International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
IJCS 2019; 7(4): 1582-1589

Received: 25-05-2019
Accepted: 27-06-2019

Ramani VP
Micronutrient Research Project (ICAR), Anand Agricultural University, Anand, Gujarat, India

Amin Vr
Micronutrient Research Project (ICAR), Anand Agricultural University, Anand, Gujarat, India

Patel Ra
Micronutrient Research Project (ICAR), Anand Agricultural University, Anand, Gujarat, India

Correspondence
Ramani VP
Micronutrient Research Project (ICAR), Anand Agricultural University, Anand, Gujarat, India

Iron kinetics and its uptake efficiency of pigeonpea grown on Fe deficient soil

Ramani VP, Amin VR and Patel Ra

Abstract
To understand the mobility of Fe the Mechanistic models are useful tools for soil and plant parameter in the system through sensitivity analysis. The experiment was aimed to study the uptake pattern of Fe in pigeonpea. The pigeonpea was harvested at three different growth stages at 40, 55 and 70 days after emergence along with 20 and 40 mg kg^{-1} Fe soil besides no Fe. To predict Fe uptake and Fe influx as well as to carry out sensitivity analysis of the rhizosphere of pigeonpea, recent version of NST 3.0 nutrient uptake model was used. In sensitivity analysis, root radius (r_0) was most sensitive parameter controlling Fe uptake of pigeonpea, which was followed by maximum net influx (I_{max}) and initial Fe concentration in soil solution (C_{Li}). On the basis of nutrient uptake model higher values of r_o, I_{max} and C_{Li} are found beneficial to increase Fe uptake by pigeonpea, while it was true for lower value of k_m. Application of Fe @ 20 mg kg^{-1} on Fe-deficient soil to pigeonpea is desirable for good growth of the crop besides Fe content in plant.

Keywords: Iron kinetics, I_{MAX}, pigeonpea, sensitivity analysis

1. Introduction

As human population continue to increase, human disturbance of the earth's ecosystem to produce food and fiber will place greater demand on soils to supply essential nutrients. The practice of intensive cropping with hybrid varieties for boosting food production has caused nutrient depletion in soil, little return of crop residues and manures to soils exasperate deficiencies. Therefore, there is a need to improve and/or sustain the productive capacity of our soils to support the food and fiber demand of our growing population.

Micronutrients deficiencies and their impacts on crop yields are widely reported in various parts of the country (Singh, 2008) [16]. In fact, one third of the world's cultivated soils is calcareous and considered Fe deficient. Corrections of Fe deficiency requires application of high doses of fertilizer to soils because of low nutrient-use efficiency. Foliar sprays have limitations because they ameliorate deficiencies in crops at a later stage when crops have sufficient foliage to receive the spray.

In the human being, about 2 billion people, mainly women and young children suffer from malnutrition problems caused by iron deficiency in the developing world (Go'mez-Galera *et al*., 2010) [7]. The supply of iron falls short as a result of low Fe content in consumed foods.

Nutrient availability in soil and acquisition by plants interact at the soil root interface and thus it is useful to evaluate the rate and amount of nutrient that are actually taken up by plants (Jungk and Claassen, 1997) [10]. The availability of mineral nutrient in soil is the result of interactions between two complex phenomena: supply of nutrients in soil and the ability of plant to acquire nutrients. Both soil and plant parameters are therefore, important for plant nutrition point of view.

Validated mechanistic models are able to provide prediction under various situations, which may avoid the need for costly field trials (Nye and Marriot, 1969) [12]. They can also be used to calculate values that are difficult to determine experimentally (Claassen and Steingrobe, 1999) [5] in addition to revealing the factors that have the greatest influence on the nutrient uptake processes (Barber and Silberbush, 1984) [2].

In the study of kinetics and uptake efficiency many scientists used mathematical models to secure a better understanding of fundamental principals involved in the process of nutrient uptake by plant roots growing in soil. These models are based on ion transport from soil to roots by means of mass flow and diffusion and on nutrient uptake kinetics, mostly following Michaelis - Menten kinetics (Nye and Marriott, 1969 [12]; Claassen and Steingrobe, 1999 [5];

Barber and Cushman, 1981 [1]; Claassen *et al*., 1986 [6]; Claassen and Barber, 1976) [4].Mechanistic models are useful tools for evaluating the significance of individual soil and plant parameters in the system through sensitivity analysis. Keeping this in view, the present investigation has been planned with the objectives (i) Compare the prediction of Fe uptake by NST 3.0 model against experimentally measured value (ii) to evaluate the effect of iron on soil - plant parameters and biomass of pigeonpea.

2. Materials and Methods

The research was carried out in Factorial Completely Randomized Design and treatments were repeated three times. The Fe-inefficient pigeonpea variety C-11 was used for sensitivity analysis. The three levels of Fe (through $FeSO_4$) *viz.*, (i) Control (Fe_0), (ii) 20 mg kg^{-1} Fe soil application (Fe_{20}) and (iii) 40 mg kg^{-1} Fe soil application (Fe_{40}) were selected. The crop was harvested at three different growth stages *viz.* 40, 55 and 75 Days after Emergence (DAE).

2.1 Procurement of materials

Soil: Soil samples were collected from the various fields. Analyzed for their iron contents and identified Fe-deficient soil having 4.63 mg kg^{-1} Fe.

Seed: Iron-inefficient C-11 cultivar was procured for mechanistic study from the twenty varieties under the preliminary screening of World Bank funded Project NAIP Component-4 from Micronutrient Research Project, Anand.

Pots: The pots having capacity of 15, 18 and 35 kg soil were selected for the crops grown up to 40, 55 and 70 DAE.

2.2 Sowing

In winter season, twelve, eight and four seeds were planted and six, four and two plants were maintained in 15, 18 and 35 kg soil capacity pots, respectively during the growth period.

2.3 Harvesting and preparation of samples

Plant sample: Plants were uprooted with the rhizospheric soil. Plant samples after each harvest were washed with 0.1N HCl and distilled water, dried at 70 ^{0}C till constant weight and dry shoot weight was recorded (approximately for 48 hours). Roots were carefully separated from soil by washing and floating over sieves. After cleaning roots from any foreign material, the adsorbed water was removed with filter paper and fresh as well as dry root weight was recorded. The chemical analysis of the plant samples was carried out as per the procedure outlined by Jackson (1973) [9].

Soil Sample: After harvest of the crop, post-harvest soil samples were collected and air dried in laboratory. The estimation of various parameters was done using standard procedures.

2.4 Formulas for Mathematical Calculations

2.4.1 Determination of plant parameters

(i) Maximum Net Influx (I_{MAX})

The value was obtained from influx measured from the treatment with highest iron level. Fe influx (In) was calculated by formula of Williams (1948) [18].

$$\ln = \frac{U_2 - U_1}{RL_2 - RL_1} X \frac{\ln (RL_2/RL_1)}{t_2 - t_1}$$

Where,

l_n = net influx, mol cm^{-1} s^{-1}

U = Fe content in shoots, mol plant $^{-1}$

RL = root length, cm

t = time of harvest, s

Subscripts 1 and 2 refer to first and second harvest

(ii) Mean root radius (r_0)

An average value of root radius for the whole root system was obtained from root fresh weight and root length as given below

$$r_0 = \frac{\sqrt{FRW}}{(\Pi. RL)}$$

Where,

FRW = fresh root weight, g

RL = root length, cm

r_0 = root radius, cm

(iii) Root length (RL)

Root length was measured through the Root Scanner.

Where, RL = root length, cm

(iv) Mean half distance between neighboring roots (r_1)

The value of r_1 was calculated by formula:

$$r_1 = \frac{\sqrt{Vs}}{(\Pi. RL)}$$

Where,

Vs = soil volume, cc

RL = root length, cm

r_1 = mean half distance between neighboring roots, cm

(v) Root surface area (RSA)

It was calculated by using the following formula:

RSA= 2 Πr_0 RL

Where,

r_0 = root radius, cm

RL = root length, cm

(vi) Water influx (V_0)

It was calculated by using the following formula:

$$V_0 = \frac{T_2 - T_1}{RA_2 - RA_1} X \frac{\ln (RA_2/RA_1)}{t_2 - t_1}$$

Where,

T = transpiration, cc

RA = root surface area, cm^2

T = time of harvest, s

V_0 = water influx, cm^3 cm^{-2} s^{-1}

Subscript 1 and 2 refers to first and second harvest.

(vii) Relative root growth rate (k)

Relative root growth rate was calculated by using the following formula:

$$k = \frac{\ln (RL_2/RL_1)}{t_2 - t_1}$$

Where,

k = relative root growth rate, s^{-1}

RL = root length, cm

t=time of harvest, seconds

Subscripts 1 and 2 refer to first and second harvest.

(viii) Relative shoot growth rate

Relative shoot growth rate was calculated by using the following formula:

$$RSR = \frac{\ln(SDW_1/SDW_2)}{t_2 - t_1}$$

Where,
SDW = shoot dry weight, g
t= time of harvest, s
Subscripts 1 and 2 refer to first and second harvest.
(ix) Fe uptake kinetics
Fe uptake kinetics was calculated by using the following formula:

$$I_n = \frac{I_{max}(C_{Lo} - C_{Lmin})}{K_m + (C_{Lo} - C_{Lmin})}$$

Where,
I_{max} = Maximum net influx, which is calculated by following formula:
I max = in* k_m / C_{Li}
(I_n= Fe influx, K_m= Michaelis –Mentan constant, C_{Li}= Initial Fe concentration in soil solution)
C_{Lmin} =Minimum Soil solution concentration. C_{Lmin} is the soil solution concentration at which net influx equals to zero
K_m = Michaelis –Mentan constant. K_m is the difference between C_{Lmin} and the concentration at which influx is the half the $I_{MAX.}$

2.4.2 Determination of soil parameters
(i) Soil solution Fe concentration (CLi)
The soil solution was obtained by soil displacement method and Fe concentration was measured on the Atomic Absorption Spectrophotometer.
(ii) Diffusion coefficient
DL = Diffusion coefficient of Fe in water at 250 C, cm^{-2} s^{-1} value is taken from the (Parsons, 1959) [13]
Ɵ = the volumetric water content of the soil, cm^3 cm^{-3}
This is cc of water in cm^{-3} of soil (v/v)
I.e. volume of water in pot/ vol. of soil in pot at field capacity.
f = Impedance factor was calculated from the formula of Barraclough and Tinker (1981) [3] as f = 1.58θ-0.17
b= the buffer power was calculated from DTPA- extractable Fe in the soil divided by Fe concentration in soil solution.

2.5 Nutrient uptake model calculations
Recent version of nutrient uptake model (NST 3.0) was run using all the measured soil and plant parameters to predict Fe uptake and Fe influx in rhizosphere of pigeonpea.

2.6 Sensitivity analysis
Sensitivity analysis was performed to evaluate the effect of each soil and plant parameter on Fe influx and Fe uptake, while considering that all the parameters are independent of one another. Simulation of Fe uptake was done by varying each parameter between 0.5 and 2.0 times from its measured value. While each parameter was changed, the remaining parameters were held constant at initial values.

3. Results
Data pertaining to the effect of various treatments on behavior of soil parameters, plant parameters and contents of pigeonpea were subjected to statistical analysis in order to test the significance of the results. Mathematical model NST 3.0 was run by using the data on soil and plant parameters. Sensitivity analysis was also worked out for Fe uptake and compared with measured Fe uptake by pigeonpea plant. The effects of Fe on different parameters are presented as under.

3.1 Effect of Fe on biomass of pigeonpea
The significant increase in dry root and dry shoot biomass were noticed at different growth stages (Table 1 & 2). With the advancement in time i.e. at 55 and 75 DAE the total biomass were around 2.5 and 3.0 fold over the biomass noticed at 40 DAE, respectively (Fig. 1).

Table 1: Effect of Fe application on dry root weight (g plant^{-1}) of pigeonpea varieties at different growth stages

Stage (S)	Variety (V)	Fe (mg kg^{-1} soil) 0	20	40	Mean
S_1 (40 DAE)	BDN-2	0.41	0.4	0.48	0.43
	PKV-Trombay	0.37	0.46	0.42	0.42
	C-11	0.24	0.22	0.29	0.25
	AAUT-2007-8	0.35	0.39	0.45	0.39
	Mean	0.34	0.37	0.41	
S_2 (55 DAE)	BDN-2	0.53	0.58	0.60	0.57
	PKV-Trombay	0.85	0.87	0.88	0.87
	C-11	0.57	0.60	0.60	0.59
	AAUT-2007-8	0.58	0.76	0.70	0.68
	Mean	0.63	0.7	0.70	
S_3 (70 DAE)	BDN-2	0.68	0.74	0.76	0.73
	PKV-Trombay	1.08	1.17	1.21	1.15
	C-11	0.72	0.76	0.76	0.75
	AAUT-2007-8	0.77	0.96	0.95	0.90
	Mean	0.81	0.91	0.92	

Overall mean						Parameter	S.Em. ±	CD@5%
Variety	Mean	Fe	Mean	Stage	Mean	Fe	0.01	0.04
V1	0.58	Fe0	0.60	S1	0.37	Variety	0.02	0.05
V2	0.81	Fe20	0.66	S2	0.68	Stage	0.01	0.04
V3	0.53	Fe40	0.68	S3	0.88	S X Fe	0.02	NS
V4	0.66					S X V	0.03	0.08
CV (%)		13.0				Fe X V	0.03	NS
						S X Fe X V	0.05	NS

Table 2: Effect of Fe application on dry shoot weight (g plant^{-1}) of pigeonpea varieties at different growth stages

Stage (S)	Variety (V)	Fe (mg kg^{-1} soil)						Mean
		0		20		40		
S_1 (40 DAE)	BDN-2	0.263		0.204		0.328		0.265
	PKV-Trombay	0.441		0.516		0.493		0.483
	C-11	0.386		0.467		0.428		0.427
	AAUT-2007-8	0.418		0.508		0.52		0.482
	Mean	0.377		0.423		0.442		
S_2 (55 DAE)	BDN-2	0.805		1.068		0.817		0.897
	PKV-Trombay	0.924		1.149		1.111		1.061
	C-11	1.066		0.934		1.237		1.079
	AAUT-2007-8	1.24		1.512		1.572		1.441
	Mean	1.009		1.166		1.184		
S_3 (70 DAE)	BDN-2	1.025		1.360		0.991		1.125
	PKV-Trombay	1.145		1.527		1.496		1.389
	C-11	1.309		1.189		1.583		1.361
	AAUT-2007-8	1.737		2.054		1.979		1.923
	Mean	1.304		1.533		1.512		
Overall mean						Parameter	S.Em. ±	CD@5%
Variety	Mean	Fe	Mean	Stage	Mean	Fe	0.025	0.071
V1	0.762	Fe0	0.897	S1	0.414	Variety	0.029	0.082
V2	0.978	Fe20	1.041	S2	1.120	Stage	0.025	0.071
V3	0.955	Fe40	1.046	S3	1.450	S X Fe	0.043	NS
V4	1.282					S X V	0.05	0.142
C.V. (%)		15.1				Fe X V	0.05	0.142
						S X Fe X V	0.087	NS

The increase in root biomass due to Fe_{20} and Fe_{40} was to the tune of 3.3 and 7.8 per cent, respectively over no Fe application. Similarly, the improvement in dry shoot biomass was up to 13.3 and 29.5 per cent over control, respectively. The effect of Fe was more pronounced on shoot as compared to root growth. The mean root radius was higher at 2nd harvest as compared to 1st and 3rd harvest (Table 3).

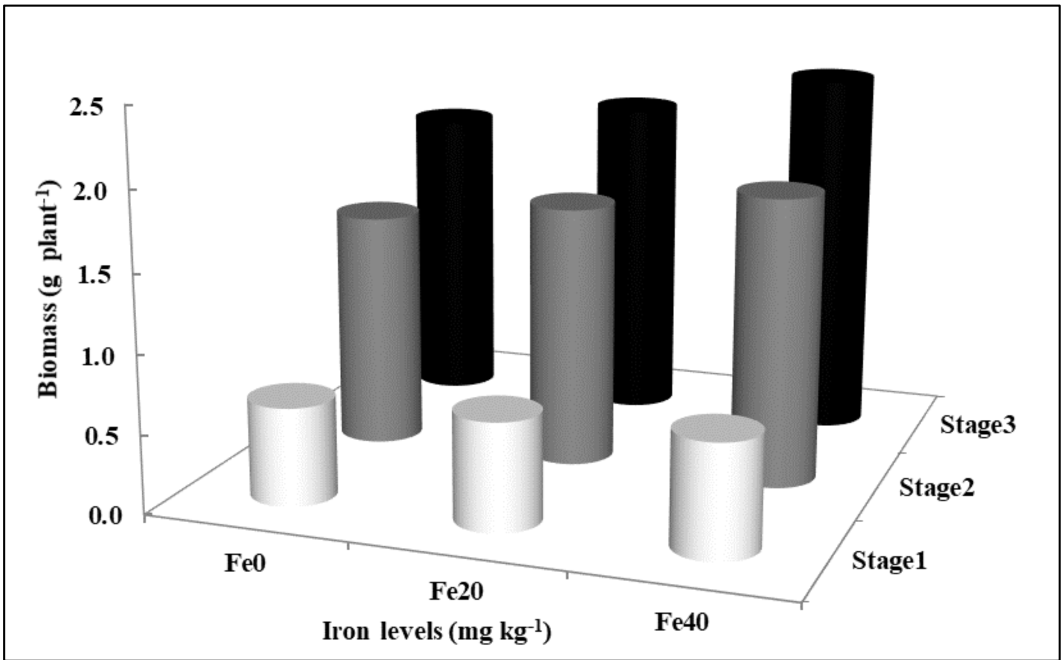

Fig 1: Effect of iron levels on total dry biomass of pigeonpea at different growth stages

Table 3: Effect of Fe application on root radius (10^{-2} cm) in different varieties of pigeonpea at different growth stages

Stage (S)	Variety (V)	Fe (mg kg^{-1} soil)			Mean
		0	20	40	
S_1 (40 DAE)	BDN-2	4.01	4.19	3.02	3.74
	PKV-Trombay	3.44	3.75	4.01	3.73
	C-11	3.43	3.93	3.80	3.72
	AAUT-2007-8	3.98	3.45	3.80	3.74
	Mean	3.71	3.83	3.66	
S_2 (55 DAE)	BDN-2	3.49	4.51	3.45	3.82
	PKV-Trombay	3.52	3.56	4.55	3.88
	C-11	3.98	4.16	3.91	4.02
	AAUT-2007-8	4.87	4.01	4.17	4.35

Stage (S)	Variety (V)	0	20	40	Mean
	Mean	3.97	4.06	4.02	
S_3 (70 DAE)	BDN-2	2.32	2.72	2.19	2.41
	PKV-Trombay	2.63	2.27	2.81	2.57
	C-11	2.34	2.72	2.24	2.43
	AAUT-2007-8	3.12	2.50	2.86	2.83
	Mean	2.60	2.55	2.53	

Overall mean						Parameter	S.Em.$\pm$	CD@5%
Variety	Mean	Fe	Mean	Stage	Mean	Fe	0.037	NS
V1	3.323	Fe0	3.43	S1	3.73	Variety	0.043	0.12
V2	3.394	Fe20	3.48	S2	4.02	Stage	0.037	0.11
V3	3.390	Fe40	3.40	S3	2.56	S X Fe	0.065	NS
V4	3.641					SX V	0.075	0.21
C.V. (%)		6.5				Fe X V	0.075	0.21
						S X Fe X V	0.13	0.37

3.2 Effect of Fe on its content in pigeonpea

The significant changes were noticed in Fe contents in pigeonpea due to Fe application and at different growth stages. The maximum Fe content was observed at Fe_{40} at all three growth stages. In case of different growth stages, the significantly highest Fe content was noticed at 2nd harvest i.e. at 55 DAE (Table 4 & Fig. 2).

Table 4: Effect of Fe application on Fe content (mg kg^{-1}) in shoots of pigeonpea varieties at different growth stages

Stage (S)	Variety (V)	Fe (mg kg^{-1} soil) levels			Mean
		0	20	40	
S_1 (40 DAE)	BDN-2	213.8	209.7	220.2	214.6
	PKV-Trombay	218.7	207.7	194.5	206.9
	C-11	181.5	191.7	216.7	196.6
	AAUT-2007-8	158.8	235.8	244	212.9
	Mean	193.2	211.2	218.8	
S_2 (55 DAE)	BDN-2	287.2	299	311.5	299.2
	PKV-Trombay	336.3	334.7	325.3	332.1
	C-11	347	357.3	370.8	358.4
	AAUT-2007-8	278.7	314.7	377.3	323.6
	Mean	312.3	326.4	346.3	
S_3 (70 DAE)	BDN-2	179.3	197.5	189.0	188.6
	PKV-Trombay	196.7	180	180.8	185.8
	C-11	154.8	189.8	193.8	179.5
	AAUT-2007-8	159.3	186.5	195.5	180.4
	Mean	172.5	188.5	189.8	

Overall mean						Parameter	S.Em.$\pm$	CD@5%
Variety	Mean	Fe	Mean	Stage	Mean	Fe	4.31	12.25
V_1	234.1	Fe0	226	S_1	207.8	Variety	4.97	NS
V_2	241.6	Fe20	242	S_2	328.3	Stage	4.31	12.25
V_3	244.8	Fe40	251.6	S_3	183.6	S X Fe	7.46	NS
V_4	239.0					S X V	8.61	24.49
C.V. (%)		10.7				Fe X V	8.61	24.49
						S X Fe X V	14.92	NS

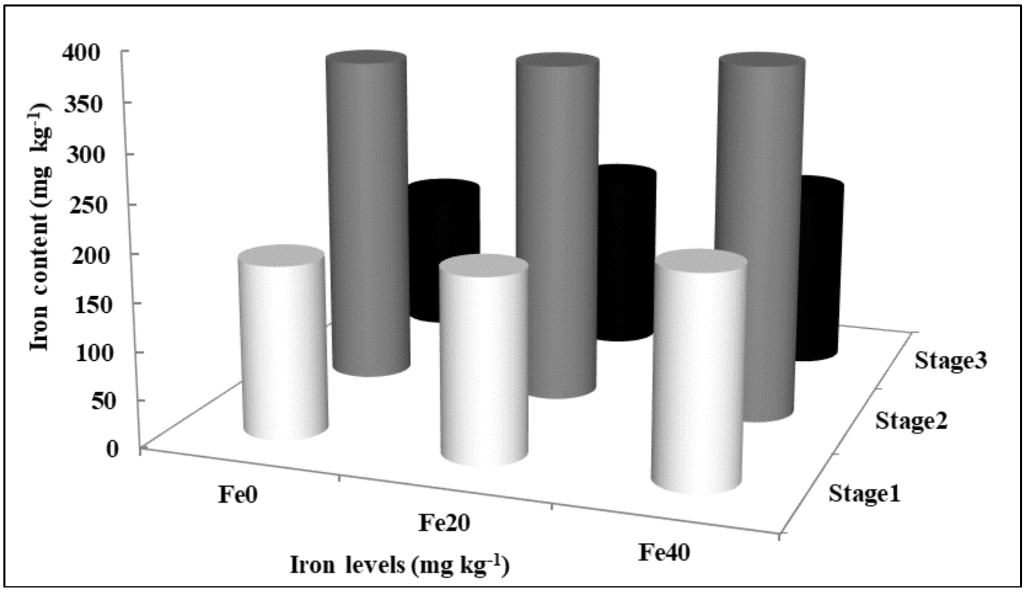

Fig 2: Effect of iron levels on its content in pigeonpea at different growth stages

3.3 Effect of Fe on its uptake by pigeonpea

Effect of Fe on its uptake by pigeonpea at different growth stages is depicted in Fig. 3. The highest uptake was noticed in the AAUT-2007-8 variety (53.4 nmol plant^{-1}) and lowest was observed in BDN-2 variety (36.4 nmol plant^{-1}). In case of treatment Application,

The maximum uptake was found under 20 mg kg^{-1} Fe (46.3 nmol plant^{-1}) which was on par with 40 mg kg^{-1} Fe. Whereas in case of growth stages, the maximum uptake of Fe was found at second growth stage (66.1 nmol plant^{-1}) while lowest was noticed at first growth stage (15.4 nmol plant^{-1}).

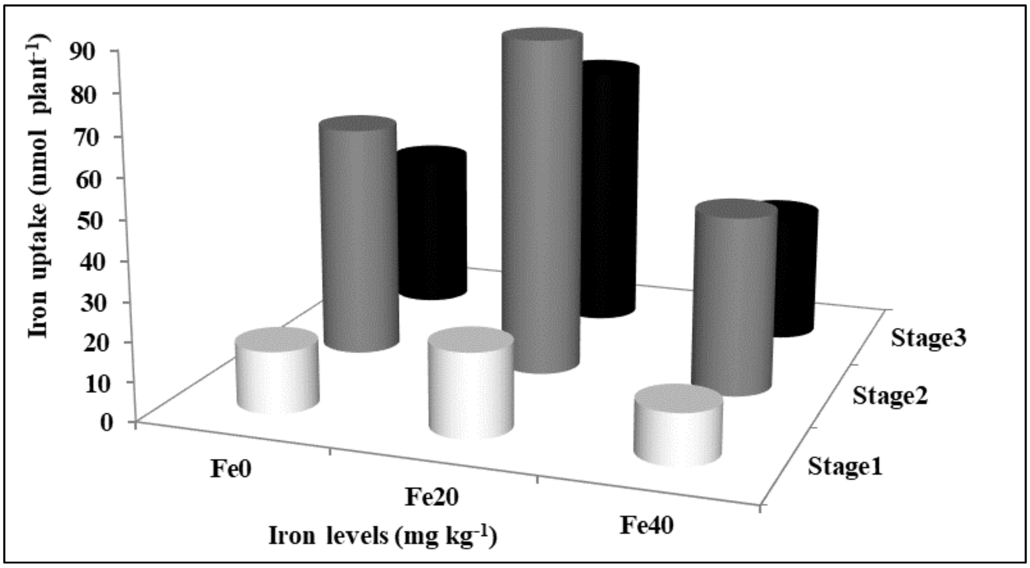

Fig 3: Effect of iron levels on its uptake by pigeonpea at different growth stages

The interaction effect was noticed significant between growth stages and different varieties of pigeonpea. The maximum uptake was found in the AAUT-2007-8 variety (84.0 nmol plant^{-1}) at second growth stage and minimum was noticed in PKV-Trombay variety (12.9 nmol plant^{-1}) at first growth stage.

The significant interaction effect between iron levels and different varieties of pigeonpea was noticed. The maximum uptake was found in the AAUT-2007-8 variety (65.8 nmol plant^{-1}) at 40 mg kg^{-1} Fe which was on par with the C-11 variety at 20 mg kg^{-1} Fe. While lowest was found in BDN-2 variety (27.9 nmol plant^{-1}) at control condition.

3.4 Physiological plant parameters

Physiological plant parameters include, maximum net influx (I_{MAX}), Michaelis-Menten constant (k_m) and minimum soil solution concentration (C_{min}).

Michaelis-Menten constant (k_m) is the difference between C_{min} and the concentration at which influx is half the I_{MAX}. The parameter gives affinity of ion with soil particles and bears inverse

relation with influx or uptake.

The value of K_m of pigeonpea 9.17µmol was taken from Swiader (1985) [17]. Minimum soil solution or C_{min} concentration at the root surface was taken zero in the model calculations because the plants can reduce Fe concentration close to zero. Maximum net influx or I_{MAX} was calculated from the influx measured at the highest soil Fe level.

3.5 Plant and Soil parameters used for NST 3.0 nutrient uptake models

The measured and calculated plant and soil parameters were used in NST 3.0 nutrient uptake model to calculate Fe uptake pigeonpea is given in Table 5. With increasing Fe supply, measured root length and Fe concentration in soil solution increased. Comparing calculated and measured values, there was a close prediction of Fe uptake under low Fe supply for C-11 variety of pigeonpea.

Table 5: Plant and soil parameters used in nutrient uptake model (NST 3.0) calculations

Sr. No.	Parameter	Symbol	Unit	Iron Levels (mg kg^{-1} Soil)		
				0	20	40
Plant parameters						
1	Maximum net influx	I_{max}	10^{-6} nmol cm^{-2} s^{-1}	1.35	1.35	1.35
2	Michaelis-Menten constant	K_m	nmol cm^{-3}	9.17	9.17	9.17
3	Concentration in solution	C_{min}	nmol cm^{-3}	0	0	0
4	Mean root radius	r_0	10^{-2} cm	3.98	4.16	3.91
5	Mean water influx at root surface	V_0	10^{-7} cm^3 cm^{-2} s^{-1}	22.4	23.0	23.2
6	Half-distance between root axes	r_1	cm	4.19	4.08	4.09
7	Rate of root growth	k	10^{-7} s^{-1}	0.0310	0.0301	0.0239
8	Root length	RL_0	cm	156	137	146
Soil parameters						
9	Concentration of the nutrient in the soil solution	Cli	nmol cm^{-3}	0.14	0.15	0.17
10	Volumetric soil moisture	θ	cm^3 cm^{-3}	0.26	0.26	0.26
11	Impedance factor	f	-	0.24	0.24	0.24
12	Buffer power of nutrient	b	-	428.3	471.2	494.6
13	Diffusion coefficient of solute in water	D_L	10^{-6} cm^2 s^{-1}	7.1	7.1	7.1

4. Discussion

The effect of Fe application on different characterized at various growth stages of different pigeonpea varieties are discussed as under.

At different growth stages, Fe application increased in shoot and root biomass. The Similar trend was also observed by Gobinath (2011) [8] for gram crop. Further, the root radius was positively correlated with Fe uptake as per sensitivity analysis (Fig. 4). The similar trend was also reported by Gobinath (2011) [8].

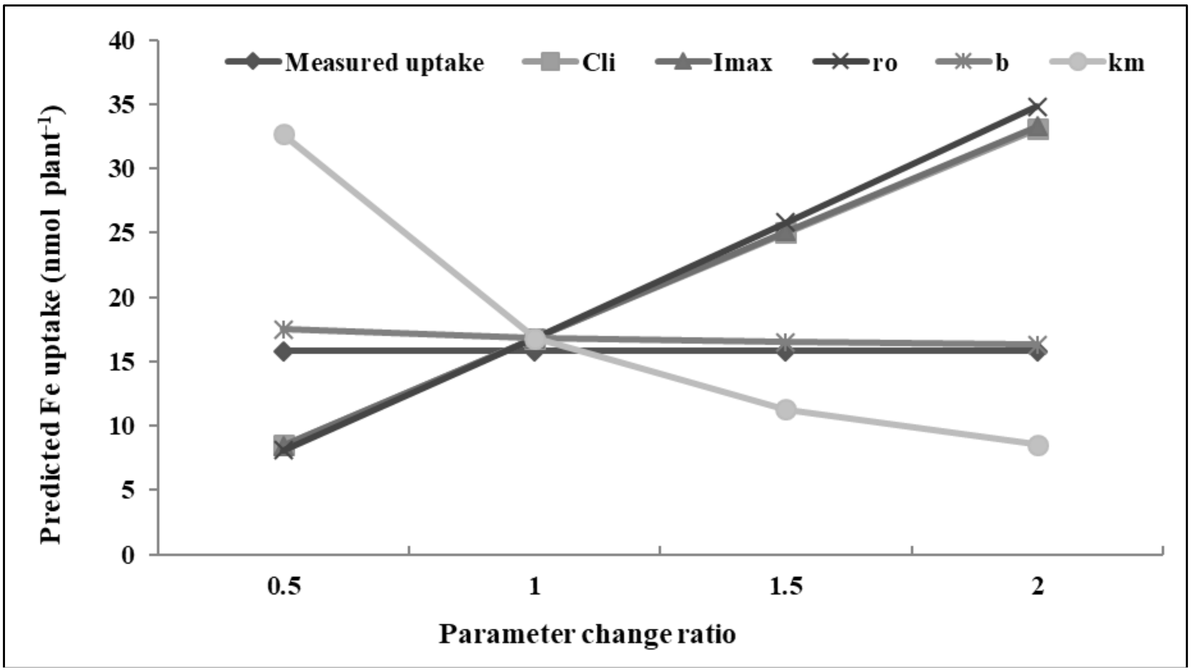

Fig 4: One dimensional sensitivity analysis using NST 3.0 mechanistic model with iron uptake data for pigeonpea at 0.14 µM iron in soil solution

The overall effect of Fe_{40} in case of shoot weight, root weight and Fe content in shoot were found significantly higher over control may be due to the soil was deficient in Fe content (4.63 mg kg^{-1} soil). However, crop has not shown any iron deficiency during its growth period. Further, the lower level of Fe application @ 20 mg kg^{-1} soil (Fe_{20}) was at par with Fe_{40} in all the cases. Thus, Fe_{20} is sufficient for good growth of pigeonpea, hence indicated as beneficial level for pigeonpea.

Similar to Fe content, the uptake of Fe by pigeonpea was also altered significantly due to Fe application and at different growth stages. Due to higher Fe content at vegetative growth stage, the removal of Fe was also noticed higher at 2^{nd} harvest. Further, the higher mean root radius is reflected here For higher utilization of Fe from soil.

4.1 Sensitivity analysis

Sensitivity analysis is a useful tool for evaluating significance of each soil and plant parameters regulating Fe uptake in plant (Lin, 2009) [11]. Systematic changes in each parameter from 0.5 to 2.0 times of its initial uptake value were calculated by simulation of Fe uptake model, keeping all other parameters constant (Fig.4). Sensitivity calculated uptake of C-11 variety at 0.14 µmol to changing the initial soil solution concentration (C_{Li}), Maximum net influx (I_{max}), root radius (r_0) and Michaelis –menten constant (k_m) by a factor given by change ratio are given in Fig. 4. Where in measured uptake is given by horizontal line (15.8 nmol $plant^{-1}$).

Sensitivity analysis was worked out by using nutrient uptake model (Mechanistic model NST 3.0). The data used to run this model are presented in Table 5.

The results revealed that, increasing r_o, I_{MAX} and C_{Li} from 0.5, 1.0, 1.5 and 2.0 found to increase Fe uptake by pigeonpea. The change ratio of 2.0 individually resulted increase in Fe uptake in proportions of 2.1, 1.98 and 1.97 times, respectively while, increasing k_m and b separately by a factor of 2.0 reduced uptake by 0.97 and 0.51 times, respectively (Fig. 4). Similarly, Samal *et al*. (2003) [15] reported that *raya* could obtain 2.5 times higher Mn influx, which resulted in 4 times more Mn uptake than wheat even under Mn deficient conditions. Samal *et al*. (2010) [14] also observed that, sensitivity analysis showed that both maximum influx and buffer power were increased by a factor of 2.5 times in maize and wheat and 25 times in sugar beet, the model could predict measured K influx to the extent 100%. The factors like r_0, I_{MAX}, C_{Li} and k_m altered the Fe uptake by pigeonpea. To increase the Fe uptake by pigeonpea, higher values of r_0, I_{MAX} and C_{Li} while lower value of km are desirable. Under low Fe supply conditions, increasing initial soil solution concentration of Fe or selecting crop species with thicker roots or with more efficient uptake kinetics would be helpful in overcoming Fe deficiency in food grain.

5. Conclusion

Nutrient uptake model described the sensitivity of Fe uptake by pigeonpea, which suggest that the higher values of r_o, I_{MAX} and C_{Li} are desirable, while low k_m increased uptake of Fe by pigeonpea. Mechanistic model closely described Fe uptake, which suggests that the parameters were estimated accurately and the calculated uptake were realistic. The application of @ 20 mg kg^{-1} on Fe deficient soil is beneficial for better growth and development of Fe inefficient pigeonpea variety C-11 besides higher Fe content in pigeonpea.

6. Acknowledgements

The authors are thankful to the Anand Agricultural University, Anand, Gujarat for providing necessary facility to carry out the research.

7. References

1. Barber SA, Cushman JH. Nitrogen uptake model for agronomic crops. In Modeling Waste Water Renovation-Land Treatment, JK. Ishandar, Ed. New York: Wiley Inter-Science, 1981, 382-409.
2. Barber SA, Silberbush M. Plant root morphology and nutrient uptake. In: Roots Nutrient and water influx and plant growth. ASA Special Publication No.49, 1984.
3. Barraclough PB, Tinker PB. The determination of ionic diffusion coefficients in field soils. I. Diffusion coefficients in sieved soils in relation to water content and bulk density. Ind. J Soil. Sci. 1981; 3:225-236.
4. Claassen N, Barber SA. Simulation model for nutrient uptake from soil by growing plant root systems. Agronomy Journal. 1976, 68:961-964.
5. Claassen N, Steingrobe B. Mechanistic simulation models for a better understanding of nutrient uptake from soil. In Mineral Nutrition of Crops: Fundamental Mechanisms and Implications, Ed. Rengel, Z: New York Food Products Press, 1999, 327-367.
6. Claassen N, Syring KM, Jungk A. Verification of a mathematical model by simulating potassium uptake from soil. Plant Soil. 1986, 95:209-220.
7. Go'mez-Galera S, Rojas E, Sudhakar D, Zhu C, Pelacho AM, Capell T, Christou P *et al.* Critical evaluation of strategies for mineral fortification of staple food crops. Transgenic Research. 2010; 19:165-180.
8. Gobinath R. Iron kinetics and its uptake efficiency of chickpea cultivars grown on Fe-deficient soil". Thesis, Dept. Of Soil Sci. And Agril. Chemistry, Anand Agricultural Univ., Anand, Gujarat, India, 2011.
9. Jackson ML. Soil Chemical Analysis, New Delhi: Prentice Hall, 1973.
10. Jungk A, Claassen N. Ion diffusion in the soil root system. Adv. Agron. 1997; 61:53-100.
11. Lin W. Nutrient uptake estimates for woody species as described by the NST 3.0, SSAND and PCATS mechanistic nutrient uptake models. Thesis, Faculty of the Virginia Polytechnic Institute and state Univ., Blacksburg, VA, 2009.
12. Nye PH, Marriott FHC. A theoretical study of the distribution of substances around roots resulting from simultaneous diffusion and mass flow. Pl. Soil. 1969, 30:459-472.
13. Parsons R. Handbook of electrochemical constants, New York: Academic Press, 1959.
14. Samal D, Kovar JL, Steingrobe B, Sadana US, Bhadoria PS, Claassen N *et al.* Potassium uptake efficiency and dynamics in the rhizosphere of maize, wheat and sugar beet evaluated with a mechanistic model. Plant and Soil. 2010; 332:105-121.
15. Samal D, Sadana US, Gill AS. Mechanistic approach to study manganese influx and its depletion in the rhizosphere of wheat and raya. Communications in Soil science and Plant Analysis. 2003; 34:3033-3044.
16. Singh MV. Micronutrient deficiencies in crops and soils in India. Micronutrient deficiencies in global crop production Ed. Alloway BJ. Graham RD, 2008.
17. Swiader JM. Iron and Zinc absorption characteristics and copper inhibitions in cucurbitaceae. Journal of Plant Nutrition. 1985; 8(10):921-931.
18. William RF. The effect of phosphorus supply on the rates of intake of phosphorus and nitrogen upon certain aspects of phosphorus metabolism in gramineous plants. Aust. J Sci. Res. 1948; 1:333-361.