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Soil Fertility Appraisal for Hot Arid Regions of Thar Desert, Rajasthan, India

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Abstract: Soil fertility assessment for hot arid regions of Thar Desert in the Indian state of Rajasthan was carried out and on the basis of fertility ratings the soils were classified as low, medium and high. In the present assessment a systematic set of 5655 geo-referenced soil samples across the land use systems viz. rainfed croplands, irrigated croplands and rangelands covering 12 districts of hot arid Rajasthan were collected. The soil samples were analyzed for pH, EC, soil organic carbon (SOC), available P, available K, available Fe, Zn Cu, and Mn. Results of the soil analysis revealed that SOC is low throughout the region, while available P was low to medium, but generally medium to high in available K. Among the micronutrients Cu and Mn were adequately supplied in most areas, but Zn and Fe were inadequate in large parts. As a whole, SOC, P, Fe and Zn are the major nutrients constraint in hot arid regions of Rajasthan that warrants the attention for development and implementation of soil test based nutrient management plans and application of corresponding nutrients. The Nutrient Index Values (NIV) was low for available P (1.61) and medium for available K (2.14). Amongst the micronutrients NIV for DTPA Zn (1.51) was low, marginal for Fe (1.67), adequate for Cu (2.14) and high for Mn (2.47). The wide spread deficiencies of P, Fe and Zn were most revealing; their deficiencies varies with districts and land use pattern. Irrigated croplands were better endowed than other land uses in respect of SOC, P, Zn and Cu; rangelands in respect of K and Fe, and rainfed croplands in respect of Mn.

Key words: Hot arid Rajasthan, major nutrients, micro-nutrients, deficiency, nutrient index value.

Soil fertility management assumes great significance and constitute one of the important key inputs for achieving high productivity. Soil fertility status information helps to relate nutrient requirement with crop demand and thus conserve the resources. By characterization of the soils one can clearly understand the inherent capacity of soils for crop production as well as problems that arises in successful management of such soils for achieving higher crop production. Soils of India exhibits widespread deficiencies of nutrients like N, P, K, S, Zn, Fe and B (Muralidharudu *et al.*, 2011; Shukla and Tiwari, 2014). The pace of soil fertility depletion due to excessive nutrient mining coupled with continuous neglect of the plant nutrients replenishment have been reported with increasing frequencies in intensive agricultural production system. In the hot arid Rajasthan, the soils are usually sandy, deficient in several major and micro-nutrients, and there is large spatial variability in the plant available nutrients content of the soils (Gupta *et al.*, 2000; Praveen-Kumar *et al.*, 2009; Kumar *et al.*, 2019). Further, the soils of the region do not receive adequate nutrient replenishment through fertilizers and organic manures. Consequently, productivity of the soils in arid region is also relatively low. Ever since the production and productivity of crops in hot arid regions of India have become lucrative from commercial point of view, the pressure on the region's soil resources and the concern for fertility status of the soil have increased. Since the 1970s, however, demand from these soils started to increase manifold as Green Revolution and innovations in agricultural practices triggered large-scale expansion of irrigated cropping, especially after groundwater exploration encouraged the spread of energized wells. These developments turned many erstwhile rain-fed croplands into double-cropped lands, and also expanded the irrigated croplands into open rangelands and otherwise non-agricultural lands with meagre input of major and micronutrients. Such indiscriminate use of fertilizer nutrients not only aggravated fertility depletion but also

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caused multi nutrient deficiencies (Kumar *et al.,* 2011 and 2019). Limited studies are available so far on the soil nutrient status in the drylands in general, and hot arid regions in particular. Here the dominantly sandy soils mostly suffer from several plant-available nutrient deficiencies. Such information on available soil nutrients shall not only serve the purpose of benchmarking but shall also enable grouping of the soils into homogenous units for better nutrient management. This may also help in avoidance of excessive and imbalanced application of fertilizers. Considering the need for such data in proper assessment of the soil fertility status the study was undertaken with special reference to hot arid Rajasthan.

Materials and Methods

Study area

Hot arid Rajasthan situated in north western parts of India located between 24º19'N-30º11'N and 69º28'E-76º05' E covers an area of 20.8 mha area which includes 12 districts namely Jaisalmer, Barmer, Bikaner, Jodhpur, Jalore, Pali, Nagaur, Jhunjhunu, Sikar, Churu, Hanumangarh and Sri Gangangar. The soils of hot arid Rajasthan are predominantly sandy with low clay, silt and organic carbon and are poor in available nutrients. Because of aridic moisture regime and hyperthermic temperature regimes, weathering of minerals and pedogenesis are weak. The soils have been classified in orders Aridisols and Entisols covering respectively, 41.05 and 51.84% area (Dhir *et al.*, 1997). The major landforms in the region are the sand dunes, hills and colluvial plains, alluvial plains, saline depressions, riverbed and water bodies. Land use pattern in hot arid Rajasthan indicated that agriculture is the dominant land use which occupies 56.51% area of total geographical area (TGA), followed by area not available for cultivation excluding fallow (28.32% of TGA), current and long fallow (12.81% of TGA) and forest land (2.34% of TGA). About 61% of net irrigated area in the region is irrigated through wells and tube wells and 38% is irrigated through canals in north, western, north western and southern parts of the arid (Rajasthan Agricultural statistics, 2016-17). Low and erratic rainfall (100 mm to 450 mm, CV >50%), extreme temperature (-5.7 to 50.0°C), low relative humidity (30-80%) high wind velocity (9-13 kmph) and high evapotranspiration (1600-1800 mm) are the characteristic features of the region (Kar *et al.,* 2009).

Soil sampling and laboratory analysis

Soil samples (0-15 cm depth) were collected from 12 districts of hot arid Rajasthan from 5655 sites across the dominant land uses i.e. irrigated cropland, rainfed cropland and rangeland. Location of the sampling sites was recorded with the help of a hand-held Global Positioning System (GPS). In the laboratory, the samples were air-dried and sieved with a 2 mm screen and subjected to physical and chemical analyses following standard analytical procedures. The soil reaction (pH of 1:2, soil: water suspensions) was determined by pH meter (Jackson, 1973). Electrical conductivity (EC) of 1:2 soil:water extract was determined using conductivity bridge (Richards, 1954). Organic carbon was determined by rapid titration method (Walkley and Black, 1934). Available phosphorus was extracted with 0.5 M $NaHCO_3$ solution (8.5 pH) and phosphorus in the extract was estimated colorimetrically (Olsen *et al.*, 1954). Available potassium was determined by extraction of soil with neutral normal ammonium acetate (pH 7.0 in 1:5, soil: solution ratio) and was estimated with the help of flame photometer (Pratt, 1982). Available iron, manganese, zinc and copper in the soil were extracted with DTPA reagent (Lindsay and Norvell, 1978) and were determined with the help of Atomic Absorption Spectrophotometer (GBC-932A). To quantify the level of deficiency or sufficiency of soil nutrients (major and micro-nutrients), the analysed soil nutrient data were classified into levels of availability of 'low' to 'high', based on the classifications followed in most of the soil testing laboratories in India (Dwivedi, 2014; Singh, 2008). The limits used for the study are provided in Table 1 (a and b). The per cent sample categories for the nutrients were computed using following formula as given below.

$$\text{Per cent sample category} = \frac{\text{No. of L or M or H category}}{\text{Total number of samples}} \times 100$$

L = low, M = medium, H= high.

The nutrient index values (NIV) for available nutrients was calculated using the formula as suggested by Ramamoorthy and Bajaj (1969):

$$NIV = [(P_H*3) + (P_M*2) + (P_L*1)] /100$$

Table 1a. Criteria used for assessing sufficiency/deficiency of selected major nutrients in soils

Major nutrients	Low	Medium	High
OC (%)	0.01-0.50	0.51-0.75	>0.75
P (kg ha^{-1})	0.01-10.0	10.01-25.0	>25.00
K (kg ha^{-1})	<120.00	120.01-280.00	>280.00

Table 1b. Criteria used for assessing sufficiency/deficiency of selected available micro nutrients in soils

Micronutrients (mg kg^{-1})	Very low	Low	Marginal	Adequate	Moderately high	High
Fe	0.01-2.50	2.51-4.50	4.51-9.00	9.01-18.00	18.01-27.00	>27.00
Zn	0.01-0.30	0.31-0.60	0.61-1.20	1.21-1.80	1.81-2.40	>2.40
Cu	0.01-0.10	0.11-0.20	0.21-0.40	0.41-0.80	0.81-1.20	>1.20
Mn	0.01-1.00	1.01-2.00	2.01-4.00	4.01-8.00	8.01-16.00	>16.00

where, P_H, P_M, and P_L are the percentage of soil samples falling in high, medium and low nutrient status and are given weightage of 3, 2 and 1, respectively (Ramamoorthy and Bajaj, 1969). The nutrient index values are classified in to different categories viz. low (<1.66), medium (1.67 to 2.33) and high (>2.33). For available micronutrients, the ratings are very low (<1.33), low (1.33-1.66), marginal (1.66-2.00), adequate (2.00-2.33), high (2.33-2.66) and very high (>2.66). The hot arid Rajasthan was categorized into different fertility ratings based on per cent sample category and NIV values.

Results and Discussion

Physico-chemical characteristics of soils

The soils of the region being dominantly sandy, the sand content in the soils varies generally from 40% to 97%. The clay and silt contents vary from 2.0% to 35.8% and 1% to 33.4%, respectively. The higher amounts being recorded in the alluvial plains while the lower amounts were found in the sand dunes. The pH of the soils of entire hot arid region ranged from 7.10 to 10.00 with a mean value of 8.63 (Table 2) indicating that the soils are neutral to strongly alkaline. Since the groundwater for irrigation in the region is brackish to saline-alkaline, often with high residual sodium bicarbonate (RSC) content, continuous irrigation with such water may have accentuated the soil pH to some extent, as evidenced by the higher soil pH under irrigated condition, as compared to those under rainfed croplands and rangelands (Kar *et al.,* 2009). The electrical conductivity (EC) varies from 0.01 to 9.95 dS m^{-1} (Table 2). The wide variations in EC values could be due to use of poor quality water and inherent properties of soils as also reported by Dhir (1977), Gupta *et al.* (2000) and Kumar *et al.* (2019). Majority of agricultural lands are normal to slightly saline as per limits suggested by Muhr *et al.,* (1963). Similar results were also reported by Kumar *et al.* (2019) and by Shirgire *et al.* (2018) for hot arid regions of Rajasthan and Gujarat.

Available major nutrients

Soil organic carbon: The soil organic carbon (SOC) ranges from 0.01% to 0.84%, with a mean of 0.16% (Table 2). The organic carbon status was extremely low in Jaisalmer, Barmer, Bikaner, Churu and Nagaur districts where all the soil samples (100% soil samples) were low (Fig. 1) in organic carbon content (<0.50%). Overall, 97% of soil samples were under low status with an overall fertility rating of low primarily (Table 4) due to high temperature, low rainfall, scanty scrub vegetation, and sandy texture of the soils, which favour high oxidation (Kumar *et al.,* 2011 and 2019). Tillage operation during summer and very little addition of organic matter annually could also be the responsible factors. Earlier workers (Sahrawat, 2007; Singh *et al.,* 2007; Sharma *et al.,* 2006; Santra *et al.,* 2012; Kumar *et al.,* 2019) also reported low SOC content in soils of arid and semi-arid regions of India. The mean contents in the region are the lowest in the rainfed croplands, followed by the rangelands and irrigated croplands (Table 3). The large differences between the mean values in the districts are the results of large variability in the landscape condition in the region. The better status in rangelands over the rainfed croplands is due to slightly higher plant cover (especially the small shrubs) round the year in the former, which favor more leaf litter fall and its subsequent decomposition under natural condition (Singh *et al.,* 2007; Kumar *et al.,* 2017). The high SOC content in irrigated

Table 2. Range and mean of pH, EC and available major and micro nutrients in soils of hot arid Rajasthan

Name of District	Total samples	pH (1:2)	EC (dS m^{-1})	Organic carbon (%)	Available- P (kg ha^{-1})	Available-K (kg ha^{-1})	Fe	Zn	Cu	Mn
							(mg kg^{-1})			
Barmer	517	7.80-9.82 (8.75)	0.01-6.62 (0.15)	0.01-0.39 (0.093)	1.20-35.81 (8.30)	78.80-821.30 (208.60)	0.86-27.80 (3.46)	0.08-3.74 (0.49)	0.06-2.56 (0.38)	0.84-23.15 (6.70)
Bikaner	526	7.72-9.82 (8.80)	0.01-3.82 (0.15)	0.01-0.38 (0.087)	1.29-78.00 (10.93)	62.00-821.00 (170.31)	1.20-34.00 (4.47)	0.05-1.86 (0.40)	0.06-2.74 (0.48)	0.80-28.37 (4.58)
Churu	247	7.33-9.80 (8.44)	0.01-3.82 (0.28)	0.04-0.42 (0.130)	2.25-47.66 (10.08)	81.50-726.00 (204.48)	2.35-32.00 (7.43)	0.13-4.60 (0.84)	0.14-2.80 (0.88)	2.18-35.00 (11.68)
Sri Ganganagar	383	7.80-9.60 (8.56)	0.01-5.45 (0.34)	0.02-0.56 (0.192)	3.20-78.50 (15.10)	112.00-843.00 (362.77)	1.20-16.60 (5.04)	0.32-4.20 (1.35)	0.10-2.30 (0.67)	1.90-26.50 (9.00)
Hanumangarh	396	7.20-9.60 (8.41)	0.01-5.92 (0.47)	0.02-0.68 (0.184)	1.56-87.78 (14.89)	108.00-847.00 (349.00)	1.72-42.74 (9.08)	0.16-4.54 (1.23)	0.05-3.38 (0.67)	1.40-29.04 (8.96)
Jaisalmer	491	7.90-9.80 (8.78)	0.01-1.90 (0.19)	0.01-0.30 (0.077)	1.40-28.20 (6.55)	67.00-675.00 (215.00)	1.76-17.20 (6.98)	0.08-2.24 (0.50)	0.06-1.82 (0.43)	0.92-23.72 (8.13)
Jalore	676	7.40-9.87 (8.69)	0.01-5.40 (0.25)	0.015-0.706 (0.193)	2.27-92.60 (15.30)	61.87-855.00 (265.32)	1.58-24.50 (4.90)	0.08-3.84 (0.57)	0.06-3.24 (0.85)	1.30-42.52 (9.97)
Jhunjhunu	295	7.26-9.70 (8.48)	0.02-2.50 (0.19)	0.030-0.620 (0.161)	2.70-58.20 (14.80)	84.00-616.00 (171.16)	3.20-30.40 (7.78)	0.28-4.50 (0.96)	0.12-4.86 (1.05)	2.32-40.54 (12.12)
Jodhpur	561	7.63-9.97 (8.72)	0.05-9.95 (0.23)	0.030-0.660 (0.152)	3.20-67.50 (14.40)	84.37-846.00 (240.60)	2.14-28.90 (7.94)	0.090-4.24 (0.90)	0.06-2.44 (0.64)	1.68-32.30 (10.72)
Nagaur	494	7.50-9.80 (8.61)	0.01-2.20 (0.27)	0.02-0.43 (0.188)	2.69-85.03 (16.84)	67.50-790.00 (266.13)	0.86-40.80 (7.93)	0.11-3.88 (0.77)	0.08-2.57 (0.61)	2.80-45.90 (13.01)
Pali	563	7.10-10.00 (8.62)	0.01-9.66 (0.39)	0.01-0.74 (0.321)	2.24-96.64 (15.87)	113.00-974.00 (318.69)	0.84-26.32 (5.47)	0.10-5.20 (0.74)	0.04-3.24 (0.80)	0.70-45.33 (10.32)
Sikar	506	7.26-9.84 (8.48)	0.01-4.20 (0.27)	0.02-0.68 (0.144)	2.25-76.60 (13.72)	67.00-731.30 (197.94)	1.87-32.72 (7.86)	0.10-4.74 (0.89)	0.12-3.34 (0.82)	2.32-40.70 (10.65)
Arid Rajasthan	5655	7.10-10.00 (8.63)	0.01-9.95 (0.26)	0.01-0.84 (0.162)	1.19-96.64 13.36)	56.00-974.00 (250.60)	0.84-42.74 (6.42)	0.05-5.20 (0.76)	0.04-4.86 (0.66)	0.70-45.90 (9.44)

Values within parenthesis are mean values.

Table 3. Soil properties as influenced by land use pattern in hot arid Rajasthan

	Organic carbon (%)	Available-P (kg ha^{-1})	Available-K (kg ha^{-1})	Fe	Mn	Zn	Cu
				(mg kg^{-1})			
Rainfed croplands							
Range	0.01-0.62	1.19-42.56	62.00-847.00	0.86-37.62	0.75-42.60	0.05-5.20	0.06-4.80
Mean	0.150	11.18	237.40	6.07	9.50	0.70	0.63
SD	±0.10	±8.11	±129.28	±3.69	±5.49	±0.63	±0.42
Irrigated croplands							
Range	0.01-0.84	1.69-96.64	61.87-974.00	1.20-42.74	0.80-40.54	0.06-5.20	0.05-4.86
Mean	0.19	16.12	253.44	6.45	9.42	0.90	0.70
SD	±0.13	±15.24	±157.04	±4.46	±5.83	±0.76	±0.55
Rangelands							
Range	0.01-0.72	1.87-56.60	61.90-945.00	0.90-32.72	0.84-45.90	0.06-5.20	0.04-3.24
Mean	0.16	12.83	274.00	6.58	8.77	0.67	0.62
SD	±0.12	±13.39	±163.42	±3.99	±5.29	±0.64	±0.43

croplands is due to high crop cover and crop residue addition, as well as application of organic matter through external sources (e.g., FYM and compost) and good management practices (Kumar *et al.*, 2009; Singh *et al.*, 2009). The land in the alluvial plains of the Kantli River (Jhunjhunu district), Gaghar (Sri Ganganagar and Hanumangarh districts), Luni (Pali, Jalore, Barmer and Jodhpur) is also found to have a distinctly high content of SOC, which possibly relates to the spreading of clay and silt rich alluvium by these rivers.

Available Phosphorus: The available phosphorus in the soils shows wide variability (1.19-96.64 kg ha^{-1}), with mean value of 13.36 kg ha^{-1}. The mean values across the region suggests that in general the quantity is low to medium (Table 2). Overall the percent sample category revealed 55, 31 and 14% under low, medium and high category with low fertility rating with respect to NIV (Table 4). The situation broadly matches with the findings of Gupta *et al.* (2000). They reported that the mean content in different soils is <20 kg P_2O_5 ha^{-1}. The results also demonstrated that 85, 79, 67, 67, 54, 53 and 50% of samples were deficient in available phosphorus in Jaisalmer, Barmer, Churu, Bikaner, Jalore, Pali and Sikar districts, respectively (Fig. 2). While Hanumangarh, Jodhpur, Nagaur, Sri Ganganagar and Jhunjhunu districts have 41,

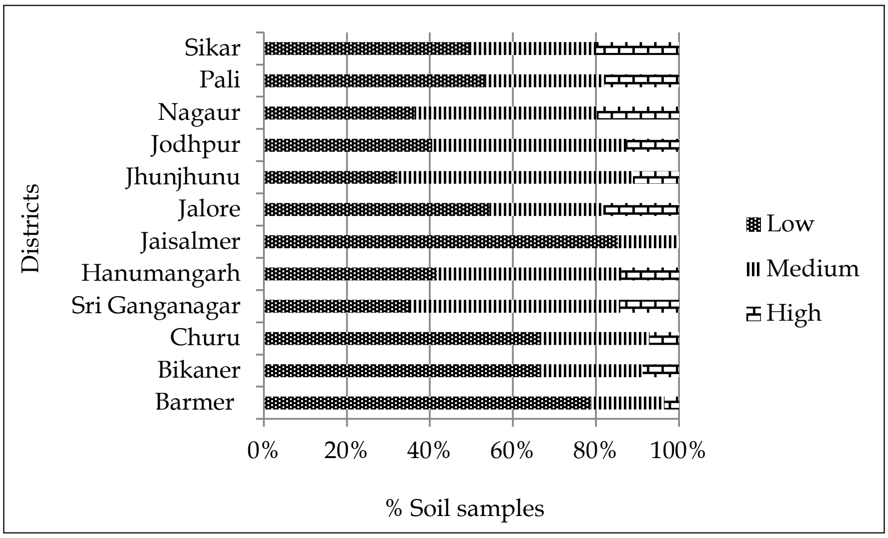

Fig. 1. Per cent of soil samples under low, medium and high categories for organic carbon in districts of arid Rajasthan.

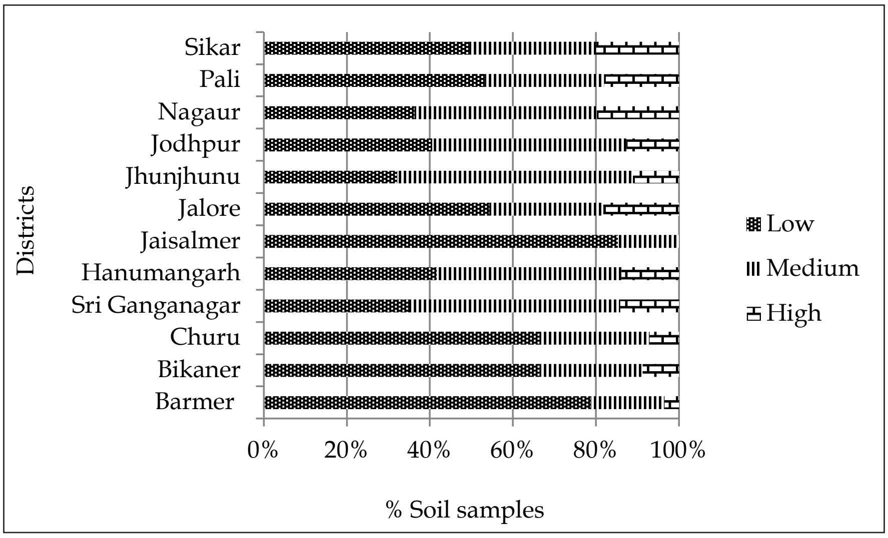

Fig. 2. Per cent of soil samples under low, medium and high categories for available phosphorus in districts of arid Rajasthan.

41, 36, 35 and 32% of total samples deficient in available P (Fig. 2). Spatially, the status is poorer in the dune-interdune areas, especially under the rainfed croplands and rangelands. In comparison situation is considerably better in alluvial soils under irrigated croplands, where the high values are especially obtained in the alluvial plains in Pali, Jodhpur, Jalore, Jhunjhunu, Sikar, Sri Ganganagar and Hanumagarh districts in isolated pockets (Table 3). This higher amount may be partly due to the inheritance from parent materials and also due to the effects of continuous application of phosphate fertilizers for the past 3-4 decades (Singh *et al.,* 2007; Singh *et al.,* 2013; Kumar *et al.,* 2018; Kumar *et al.,* 2019). These irrigated soils are cultivated in both rabi and kharif seasons, and receive recommended doses of fertilizers (urea and DAP) and organic manures. There are many examples globally of increase in available phosphorus under intensive agriculture (Kenney, 2002).

Available potassium: The available potassium (K) ranges from 56.00 to 974.00 kg ha^{-1} with mean values of 250.60 kg ha^{-1} (Table 2) and the per cent sample category under low, medium and high was 15, 55 and 30, with an overall medium fertility rating with respect to NIV (Table 4). District wise about 66, 55, 50, 37 and 36% of samples were high in available

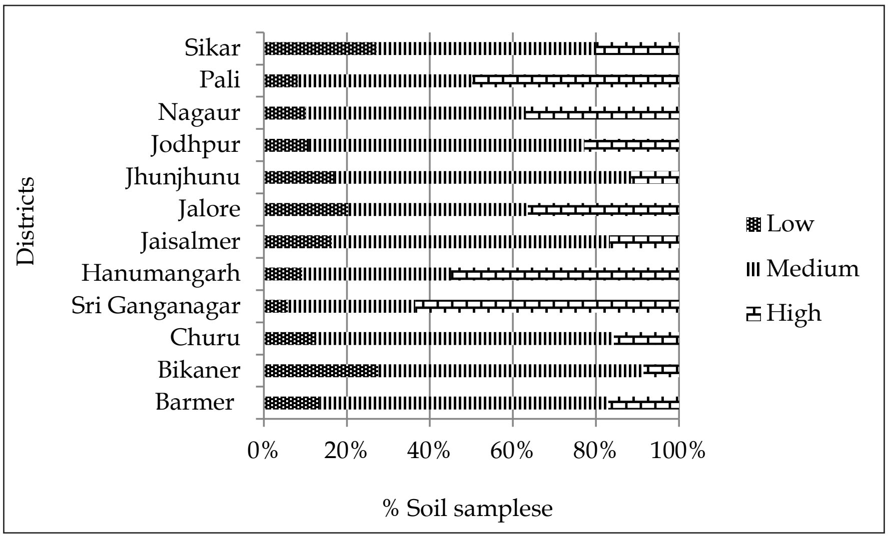

Fig. 3. Per cent of soil samples under low, medium and high categories for available potassium in districts of arid Rajasthan.

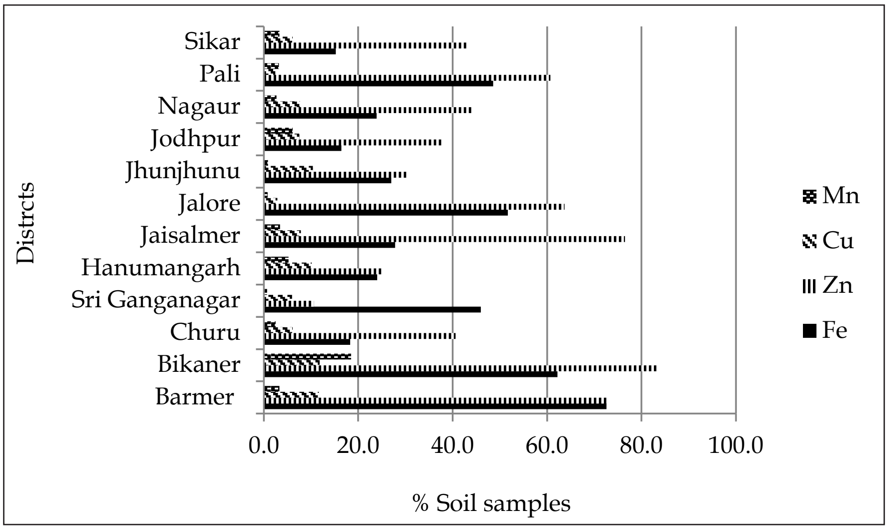

Fig. 4. Per cent of soil samples deficient in Fe, Zn, Cu and Mn in districts of arid Rajasthan.

potassium in Sri Ganganagr, Hanumangarh, Pali, Nagaur and Jalore districts, respectively (Fig. 3). While Bikaner, Sikar, Jalore, Jhunjhunu and Jaisalmer districts have 28, 27, 20, 17 and 16% of total samples deficient in available K (Fig. 3). Contrary to the situation of P, however, the mean status of K is the highest in the rangelands, followed by irrigated croplands and rainfed croplands (Table 3). This is mainly due to continuous cultivation of the soils for climatically adapted crops like pearl millet, guar, mung bean, moth bean, castor, wheat, barley, mustard and occasionally cotton, but without any replenishment of potassium to the soils. Consequently the stored K got gradually depleted. Generally farmers of the region apply nitrogenous and phosphate fertilizers like urea, DAP and SSP. However, some farmers are using sulphur powder, bentonite sulphur and gypsum also as source of sulphur. Further, the application of potasic fertilizers is not common in the hot arid Rajasthan. The higher content of K in rangelands may be due to the root activities of existing vegetation for transporting K to the surface and also through addition of organic matter under natural condition (Kumar *et al.,* 2009). The over-extraction of major soil nutrients due to continuous cultivation has also been reported from other parts of desert areas (Kumar *et al*., 2011 and 2019). Tsunekawa *et al.* (1997) reported from a study near Jodhpur in central Thar that the small K reserve in the soil dwindled faster in the rainfed croplands when they were subjected to continuous cultivation, while the land under a fallow system had comparatively better K reserve, as also in the rangelands, due to high plant root density.

Available micronutrients

Iron: The DTPA-extractable iron (Fe) ranged from 0.84 mg kg^{-1} to 42.74 mg kg^{-1}, with a mean of 6.42 mg kg^{-1} and could be considered as marginally adequate (Table 2). About 40% of the soil samples were deficient in available Fe with overall marginal fertility rating with respect to NIV (Table 4). Rangelands are better endowed, with respect to DTPA extractable

Table 4. Nutrient index values and fertility rating for available nutrients in the soils of hot arid Rajasthan

Soil properties	Range	Mean	SD	Percent sample category			NIV	Fertility rating
				Low	Medium	High		
Organic carbon (%)	0.01-0.84	0.16	±0.123	97	2.5	0.50	1.03	Low
Available-P (kg ha^{-1})	1.19-96.64	13.34	±12.63	55	31	14	1.61	Low
Available-K (kg ha^{-1})	56.00-974.00	249.40	±147.49	15	55	30	2.14	Medium
Fe (mg kg^{-1})	0.84-42.74	6.42	±4.192	40	58	2	1.67	Marginal
Mn (mg kg^{-1})	0.70-45.90	9.44	±5.610	4	44	51	2.47	High
Zn (mg kg^{-1})	0.05-5.20	0.76	±0.681	55	39	6	1.51	Low
Cu (mg kg^{-1})	0.04-4.86	0.66	±0.476	6	67	27	2.17	Adequate

Fe followed by the irrigated croplands and rainfed croplands (Table 3). With regards to different districts of hot arid Rajasthan DTPA extractable Fe is deficient in 73% samples in Barmer, 62% samples in Bikaner, 52% samples in Jalore, 49% samples in Pali, 46% samples in Sri Ganganagar, 28% samples in Jaisalmer, 27% samples in Jhunjhunu, 24% samples in each of Nagaur and Hanumangarh districts (Fig. 4). While remaining districts like Churu, Jodhpur and Sikar have 18%, 16% and 15% of total samples deficient in Fe, respectively (Fig. 4). Spatially, the better-endowed areas are within the Aravallis in Nagaur, Sikar, Jhunjhunu, Churu in the east and the adjoining plains in the southeast. The higher content in the rangelands could be due to regular addition of Fe under natural condition through litter fall and its decomposition. However, in the irrigated croplands this may be due to external application through inorganic sources. Even the inputs of the micronutrients are meager in the rainfed and rangelands, but it is assumed that mining of micronutrients are also much less than in the irrigated croplands. The results are in close agreement with those reported by earlier workers (Praveen-Kumar *et al.,* 2009; Kumar *et al.,* 2019). Despite the adequacy over a large area, deficiency of Fe has been noticed in about 40% samples, that needs to be addressed. The most notable deficient area lies in a N-W belt through the dune-interdune terrain between Jaisalmer, Bikaner, Churu and SW-SE belt through Barmer, Jalore and Nagaur, where some of the taller dunes with narrow interdune plains occur, and the major land uses are irrigated and rainfed croplands.

Zinc: The DTPA-extractable zinc (Zn) in the soils of hot arid region of Rajasthan ranged from 0.05 mg kg^{-1} to 5.20 mg kg^{-1}, with a mean of 0.76 mg kg^{-1}, which is marginal (Table 2). Nearly 55% of samples showed low, 39% samples had medium and 6% had high Zn. Overall rating of the samples with respect to zinc NIV was low (Table 4). Out of total samples collected from different districts 83, 77, 73, 64, 61, 44, 43 and 41% samples were deficient in DTPA extractable Zn in Bikaner, Jaisalmer, Barmer, Jalore, Pali, Nagaur, Sikar and Churu districts, respectively (Fig. 4). While, Jodhpur, Jhunjhunu, Hanumangarh and Sri Ganganagar districts have 38, 30, 25, 11% of total samples deficient in Zn respectively (Fig. 4). Coarse texture, parent material, high pH, poor organic carbon status and management practices accentuated Zn deficiency in the soils. These results are in the conformity of those of Takkar *et al.,* 1997; Katyal and Rattan, 1993 and Kumar *et al.,* 2019. Relatively higher mean contents occur in the irrigated croplands, followed by the rainfed croplands and the rangelands (Table 3). The better-endowed areas in terms of available zinc are found to occur in south of Jodhpur, running belt of the Kantli river, covering Jhunjhunu and Churu encompassing, rangelands and irrigated croplands; NE-SW parts of Sikar district encompassing mostly the irrigated croplands and rangelands on alluvial and colluvial plains; northern, north eastern and western parts of Sri Ganganagar and Hanumangarh district. The most notable deficient area lies in N-W belt through the dune-interdune terrain between Bikaner, Jaisalmer and Barmer and eastern parts of Churu where the major land uses are rainfed croplands and rangelands (Table 3 and Fig. 4). The probable reason for the localized higher contents of Zn is its application through inorganic and organic sources in the irrigated croplands. Additionally, our observations on higher contents occurring in a topo-sequence encompassing the hilly tracts of the Aravallis to the alluvial plains of the ephemeral streams suggest its washing down by the steams from the hilly tract, which is rich in copper and zinc. This followed by local weathering could also have some control on the distribution pattern of plant-available Zn. Despite the localized natural endowment, Zn deficiency is found over large parts of the region and, therefore, there is a need for Zn fertilization at recommended doses for rational crop yields. Zn deficiency in soil has been reported by several other workers in arid and semi-arid areas of the country (Dhir *et al.,* 1977; Sakal, 2001; Pradeep Kumar *et al.,* 2006; Praveen-Kumar *et al.,* 2009).

Copper: The DTPA-extractable copper (Cu) in the soils varied from 0.04 mg kg^{-1} to 4.86 mg kg^{-1}, with overall mean of 0.66 mg kg^{-1}, which suggests adequacy as the critical limit of Cu is 0.20 mg kg^{-1}. The higher mean contents are obtained from the irrigated croplands, followed by the rainfed croplands and the rangelands. In total, out of 5655 samples only 6% were deficient in DTPA extractable Cu in hot arid Rajasthan, more than 10% in Bikaner, Barmer, Hanumangarh and Jhunjhunu, 8% in Jaisalmer, Jodhpur and Nagaur, 6% in Churu, Sikar and Sri Ganganagar (Fig. 4). Pali and Jalore districts have <3% of total samples deficient in Cu. As in the case of the Zn distribution, the spatial pattern of Cu also shows higher concentrations in the alluvial plains of Luni river in Pali, Barmer, Jalore districts, alluvial soils of Kantli river in Jhunjhunu and Churu districts, alluvial plains of Ghaggar river in Sri Ganganagar and Hanumagarh districts, where all the three land uses are represented. Large areas under adequate Cu contents occur in the Jaisalmer-Barmer-Jodhpur-Churu tract in in the west and south west, all of which are dominated by rainfed croplands and rangelands. The most notable marginal area lies in west and S-W belt through the dune-interdune terrain between Barmer and Jaisalmer, and in the east of Bikaner and the major land uses are rainfed croplands and rangelands (Table 3).

Manganese: The DTPA-extractable manganese (Mn) in the soils ranged from 0.70 mg kg^{-1} to 45.90 mg kg^{-1}, with mean value of 9.44 mg kg^{-1} (Table 2), and could be considered as moderately high. Based on the threshold limit (2.0 mg kg^{-1}), only 4% sample was deficient in DTPA extractable Mn in hot arid Rajasthan, 18% in Bikaner, 6% in Jodhpur, 5% in Hanumangarh and 3% each in Jaisalmer, Pali, Churu, Nagaur and Sikar. While, Sri Ganganagar, Jhunjhunu and Jalore districts have <1% of total samples deficient in Mn. Deficiency of Mn is not a serious problem in hot arid regions of Rajasthan. Overall, the region has sufficient Mn, with 85% samples under adequate to high contents. The results corroborate with the findings of Gupta *et al.,* (2000) and Kumar *et al.* (2019). Some small pockets across the land uses in Barmer, Jodhpur, Pali, Nagaur, Jhunjhunu and Sikar have been found to contain some of the highest Mn values. The most distinguished marginal area lies in N-E and N-S belt through the dune-interdune terrain between Jaisalmer, Bikaner and parts of Sri Ganganagar, where some of the transverse dunes with narrow interdune plains occur, and the major land uses are rainfed croplands with occasional irrigated croplands (Table 3).

Nutrient index values

The nutrient index values for hot arid region of Rajasthan was calculated based on per cent sample in different categories (Table 4). The overall nutrient index values were low for OC (1.03) and available P (1.61) and medium for available K (2.14). With regards to micronutrients nutrient index values were low for Zn (1.54), marginal for Fe (1.67), adequate for Cu (2.14) and high for DTPA-Mn (2.47). Based on the nutrient index values of soils and modified criteria suggested by Ramamoorthy and Bajaj (1969), the soils of hot arid regions of Rajasthan were deficient with respect to organic carbon and available P, while medium for available K, DTPA-Fe, DTPA-Zn and high for DTPA-Mn and Cu status. The findings are in close agreement with those reported by Shirgire *et al.,* 2018 for Jamnagar and by Rajput and Polara (2012) for Bhavnagar districts of Gujarat state.

Conclusions

Based on the findings of the present investigation, it is concluded that soils of the region are generally mild to moderately alkaline in reaction, poor in organic carbon content. The contents of P, Zn and Fe are low to marginal in large areas, especially in the dune-covered west. Continuous use of phosphatic fertilizers resulted in the accumulation of P in some pockets, mostly in the east. About 55, 15, 55 and 40% samples are deficient in available P, K, Zn and Fe. Deficiency of Cu and Mn is negligible. The patterns get reflected in the multi-nutrient deficiency maps on the major and the micro nutrients in the region. The nutrient index values are low for available P and Zn, medium for K, marginal for Fe, adequate for Cu and high for Mn. This information is useful in developing soil test based integrated plant nutrient management system for entire hot arid Rajasthan which would enhance the crop productivity, fertilizer use efficiency and would provide balance nutrition to crops for optimization of yield. These geo-referenced sites can be revisited for assessment of soil fertility changes over a period of time. Further, it will be useful for policy planners, researchers, state agriculture department, fertilizer industries and farmers for future planning.

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