi Science and Technology) as per the protocol of USDA (1996).

The total culturable count of bacteria (TCB), fungi (TCF), actinomycetes (TCA) and *Azotobacter* (AZO) were estimated by using nutrient agar media having 50 mg L⁻¹ cyclohexamide (Parkinson et al., 1971), Rose Bengal chloramphenicol agar media containing 100 mg L⁻¹ chloramphenicol (Martin, 1950), Ken Knight and Ashbys mannitol (Subba Rao, 1977), respectively through serial dilution and plate counting techniques. The chloroform fumigation-extraction method (Vance et al., 1987) was applied for determination of microbial biomass carbon (MBC), whereas, microbial biomass nitrogen (MBN) was analyzed by chloroform-fumigation-incubation and distillation method (Jenkinson & Powlson, 1976). The basal soil respiration (BSR) was analyzed through barium chloride method as suggested by Anderson (1983). The dehydrogenase activity (DHA), fluorescein diacetate hydrolytic (FDA), urease and β-glucosidase (β-glu), acid (ACP) and alkaline phosphatase activities (ALP) were determined as per the methods of Alef & Nannipieri (1995).

2.2. Soil quality assessment

The method used to determine soil quality index following by four steps: (i) setting the goal, (ii) picking minimum data set (MDS) of indicators which depict the best soil function, (iii) scoring the MDS indicators, and (iv) the integration of an indicator score into a relative soil quality index (Masto et al., 2007). Cane productivity was considered as the goal due to variations in different cane producing zones. A total of 25 soil attributes were analyzed using principal component analysis (PCA) for selecting as representative MDS (Andrews et al., 2002). PCs that had high eigenvalues and variables with greater factor loading were pondered as the best delineated attributes. Hence, PCs with eigenvalues >1 and those illustrated at least 5% variations in the data were examined (Bregda et al., 2000). The factor loading of each variable in a particular PC represents the contribution of that variant to the composition of the PC. Highly weighted variable were categories as per the absolute values existed within 10% of the highest factor loading. Correlation coefficient was employed among the indicators for selecting ideal indicator if any variable was redundant as more than one variable was retained within a single PC and hence, eliminated from the minimum data set (MDS). In terms of soil function, the indicators were put in order depending on whether a higher value was considered as 'good' or 'bad'. Indicators like N_a, P_a, K_a, S_a, Fe, Zn, ALP and BSR in the MDS were considered "good" and were scored as 'more is better'. However, Fe content was pondered "good" as existed in the optimum range, hence scored as 'optimum is better'. A value between 0 and 1 is used as a standard scoring function for transmission and normalized of each indicator (Fig. S1) which were calculated by using non-linear scoring function (NLSF): $NLSF(Y) = 1 / [1 + e^{-b(x-A)}]$.

where, 'x' is value of soil attributes, 'A' the baseline or value of soil property where score equal to 0.5 and 'b' is slope.

Once indicator transformed based on soil functions, the MDS attributes for each observation were weighted by applying the PCA outcome. Each PC incites a certain amount (%) of the variation in the total data set. This percentage divided by the total percentage of variance explained by all PCs with eigenvectors >1, given the weighted factor for variants selected under a given PC. Then the weighted MDS variables scores were summed up for each observation using the following equation as suggested by Li et al. (2013): $SQI = \sum_{i=1}^n W_i \times S_i$

Where, 'W_i' is denoting weighing value of each indicators; 'S_i' is the indicator score; 'n' is the number of indicators in the MDS.

The SQ indexing methods were also measured by employing sensitivity analysis as suggested by Masto et al. (2008): Sensitivity (?) = $SQI_{(max)} / SQI_{(min)}$, where $SQI_{(max)}$ and $SQI_{(min)}$ are the maximum and minimum SQI observed under each cane producing zones of Uttar Pradesh. The higher value of sensitivity is more preferable and sensitive to perturbations and management practices.

2.3. Computation of mineral fertilizers

Since, wide variations in soil fertility across the cane producing zones, a workable targeted yield equation (TYE) for plant (FN = 7.37 T- 1.95 SN, $FP_2O_5 = 0.96 T - 2.21 SP$ and $FK_2O = 3.36 T - 0.83 SK$) and ratoon crop (FN = 5.91 T-1.83 SN, $FP_2O_5 = 0.64 T - 1.85 SP$ and $FK_2O = 2.33 T - 0.60 SK$) were used for balance fertilization in different cane producing zones by employing initial soil test value and defined targeted cane yield. A wonder sugarcane variety (Co 0238) which covered larger area (alluvial soil) in Uttar Pradesh was used for developing TYE during 2016-17 and 2017-18 by considering nutrient required to achieve per Mg cane yield, utilization efficiencies of nutrients available in soil and those applied through inorganic fertilizers were considered for developing TYE (Ramamoorthy & Velayutham 1971).

where, FN, FP_2O_5 and FK_2O are mineral fertilizers N, P_2O_5 and K_2O (kg ha⁻¹); SN, SP and SK are initial soil test values estimated before planting. To make symmetry, P_2O_5 and K_2O were converted into P and K by applying factor 2.29 and 1.20, respectively. T-targeted cane yield (Mg ha⁻¹). N, P_2O_5 and K_2O fertilizers were calculated on the basis of above equations for balance fertilization.

2.4. Statistical analysis

The SPSS16.0 (2001) software was used for descriptive statistical and correlation analysis. Pearson product moment correlation test was applied to assess the relationship among the soil variables. The sampling adequacy of individual and set variables were computed by using Kaiser-Meyer-Olkin test (>0.5) and Bartlett's test of sphericity ($P < 0.05$). The PCA was computed to derive the most identical soil indicators. To assess the long-term sugarcane monocropping impact, two approaches were employed. First, the percentage alter in the individual soil fertility parameters under different cane producing zones of Uttar Pradesh to assess whether soil fertility parameters were declines or improve. Second, Nutrient Index (NI) was calculated using parameters following the Ramamurthy & Bajaj (1969) approach. A Nutrient Index is an estimate of the % distribution of soil samples across categories: low, medium and high classes of nutrient status as per the soil test value interpretation (Amara et al., 2017) by using: Nutrient Index (NI) = $[(N_L \times 1) + (N_M \times 2) + (N_H \times 3)] / N_T$

where, 'N_L', 'N_M' and 'N_H' typify the number of samples falling in the low, medium and high class of nutrient status, respectively, and 'N_T' is the total number of samples analyzed across the cane producing zones of Uttar Pradesh. The NI levels were computed according to low (<1.67), medium (1.67-2.33) and high (>2.33) category. Maps showing geographical locations of the soil sampling site were created through Google map.

3. RESULT

3.1. Soil characteristics of different sugarcane zones

Sampling adequacy of 131, 198 and 122 soil samples collected from different cane producing zones of Uttar Pradesh were measured using Kaiser-Meyer-Olkin and Bartlett's test to assess the goodness of its analysis. The KMO value of EZ, CZ and WZ were greater than $p > 0.50$ evinced that the sampling was adequate (Table S1). Moisture content was the most crucial factor, ranged between 11.6 to 29.8% across the cane producing zones of Uttar Pradesh. The highest moisture content was retained in EZ soils followed by WZ and CZ. Value of soil pH varied from 6.12-8.80, being the highest in EZ followed by CZ and WZ, while EC value existed in normal range across the cane growing zones. Although, no definite trends were observed in SOC, N_a , P_a , K_a and S_a , but were ranged between 2.0-7.90 g kg⁻¹, 100.3-290.9 kg ha⁻¹, 3.35-45.3 kg ha⁻¹ and 2.48-28.1 mg kg⁻¹, respectively. The highest mean values of N_a , P_a and K_a in CZ, while as SOC and S_a were in EZ and WZ soils, respectively. Reversely, EZ soils contained highest values of Zn, Cu, Fe and Mn than CZ and WZ. The lowest value of Zn, Cu, Fe and Mn were recorded in WZ soils (Table 2).

The MBC, MBN and BSR were ranged between 68.4-498.7 µg C g⁻¹, 0.60– 4.17 m g NH₃-N kg⁻¹ d⁻¹ and 7.06-42.0 mg CO₂-Cg⁻¹d⁻¹ across the cane producing zones of Uttar Pradesh (Table 3). MBC, MBN and BSR were recorded maximum in WZ, which was 49.3 and 72.9%, 74.6 and 32.0% and 14.5 and 22.9% more than EZ and CZ soils, respectively. Similarly, the highest mean value of TCB, TCA and AZO were counted in WZ soils, but TCF noted maximum in EZ that was 3.48 and 83.8% greater than CZ and WZ, respectively. Reversely, FDA, β-glucosidase and urease activities were highest in CZ soils, and the lowest in EZ, while DHA was greater in EZ (Table 3). ACP and ALP were highest in WZ followed by CZ and EZ.

3.2. Nutrient index of different sugarcane zones

The NI ranking was used to assess the long-term sugarcane mono-cropping impact on nutrient pattern changes (Table 4). The NI of SOC altered from medium to low category (<1.67) in CZ and WZ, but EZ maintained at medium level (1.69). Lower NI (<1.67) of N_a was recorded entire the cane producing zones under the study, being the highest was in CZ (1.04) than that of EZ and WZ (1.00). NI of P_a and K_a was falls under medium category (1.67-2.33) in CZ and WZ, whereas lower level was existed in EZ. The medium NI category of S_a was maintained only in WZ but EZ (1.51) and CZ (1.38) showed <1.67. The NI of Zn was recorded in medium level which ranged between 1.67-2.33 in EZ and CZ, whereas WZ soils had lower NI levels of Zn (1.66). The NI level of Cu, Fe and Mn were highest (>2.33) across the cane producing zones of Uttar Pradesh, except NI of Fe was maintained at medium level in WZ. Overall, the higher mean NI value was observed in CZ (2.19) followed by EZ (1.98) and WZ (1.97).

3.3. Soil quality

For productivity goal, a total of 25 soil attributes of 131, 198 and 122 soil samples were collected from EZ, CZ and WZ were analyzed using PCA. Seven PCs from each EZ and CZ were pondered, while eight PCs were identified in WZ that showed 74.9, 68.3 and 69.3% of the cumulative variation, respectively. Variables which consisted high factor loading, eigenvalue >1 and explained at least 5% of the variation from each PC in EZ, CZ and WZ were mull as best representative attributes. The variability explained under each PC in EZ, CZ and WZ were varied (Tables 5). In EZ, N_a , K_a , Fe, SOC, P_a , S_a and AZO were considered as best representative under MDS from PC1, PC2, PC3, PC4, PC5, PC6 and PC7 due to high factor loading, respectively. In CZ, N_a , AZO, ALP, SOC, Fe, S_a and BSR were highly weighted attributes in PC1, PC2, PC3, PC4, PC5, PC6 and PC7, respectively. In WZ, N_a , SOC, AZO, K_a , ALP, S_a , BSR and Zn had high factor loading value in PC1, PC2, PC3, PC4, PC5, PC6, PC7 and PC8, respectively, hence retained as the final MDS for indexing procedure of SQI. After completing the MDS process, the shape of the expected response i.e., "more is better" soil function was decided to all the variables retained in EZ, CZ and WZ, except for Fe content which was adjudged as "optimum is better" soil function (Table 6). The thresholds values were allotted taking into account the site specific characteristics and management goal. Weights were assigned to the MDS indicator using the PCA outcomes (Table 6) which were equal to the percentage of total variance explained by the PC. The single weighted variables were hold in each PC, hence, the full weight equal of each PC was entrusted to each variable. Thus, each of the MDS parameters was changed to a value between 0 and 1. Soil quality index was computed by sum up of the entire weighted variable retained under MDS as follows:

SQI for eastern zone (EZ)

$$[0.237S_{Na} + 0.135S_{Ka} + 0.107S_{Fe} + 0.829S_{SOC} + 0.0722S_{Pa} + 0.0632S_{Sa} + 0.0513S_{AZO}]/0.75$$

$$SQI = 0.316S_{Na} + 0.180S_{Ka} + 0.143S_{Ka} + 0.111S_{SOC} + 0.0963S_{Pa} + 0.0844S_{Sa} + 0.0684S_{AZO}$$

SQI for central zone (CZ)

$$SQI = [0.212S_{Na} + 0.127S_{AZO} + 0.0936S_{ALP} + 0.0724S_{SOC} + 0.0639S_{Fe} + 0.0628S_{Sa} + 0.0508S_{BSR}] / 0.68$$

$$SQI = 0.312S_{Na} + 0.187S_{AZO} + 0.138S_{ALP} + 0.106S_{SOC} + 0.0940S_{Fe} + 0.0923S_{Sa} + 0.0747S_{BSR}$$

SQI for western zone (WZ)

$$SQI = [0.194S_{Na} + 0.108S_{SOC} + 0.0858S_{AZO} + 0.0736S_{Ka} + 0.0651S_{ALP} + 0.0581S_{Sa} + 0.0568S_{BSR} + 0.0511S_{Zn}] / 0.69$$

$$SQI = 0.281S_{Na} + 0.157S_{SOC} + 0.1248S_{AZO} + 0.107S_{Ka} + 0.0904S_{ALP} + 0.0840S_{Sa} + 0.0823S_{BSR} + 0.0741S_{Zn}$$

The SQI varied from 0.469 to 0.972 across the cane producing zones of Uttar Pradesh with mean values ranged from 0.708 to 0.795. The SQI followed in the descending order of CZ (0.795) > WZ (0.785) > EZ (0.708) soils with coefficient variations of 11.5, 6.83 and 11.2, respectively. The contribution among the MDS retained in EZ, CZ and WZ towards the soil quality development fluctuated, but N_a showed closely comparable contribution across the cane producing zones of Uttar Pradesh (Table 7). The sensitivity index was lowest in CZ (1.42) followed by WZ (1.81) and EZ (1.94).

3.4. Recommendation of balanced mineral fertilizers for different cane producing zones

The doses of mineral fertilizers for achieving 100 Mg cane yield ha^{-1} varied in different cane producing zones of Uttar Pradesh (Table 8). Based on TYE, the greater nutrient will be required for plant crop than ratoon compared to recommended dose of mineral fertilizers (RDF) across the cane producing zones. The highest N fertilizers required in WZ soils followed by EZ and CZ, while EZ soils required greater amount of P and K followed by WZ and CZ for both plant and ratoon crops. Nitrogen doses varied from 211-541, 170-344 and 260-474 kg N ha^{-1} with mean values of 348, 261 and 386 kg N ha^{-1} for plant crop, whereas 98-407, 59-222 and 144-344 kg N ha^{-1} with mean value of 226, 144 and 262 kg N ha^{-1} for ratoon crop in EZ, CZ and WZ, respectively. Phosphorus doses ranged from 6-89, -4-70 and 23-88 with mean value of 73, 33 and 55 kg P_2O_5 ha^{-1} for plant crop, whereas slight lower P doses will be require for ratoon crop which ranged from -12-58, -20-42 and 3-58 kg P_2O_5 ha^{-1} with mean value of 45, 11 and 29 kg P_2O_5 ha^{-1} in EZ, CZ and WZ, respectively. For plant crop, the doses of K varied from 98-302, 83-241 and 62-277 kg K_2O ha^{-1} with mean value of 262, 152 and 211 kg K_2O ha^{-1} , whereas 61-209, 50-164 and 35-191 kg K_2O ha^{-1} with mean value of 180, 100 and 142 kg K_2O ha^{-1} required for ratoon crop in different cane producing zones of Uttar Pradesh, respectively.

4. DISCUSSION

4.1. Physical and chemical properties of soils

Sugarcane mono-sequencing over the years degraded agro-ecosystem due to alteration of physical, chemical and biological properties of soil, and destroy self-adjustment capability of the ecosystem (Lin et al., 2012). Magarey (1996); Pankhurst et al., (2003) and Lin et al. (2012) revealed that several factors like as imbalance fertilization and excessive use of agrochemicals, tillage, mechanical harvesting and haul-out with heavy machinery are accountable for the degrading physical, chemical and biological attributes of soil under long-term sugarcane monoculture. The MC, soil pH, SOC, and micro-nutrients (Zn, Cu, Fe and Mn) were higher in EZ soils than CZ and WZ due to low-lying areas which hold more moisture content. Quietly higher soil pH in EZ could be related to accumulate more basic cations in upper surface of soil (Jenny, 1941). The SOC was increased by 14.1 and 11.8% in EZ soils than CZ and WZ, respectively due to more organic matter added through newly developed roots in low lying areas. Hidaka et al. (2007) also suggested that newly developed cane roots shared more in dry matter accumulation under flooding condition. Reversely,

decreased SOC in WZ and CZ soils than EZ was associated with excess management practices followed in soil preparation (chiseling, plowing and harrowing) resulting exposed soil micro-aggregates favours C mineralization, and increasing CO₂ emissions (Moscatelli et al., 2007). Naranjo et al. (2006) supported our results as 17% decline in total soil carbon over the 30 years of sugarcane monoculture compared to natural land uses (Naranjo et al., 2006).

The low N_a, P_a, K_a and S_a were in EZ soil might be due to lower doses of mineral fertilizers were applied even though recommended dose of mineral fertilizers (150, 60 and 60 kg N, P₂O₅ and K₂O ha⁻¹). It mismatches between nutrient applied and removal (205, 53 and 280 kg N, P and K for the production of 100 Mg cane yield ha⁻¹) over the decades caused nutrient imbalances (Shukla et al., 2017). Moreover, low lying area led to decrease N_a through leaching and denitrification. Similarly, P_a also decreased in EZ soil through surface overflow and greater soil pH. Hart, Quin, & Nguyen, (2004) reported P loss via runoff, which ranged between 0.7 and 42% of the fertilizer applied. Hence, low P_a in EZ soil related to higher soil pH and moisture content as significant negative correlation existed among them (Table 3S). The lowest S_a in EZ due to gradual removal from the soil as leaching, overflow and through plant removal, but it could not applied as mineral fertilizers regularly (Shukla & Lal, 2004). The low-lying areas that waterlogged during monsoon season caused favorable condition to reduce Cu⁺, Fe²⁺ and Mn⁺ resulting to increase its availability in EZ soils. Contrary to that, decrease Zn, Cu, Fe and Mn availability in WZ soil due to greater redox potential liable to converted Cu⁺ to Cu²⁺, Fe²⁺ to Fe³⁺ and Mn²⁺ to Mn⁴⁺ (Pavanadasivam & Axley, 1980). Further, harvesting more cane yield in WZ zone thereby reduced its availability due to its greater mining through crop removal.

4.2. Microbial and enzymatic activity

Microbial counts (TCB, TCA and AZO), MBC, MBN and BSR were highest in WZ soil could be related to producing greater root biomass and its exudates thereby producing higher cane yield as 25% extra N fertilizers applied over the recommended dose than CZ and EZ due to low initial N status (<280 kg N ha⁻¹). As a result, microbial counts accelerated their growth by enhancing nutrient availability which used as carbon substrate (Meena et al., 2014; Shukla et al., 2020). The greater microbial counts, root biomass and its exudates liable to enhanced MBC and MBN as are mull to the living part of organic matter, and augmenting BSR by accelerating microbial residues decomposition process (Vinh-Freitas et al., 2017). Though, the excess N fertilization had negative correlation with microbial activity, but lower N_a (<280 kg N ha⁻¹) across the cane producing zones of Uttar Pradesh (98.2% soil samples) had positive effects on microbial growth. The neutral soil pH and greater availability of macro and micro-nutrients favorable for fungal counts resulted more in CZ soils. Our results supported by Graham & Haynes (2005) and Vieira-Megda et al. (2015) who suggested that moderate and high N fertilization induced microbial population in sugarcane thereby increased MBC and MBN. The lowest MBC, MBN and BSR in EZ soils coupled with N, P, K and S deficiency affected synthesis of microbial biomass. In addition, higher micronutrient caused adverse effect on microbial accounts as our results also showed significant negative correlations to these nutrients with TCB, TCA and AZO (Table S3).

Soil enzymes are integral parts of soil fertility as it played crucial role in nutrient recycling, decomposition and nutrient fixation. The FDA, β -glucosidase and urease activities were more in CZ soils could be due to lower pH value, and greater macronutrient and microbial counts led to enhance their activity as these factor played vital role in microbial and enzyme activation. Also, N is a crucial edaphic factor essentially required in large quantity for achieving higher cane productivity, and microbial growth, since it used as substrate and energy source during trash decomposition due to high C: N ratio (108:1). Hence, FDA, β -glucosidase and urease had significant positive correlation with soil pH and N_a (Table 3S). Reversely, lowest enzyme activities in EZ soils associated to higher soil pH, moisture content and lower microbial activities thereby inhibited synthesis and secretion of these enzymes (Zhang et al., 2014). The change in osmotic potential and specific ion toxicities (Rietz & Haynes, 2003) linked to lower urease activity in EZ soils. However, higher moisture content augmented DHA as active dehydrogenases utilized both O₂ and other compounds as terminal electron acceptors, although, anaerobic microorganisms liable to produce most of the dehydrogenases (Brzezińska et

al., 2001). In addition, DHA showed metabolic ability of soil proportional to SOC, as a result significant positive relation was existed between SOC and DHA. Association between DHA and total microbial activity is not always evident notably in complex soil system, wherein microbial counts actively involved in the degradation of various organic compounds that are highly diverse (Salazar et al., 2011). Hence, a significant negative correlation of DHA with microbial counts was found in our study (Table S3). ACP and ALP was highest in WZ soil could be connected to higher counts of bacteria, and MBC and FDA (Table 3) thereby induces the synthesis and secretion of phosphomonoesterases enzymes. Our results clearly indicated that ACP had significant positive correlation with TCB, MBC and FDA (Table 3S).

4.3. Soil quality

The causes for low or higher cane yield across the cane producing zones of Uttar Pradesh varied, but changes in nutrient index, microbial activity and soil quality might be the main reasons (Kang et al., 2005). About 25 physical, chemical and biological soil attributes were used to set up a minimum data set (MDS) based on higher factor loading value sort out by using PCA. These attributes have been used by several researchers (Bhaduri & Purakayastha, 2014; Masto et al., 2007; Qi et al., 2009) for selecting potential indicators to assess soil quality as each could affect crop productivity. Among them, N_a , SOC, AZO and S_a were emerges as common quality indicators across the cane producing zones, but their contribution towards SQI development were fluctuated which depend upon the management factors, site specific characters and ecological factors. N_a is one of the most crucial factors for achieving sustainable cane productivity, but it is most limiting nutrient across the cane producing zones as 98.2% soil samples showed low categories ($<280 \text{ kg N ha}^{-1}$) (Brady & Well, 2000). N_a contributes 13.5 and 4.67% more in CZ soils than WZ and EZ towards SQI development linked to greater N_a , P_a and K_a , AZO counts, urease activity and normal pH range. Our results are in line with the results of Landell et al. (2003) and Otto et al. (2017) as significant strong positive correlation of N_a with P_a , K_a , AZO, β -glucosidase and urease activity (Table 3S). SOC was retained as quality indicators across the cane producing zones due to its greater factor loading values than other soil variables. In addition, SOC is the most extensively used as a soil quality indicator owing to its multifunction role including filtering and buffering, physical stability and support, nutrient recycling and as primary food source for microorganisms (Carter, 2002; Gregorich et al., 1994). The lowest SOC contribution in WZ soils due to 57.4% soil samples falls in low category than EZ (32.8%) and CZ (56.6%). The contribution of *Azotobacter* counts were 5.01, 14.1 and 9.11% towards the SQI development in EZ, CZ and WZ, respectively. Fluctuations in their contribution related to changes in edaphic variables that alter by following management practices, and ecological condition. The lowest *Azotobacter* contribution in EZ soil linked to low O_2 availability in low-lying areas as highly aerobic in nature and very sensitive at low O_2 levels, hence affected their growth and activity. Esmailpour et al. (2013) suggest that *Azotobacter* is free living- N_2 fixer that have the ability to fix $20 \text{ kg N ha}^{-1} \text{ per y}^{-1}$ or per season thereby synthesis their cell protein notably in N-deficient soil, which mineralized after the death of their cells (Wani et al., 2016). Fe was pondered as soil quality indicators in EZ and CZ cane producing zones which contributed 8.70 and 6.50% towards SQI development, respectively. Because, EZ soils prone to water-logging resulting decreasing redox potential resulting excess electron changes from Fe^{3+} and Mn^{4+} to Fe^{2+} and Mn^{2+} (Singh & Setter, 2017). K_a was also retained as highly weighted factor in EZ and WZ, but contributed more in EZ soils (11.6%) than WZ (6.98%) in SQI development owing to 87.8 and 28.7% soil samples falls under low K category ($<120 \text{ kg ha}^{-1}$), respectively. Imbalance fertilization and excess K removal from soil through surface runoff, leaching and plants acquisition are the causes of more K-deficiency in EZ than WZ soil. However, it could not surface as quality indicators in CZ soils due to more K availability (Alemayehu, 2010; Shukla et al., 2009; Kingston, 2014). Available P was retained in EZ, whereas ALP were chosen in CZ and WZ as quality marker in MDS, and their share were 8.28, 10.7 and 6.66% towards SQI development, respectively. Since, P_a has been accepted as the limiting factor in EZ soil due to 74.8% soil samples showed its deficiency ($<10 \text{ kg P ha}^{-1}$), but current P_a levels in CZ (27.8 kg ha^{-1}) and WZ ($18.7 \text{ kg P ha}^{-1}$) are not in the deficiency range. Hence, greater P is required for cane growth notably in wherein excess aerial root occurs for their survival under water logging conditions (Tarafdar & Claassen, 1988). Landon (1984) suggested that sugarcane is a moderate P demanding crops, but its deficiency occurs only if Olsen P levels $<7 \text{ ppm}$, whereas for K, the critical value ranges from 78-125 ppm (Filho, 1985). The values obtained

under this study were above the critical levels both in CZ and WZ due to trash mulching practices are common in cane production system that return P and K back to soil, and thus mitigated exhaustion of these nutrients below critical levels. However, P and K levels below the critical levels in EZ soils might be excess P and K losses through surface-runoff in EZ soils (Khan and Qasim, 2008). Similarly, ALP retained as weighted variables in CZ and WZ despite having medium to high P levels as it played a vital role in enhancing P_a by secreting phosphomonoesterases enzymes by enhancing microbial activity. Nakas et al. (1987) reported that soil bacteria, fungi and fauna responsible for secreting extracellular phosphatases due to their large combined biomass, high metabolic activity and short lifecycles. Variations of ALP towards SQI developments are related to management practices, changes in hydrothermal conditions, microbial activity and nutrient availability in soil. Olander & Vitousek (2000) and Deng et al. (2017) attributed that high N fertilization accelerated phosphatase activity and P mobilization, since N is used as an essential nutrient for the synthesis of soil enzymes. S_a was chosen as the representative of stability function for the MDS in each EZ, CZ and WZ as 43.3, 58.8 and 27.9% soil samples falls in low categories ($<10 \text{ mg kg}^{-1}$ soil), respectively. The S_a contribution were 5.01, 5.67 and 7.06% towards the SQI in EZ, CZ and WZ soil, respectively indicated their importance in each cane producing zones. Contribution of S_a was greater in WZ over CZ and EZ soil directly linked to more S availability in WZ soil. Soil available Zn was retained as MDS in WZ due to 47.5% soil samples falls under low Zn categories ($<0.6 \text{ mg kg}^{-1}$) along with higher factor loading value. Casarin et al. (2001) report that in low fertile soil, which are exploited for many years without Zn fertilization, the occurrence of its deficiency becomes more aggravated as sugarcane frequently exhibits “hidden hunger” a situation in which the symptoms do not appear visually (Orlando Filho et al., 2001). Thus, zinc fertilization mainly in Zn-deficient sugarcane grown soils might be important to maintain adequate Zn level for affording higher internodes, top growth, stalk length and cane yields (Alloway, 2008). BSR is the most used attributes as biological indicators of soil, since, it produces through decomposition of microbial biomass which is the most active living part of the SOM formed mainly by bacteria, fungi and actinomycetes (Kaschuk et al., 2009). Hence, BSR retained as soil quality indicators in CZ and WZ soils due to higher factor loading value in respected PCs. BSR contributed 5.11 and 6.42% towards the SQI development in CZ and WZ soils, respectively. The WZ soils had more BSR thereby producing more biomass, MBC and microbial activity (Galdos et al., 2009).

4.4. Fertilizer recommendations

Sugarcane monocropping over the decades deteriorated nutrient index and soil quality due to causing multi-nutrient deficiency occurs by imbalance fertilization. Hence, targeted yield equations (TYE) ensure balanced fertilization as doses of N, P and K were applied on the basis of initial soil test value under the concept “Fertilizing the soil Vs Fertilizing the crop” proposed by Ramamurthy and Bajaj (1969). WZ soils needed greater amount of N than EZ and CZ for both plant and ratoon crop due to excess N mining from the decades resulted depleted soil N_a might be due to mismatch between applied and removal of nitrogen (Shukla et al., 2009; Shukla et al., 2017). The greater P and K fertilizers required in plant and ratoon crops grown in EZ soils linked to lower P_a and K_a status caused through surface runoff (Zhao et al., 1988; Li et al., 2007a). However, lower or even negative P_2O_5 doses required in CZ and WZ soil due to high P_a status occurs by applying excess P fertilizers. The lower K status in EZ soils (87.8% soil sample deficient) liable to required more K_2O for achieving 100 Mg cane yield ha^{-1} as it removed about 280 kg K ha^{-1} against applied 60 kg $K_2O \text{ ha}^{-1}$.

5. CONCLUSION

Sugarcane mono-cropping degraded SOC, N_a , K_a , S_a and Zn across the cane producing zones, but enormity of soil degradation was more in EZ soils due to low-lying area induces multi-nutrient deficiency, and Fe and Mn content. As a result, lowest soil quality index and highest sensitivity index was in EZ than WZ and CZ. Reversely, CZ soils observed higher nutrient index and soil quality due to greater N_a , P_a and K_a , TCF, FDA, β -glucosidase, and urease activities. N_a , SOC, AZO and S_a were the common limiting factors across the cane producing zones but, their contributions fluctuated towards SQI development owing to variation in edaphic factor under different cane producing zones. Since, wide variations existed between recommended

doses of mineral fertilizers and targeted yield equations based fertilization. Hence, it will be better to cane growers, industry people and policy makers to advise balance nutrient management based on targeted yield equations for achieving higher sugarcane productivity, and improving nutrient index and soil quality. Over all, sugarcane mono-cropping over the decades degraded nutrient index, microbial activity, and soil quality index adversely due to imbalance fertilization. This may further increased if using improper management practices notably in low-lying areas.

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