Boron Nutrition in Soil System and Management Strategy

Shaon Kumar Das[*1], Aniruddha Roy[2] and Goutam Kumar Ghosh[3]
[1]ICAR-National Organic Farming Research Institute, Gangtok, Sikkim-737102
[2]ICAR RC for NEH Region, Umiam, Meghalaya-793103
[3]Palli Siksha Bhavan, Visva Bharati, Sriniketan, West Bengal

*Email for corresponding: shaon.iari@gmail.com

This mini review represents the role of boron nutrition in soil and their management practices under field condition. Boron is concerned with precipitating excess cations, buffer action, regulatory effect on other nutrient elements etc., development of new cells in meristematic tissue, treanslocation of sugars, starches, phosphorus etc., essential for cell wall formation. Deficiency of boron occurs under moister stress and dry condition which cause reduced plant height, plants fail to produce panicles at the panicle formation stage and tips of emerging leaves are white and rolled. Boric acid (16.5% B), borax (11.3% B) or Solubor (20.5% B) can be applied to soils to correct boron deficiency. Borax, Boric Acid or Solubor can also be dissolved in water and sprayed or applied to soil as a dust. Soil application of B (1-2 Kg/ha) is superior to foliar sprays. For hidden deficiency spray 0.2% boric acid or borax at pre flowering or flower head formation stages. Symptoms of boron toxicity are brownish leaf tips and dark brown elliptical spots on leaves, necrotic spot at panicle initiation stage. Use of boron rich ground water, excessive application of boron and high temperature are the main cause of boron toxicity. Boron toxicity can be controlled by B tolerant variety, use of irrigation water having low boron content, deep ploughing etc.

Introduction

Due to intensive cropping system and higher crop productivity, multi-nutrient deficiency is reported in different soil for crop production . For imparting sustainability to the crops and cropping systems at the highest potential yield levels, crop residue recycling, proper irrigation management and micronutrient fertilizer including boron application along with major nutrient fertilization should be made wherever their sub-optimal supplies are suspected. Total boron content ranges from 9 to 85 mg kg $^{-1}$ in world soil and from 2.8 to 630 mg kg $^{-1}$ in Indian soil. Total and available micronutrient contents of the benchmark soils of India have been shown in table 1. Available boron content in Indian soil ranges from 0.04 to 7.40 mg kg $^{-1}$. Soils derived from sedimentary rocks and mineral contain high B than that derived from igneous and metamorphic rocks.

Table 1. Total and available micronutrient contents of the benchmark soils of India

Micro-nutrients	Total content			Available content	
	India		World range	India	
	Range	Mean		Range	Mean
Zn	20-97	55	17-125	0.12-2.80	0.54

Fe	13000-80000	33000	-	3.40-68.1	20.5
Mn	38-1941	537	60-1300	4.00-102.0	26.0
Cu	11-141	41	6-80	0.15-5.33	1.7
B	2.8-630		9-85	0.04-7.40	1.7
Mo	Traces-12.3		1-3	Tr-2.80	-

Among different soil orders, hot water soluble B content in Aridisols, Entisols and Oxisols are 1.7, o.57 and 0.42 mg kg-1 respectively. Aridisols have high water soluble boron due to high evaporation in that environment but Entisols and Oxisols have lower B content due to recently developed soil and highly weathered soils respectively. Out of 882 sample analysed, about 70 % sample in Orissa state and out of 3177 sample analysed in W.B., around 68% sample are deficient in available boron. Actually red and lateritic soils in Orissa and West Bengal are subjected to leaching of boron due to heavy rainfall.

Boron in soil solution

Boron is present mainly in solution, adsorbed, mineral and organic forms in soil. Its availability to plant depends on weathering, mineralization, adsorption-desorption, immobilization and leaching processes. Plant available form of boron is H_3BO_3. Most dominant ionic form in soil is $B(OH)_4^-$ because it acts as an Lewis acid i.e. it accepts electrons rather than donating proton due to its smaller atomic size and higher electronegetivity.

$$B(OH)_3 + H_2O \qquad B(OH)_4^- + H^+ \qquad pK = 9.0$$

$B(OH)_4^-$ is present in soil when soil pH $\geq$ 7.0 and $H_2BO_3^-$ form while soil pH > 9.2. Polyborate ions such as $B(OH)_4^{2-}$, $B_2O(OH)_5^{2-}$, $B_3O_3(OH)_4^-$, $B_4O_5(OH)_4^{2-}$ and hydroxyfluoroborates are present in soil when conc. of B > 0.1 ML^{-1}. Soil solution boron remains in equilibrium with adsorbed boron. Adsorption of boron is taken place by humic substances and clay minerals (crystalline or amorphous substances). Availability of boron in soil depends on several factors such as Soil texture, amount and nature of clay, soil pH and liming, organic matter, soil moisture, inter-relationship with other elements, electrical conductivity of soil, irrigation water and plant factors. Boron availability is higher in soil pH range of 5.0-7.0 and again availability increases above soil pH 8.5.

Interaction of boron with other nutrients

Interaction of nitrogen and boron within the plant is positive as indicated by the withering of growing points due to B deficiency is caused by disturbance in nucleic acid metabolism. Boron aggravates the B deficiency in the soil where boron concentration is low and on the other hand, potassium increases B toxicity in soil to plant when B concentration in soil is high. Again interaction between calcium and boron may be positive (liming of acid soil increases microbial activity in soil and hence increased mineralization) and negative in alkaline soil and under over-liming. Interactions of boron with sulphur and phosphorus are positive because sulphate and phosphate anions compete with borate anions to adsorption process.

Table 2. Interaction of boron with other nutrients [10]

Nutrients	Interaction
B × N	+ ve in plant
B × K	+ Ve at high B conc. in soil - Ve at low B conc. in soil
B × Ca	- Ve in alkaline soil and on over-liming + Ve when microbial activity increases
B × S	+ Ve
B × P	+ Ve

Different yield attributes such as number of flowers per pot, No of pegs/pot, No of pods/pot and pod yield (g/pot) became maximum when Ca:B ratio in groundnut haulm ranged 218-224 and corresponding Ca:B ratio in soil ranged 5×10^5 - 6×10^5. Boron is immobile in the plant system and its concentration is more in older leaves than younger leaves in all level of boron in soil. Interaction between B and Zn is positive in soil. Boron content in both root and shoot increased when dose of Zn increased only when 0.5 mg kg^{-1} B was applied rather than 0.05 mg kg^{-1}.

Boron-essential micronutrient for plant

Boron is an essential micronutrient for plant and its essentiality was first given by K. Warrington in 1923. Boron plays important role in carbohydrate, phenol, auxin metabolism; transport of sugar, cell wall structure and membrane associated reactions, tissue development and differentiation. Boron deficiency in plant inhibits pollen germination and pollen tube growth, nitrogen fixation and also causes flower shedding in chick pea and male sterility in wheat. Root exudates from plants grown with a normal concentration of B (0.1 mg B L^{-1}) (+B treatments) stimulated *nod*-gene expression at a high level, comparable to the induction provoked by 0.5 μM hesperetin, the *nod*-gene-inducing flavones used as a positive control. However, the activity was very low (seven times lower than +B treatments) when *nod* genes were induced by extracts from –B-grown root exudates. Therefore, the results indicated that the absence of the micronutrient affects the expression of nodulation genes in *R. leguminosarum* not by an effect on the bacteria, but by diminishing the induction capacity of root exudates extracts. This is probably due to the modification of the composition of the exudates in B-deficient plants. These results correlate with the number of nodules developed in plants inoculated with *R. leguminosarum* 3841, which was more than double in +B treatments (Table 3, nodules per plant). Interestingly, nodulation of B-deficient plants was recovered to almost 80% of the control when plants were inoculated with 3841 cells previously grown in the presence of the *nod*-gene-inducing hesperetin (–B/3841 Hesp). However, most of nodules developed under B deficiency were not functional due to B deficiency as previously reported.

Table 3. Effects of B deficiency on nodulation and nodule activity in pea plants

Plant treatment	*nod-Gene induction* (βGal activity units)	Nodulation (nodules plant^{-1})	ARA (nmol ethylene g^{-1} nodule h^{-1})
+B	638.9 ± 109.1a	84 ± 20a	42.3 ± 14.6a
-B	76.2 ± 12.1b	37 ± 15b	4.8 ± 1.2b
B/3841 Hesp	865.7 ± 58.1a	66 ± 16c	5.8 ± 0.7b

Diagnosis of boron deficiency in crops

Three important methods for diagnosis of B deficiency in crops are identification of typical B deficiency symptoms in crop, analysis of B concentration in plant and soil. Boron deficiency mainly occurs in growing tips of plants .

Rice: In moderately B deficient soil, Chlorosis of youngest leaves and stem, leaf tip burn, and pale band 2-3 mm wide occurs on leaves; and in highly B deficient soil, whitish and twisted new leaf tips occurs**.**

Wheat: Longitudinal splitting of the newer leaves close to the midrib results saw tooth effect on the margins in the vegetative stage of wheat. As a result, depressed pollen germination, the fertilization process and poor grain setting happens. Grain set failure was associated with less than 10 mg kg^{-1} B in the anthers and 8 mg kg^{-1} B in the carpel. Anthers with lower B contents appeared to have a normal tapetum and lignified endothecium.

Barley: Delay ear emergence, male sterility, degeneration of terminal spikelets, which give the ear the 'rat-tail' symptom and fewer spikelets per ear in barley and triticale.

Sunflower: Sunflower is highly sensitive to boron deficiency, which, when severe, causes the flower head to twist over, become distorted and fail to open, producing no seed and also death of growing point.

Rapeseed: Yellowing of leaves with some orange colours developing in boron-deficient rape plants. Reduced flowering with very little seed formation usually occurs before leaf colouration is seen. Seed pod abortion due to boron deficiency in rapeseed. This could have been avoided if foliar sprays had been applied before flowering

Cauliflower: It is a very good indicator of boron deficiency in an area. It is sensitive to this deficiency and also shows distinctive symptoms, including hollow cavities in the stem and often bronzing of the curd.

Chickpea: Soil B deficiency leads to excessive flower drop and hence poor seed yield in chickpea.

Plant analysis is the most important tool for the diagnosis of B deficiency to the crop as it is very specific to crop plants, independent of soil and climatic parameters, and identification of deficiency symptoms is very difficult in field level. Critical Limits of B for deficiency, sufficiency and toxicity are less than 15 ppm, 15- 100 ppm and more than 200 ppm respectively. Threshold value of boron in crops are given in the table 4.

Table 4. Threshold value of boron in crops [18]

Crops	Plant part	Age (days)	B concentration (ppm) dry weight basis		
			Deficiency	Sufficiency	Toxicity

Wheat	Leaves	14-21	4	35	600
Maize	Younger leaves	45	7	25	100
Rice	Younger leaves	48	10-20	20-40	50
Barley	Leaves	70	-	20	150
Sesame	Leaves	70	2.5	5	-
Sunflower	Middle leaves	30	12-33	40-43	-
Green gram	Younger leaves	51	23-35	86	148
Red gram	Leaves	62	30-44	52	82
Chick pea	Younger leaves	63	11-74	25-31	82

Estimation of critical concentration for deficiency and toxicity in sunflower depends on the plant parts used and age of crop plants. 95% of maximum relative dry matter yield (%) was obtained in 4-week-old sunflower whole shoots and 8-week-old whole shoots when B concentration in whole shoot were 46–60mg kg^{-1} dry matter and 37 mg B kg^{-1} dry matter respectively. Critical boron concentration ranges in soil for prognosis of B deficiency is presented in table 5. Determination of B deficiency to crop can be done by testing the availability of B in soil, but it depends on a large numbers of soil factors, crop factors and also extractants. Critical values of B concentration in soil for deficiency are given depending on crop and extractants. Critical limit of deficiency for hot water soluble B, hot calcium chloride, $CaCl_2$- mannitol and salicylic acid are 0.5, 0.61, 0.25 and 0.45 mg kg^{-1} respectively.

Table 5. Critical boron concentration ranges in soil for prognosis of B deficiency

Species	**Method of**	**Soil pH**	**Critical B conc.**
Black gram (Vigna mungo)	HWS	7.7-10	0.53
Black gram (Vigna mungo)	HWS	5.5-6.5	0.08-0.13
Broccoli, Brussel sprout, cauliflower	HWS	5.8-6.0	0.28-0.34
Peanut (*Arachis hypogaea*)	HWS	5.0-7.7	0.15
Sunflower (*Helianthus annus*)	Hot 0.01 CaCl2	4.7-7.4	0.14
Wheat (*Triticum aestivum*)	HWS	6	0.12-0.15
Wheat (*Triticum aestivum*)	HWS	alkaline	0.32-0.38
Bean (*Phaseolus vulgaris*)	HWS	7.6	0.4-0.5

Management of boron for crop nutrition

For imparting sustainability to the crops and cropping systems at the highest potential yield levels, crop residue recycling, proper irrigation management and micronutrient fertilizer including boron application should be made wherever their sub-optimal supplies are suspected. Relative B requirement of crops is presented in table 6.

Table 1. Relative B requirement of crops

High	Medium	Low
Cotton	Corn	Barley
Canola	Flax	Oats
Sunflower	Grain Sorghum	Soybeans
Cauliflower	Brussel Sprouts	Rye
Beets	Cabbage	Rice
Sugar Beets	Onions	Wheat
Carrots	Potaoes	Beans
Broccoli	Sweet Corn	Peas
Apples	Tomatoes	Pecan
Peanuts	Tobacco	Sugarcane

Table 2. B containing and its B content

Source	**Formula**	**Element**	**FAO specification**
Boric acid	H_3BO_3	17	-
Borax	$Na_2B_4O_7 . 10H_2O$	11	10.5
Solubor	$Na_2B_4O_7 . 5H_2O$ + $Na_2B_{10}O_6 . 10H_2O$	20	20.0
Sodium pentaborate	$Na_2B_{10}O_6 . 10H_2O$	18	-
Sodium tetraborate	$Na_2B_4O_7 . 5H_2O$	14	-
Colemanite	$CaB_6O_{11} . 5H_2O$	10	-
Boron frits	Fritted glass	2-6	-
Boronated SSP	-	0.18	0.18

Gunes *et al.*, conducted an experiment and showed that wheat grain yield increased significantly ($P < 0.01$) by almost 50%, from 3668 to 5475 kg ha^{-1} in Bezostaja at 4.0 kg B ha-1, and, after this level, grain yield decreased strongly to 3515 kg ha^{-1} at the highest level of applied B. Concentrations of B in the shoots and grains of the cultivar increased significantly with increasing levels of applied B (Table 2). Significant positive correlations were observed between grain B concentrations and shoot B concentrations in Bezostaja. B containing and its B content shown in table 7.

Table 3. Effect of dose of B application on the yield and B concentrations (±SE) of shoots and grains of wheat

Boron levels (kg ha^{-1})	**Yield (kg ha^{-1})**	**Shoot Boron (mg kg^{-1})**	**Grain Boron (mg kg^{-1})**
0	3668 ± 210	17.26 ± 0.48	17.13 ± 0.83
1	4441 ± 122	26.87 ± 2.66	20.57 ± 1.31

2	4394 ± 74	28.55 ± 0.69	23.51 ± 1.31
3	4292 ± 231	29.67 ± 0.51	25.75 ± 2.65
4	5475 ± 163	29.91 ± 0.72	26.26 ± 0.69
5	3515 ± 165	33.10 ± 1.86	27.44 ± 2.87
LSD P<0.05	542	4.49	5.39

With increase the rate of B application in different soil, rapeseed yield increased in the 1st year and became maximum at the 3.3 kg ha^{-1}. If again 3.3 kg B $ha^{-1}$is applied in next year, then, in general, B toxicity may happen to the direct crop and next crop (table 8 and table 9). But Wang *et al*., conducted an experiment in highly B deficient soil with oilseed rape-wheat cropping sequence in China and showed that 3.3+3.3 kg ha^{-1} did not cause significant toxicity to oilseed rape yield and rice yield.

Table 4. Effect of B fertilizer rate (kg ha^{-1}) on seed yield of oilseed rape

Soil type	B0	B1.65	B3.3	2nd year	0+0	3.3+0	F+1.65	3.3+3.3
Udifluvent	2.03	2.6	2.57		1.16	1.73	1.69	1.88
Hapludult	0.5	1.48	1.3		0.2	1.09	1.07	1.02
Udifluvent	1.38	1.57	1.41		0.43	1.31	1.28	1.02
Aquent	2.37	2.7	2.63		1.68	1.86	1.92	1.72

Table 5. Effect of residual B treatments on grain yield of rice in 2nd year

Boron treatment (kg ha^{-1})	**Udifluvent**		**Hapludult**		**Udifluvent**	**Aquent**
	Early	Late	Early	Late	Upland rice	Single season
0+0	4.7b	7.3a	5.6a	5.9a	2..6a	8.7a
3.3+0	4.9ab	7.7a	5.7a	6.1a	2.5a	8.6a
F+1.65	5.1a	7.8a	5.8a	6.3a	2.5a	8.6a
3.3+3.3	5.1a	7.6a	5.8a	6.6a	2.5a	8.5a

Starting at late flowering, and weekly throughout pod fill, foliar applications of aqueous H_3B0_3 solutions were carried out so that a total of six sprayings resulted in total elemental boron applications as indicated below. Six split foliar applications which totalled 1.12 kg B/ha in 1987 increased the number of branches/plant at harvest and significantly stimulated the number of pods on branches (per plant) as well as pods/branch. Residual B treatments on grain yield of rice have been shown in table 10. All of these parameters showed a significant ($P < 0.1$) quadratic response to B, with the 1.12 kg B/ha being the optimal treatment for these variables (table 11).

Table 6. Effect of foliar application of B on yield components of soybeans

Yield components per plant	Foliar applied boron (kg/ha)		
	0	1.12	2.24
No. of branches	0.5	0.8**	0.6
No. of pods on branches	1.4	2.4**	1.9
Pods/branch	2.9	3.3**	3.1
Main stem pods	21.5	22.4	22.1
Total pods	23.0	24.9	24.0
No. of seeds	53.2	58.1	56.1
Seeds/pod	2.3	2.3	2.3
Seed yield (g)	8.8	9.6	9.5
Wt./seed (mg)	166.4	165.7	169.5

Sensitivity of yield attributes of different crops to B deficiency varies and these are given in the table

Table 7. Differential sensitivity to low B among different crop species

Crop species	No of genotypes	Attribute measured	Range of sensitivity[a]
Black gram	10	Seed yield	9-71
Green gram	14	Seed yield	34-100
Peanut	14	Seed yield	11-71
Soybean	19	% hollow heart	0-75
Wheat	5	Male sterility	37-94
Wheat	15	Seed yield	64-100
Wheat	253	% GSI	0-100

[a] Relative to performance in B sufficiency (%)

Yield response of crop due to application of major nutrient fertilizers is high. Again, yield response of different crop due to application of B micronutrient was also reported from Bihar states. Differential sensitivity to low B among different crop species have depicted in table 12.

Table 8. Yield response (kg ha^{-1}) of crops to B application

Groups	crops	Bihar		Other states	
		Range	**Average**	**Range**	**Average**
Cereals	Rice	280-1240	310	0-1670	320

	Wheat	10-1190	370	30-1190	380
	Maize	60-990	480	170-1050	480
Pulses	Chickpea	170-980	430	130-900	420
	Pigeon pea	150-550	340	30-90	60
	Lentil	120-310	250	40-490	240
	Black gram	250-280	270	40-350	170
Oilseeds	Groundnut	310-420	370	50-420	220
	Sesame	10-140	90	-	-
	Mustard	80-300	210	-	-
	Linseed	40-310	150	-	-
	Sunflower	320	320	-	-

Application of B@ 1.5 kg ha^{-1} increased the peapod yield over no boron. The magnitude response varied with liming rate (table 13). A combination of 1.5 kg B ha^{-1} and 3.0 t ha^{-1} appeared optimum yield and toxicity of boron decreased with increasing lime rate because lime and boron has both positive and negative interaction. Effect of lime and B on the yield of pea and corn shown in table 14.

Table 9. Effect of lime and B on the yield of pea and corn

Lime rate (t ha^{-1})	**Peapod yield (t ha^{-1})**				**Lime rate (t ha^{-}**	**Corn yield (t ha^{-1})**			
	0 kg B/ha	1.5 kg B/ha	3.0 kg B/ha	4.5 kg B/ha		0 kg B/ha	1.5 kg B/ha	3.0 kg B/ha	4.5 kg B/ha
1.5	1.71	2.8	1.78	1.3	1.5	3.34	3.47	3.49	3.19
3	1.07	3.34	2.83	1.74	3	3.09	3.21	3.78	3.87
6	0.92	3.35	3.39	2.57	6	2.86	3.18	3.82	3.98

Efficient genotype can grow well in low B containing soil without decreasing in crop yield and this genotype can be effectively used for higher crop production. Some genotypes of wheat crop for different countries are given in table 15.

Table 10. Boron efficiency of selected Asian wheat varieties and genotypes

Country	**Efficient**	**Inefficient**
India	HD2307, HDR77, C 306	Janak, UP262, BW5, BW11, BW43, HP1102, HP1209, HD2285, HUW206
China	Sonora 64	Saric F70, Tanori F71, Chapingo, Spring 98

Bangladesh	Fang 60	Kanchan, Gourab, E12, Sourav, Ananda, Aghrani, Balaka, Inia 66, Kanchan, Kalyasona, Sonalika, Veery
Thailand	Fang 60, Sonora 64	Seri, Kauz, SW41, SW23, SW41, Bonza, Tatiara

Conclusions

Boron deficiency occurs in highly leached acid soils, light textured calcareous and alkaline soils characterized by low organic matter. Boron plays important role in carbohydrate, phenol, auxin metabolism; transport of sugar, cell wall structure and membrane associated reactions, tissue development and differentiation. Foliar applications of B fertilizers have direct influence on crop yield but soil applications have both direct and residual effect. Liming has a dual effect on B availability *i.e.* it increases B availability on liming of acid soil and decreases B toxicity in soil containing higher boron.

References

Das SK. 2014. Chemicals responsible for systemic acquired resistance in plants a critical review. Journal of Atoms and Molecules 4 (3): 45-51.

SK, Avasthe RK, Gopi R. 2014. Vermiwash: use in organic agriculture for improved crop production. Popular Kheti 2: 45-46.

Roy A, Das SK, Tripathi AK and Singh NU. 2015. Biodiversity in North East India and their Conservation. Progressive Agriculture 15 (2): 182-189 (2015).

Barman H, Roy A, Das SK. 2015. Evaluation of plant products and antagonistic microbes against grey blight (*Pestalotiopsis theae*), a devastating pathogen of tea. African Journal of Microbiology Research 9 (18): 1263-1267.

Das SK. 2014. Scope and Relevance of using Pesticide Mixtures in Crop Protection: A Critical Review. International Journal of Environmental Science and Toxicology 2(5): 119-123.

Das SK, Mukherjee I and Kumar A. 2015. Effect of soil type and organic manure on adsorption–desorption of flubendiamide. Environmental monitoring and assessment 187 (7): 403.

Das SK. 2013. Mode of action of pesticides and the novel trends-a critical review. International Research Journal of Agricultural Science and Soil Science. 3(11): 393-403.

Das SK. 2014. Recent development and future of botanical pesticides in India. Popular Kheti 2 (2): 93-99.

Mate CJ, Mukherjee I and Das SK. 2014. Mobility of spiromesifen in packed soil columns under laboratory conditions. Environmental monitoring and assessment 186 (11): 7195-7202.

Das SK, Avasthe RK, Singh M and Sharma K. 2015. Biobeds: on-farm biopurification for environmental protection. Current Science 109 (9): 1521-1521.

Das SK and Avasthe RK. 2015. Carbon farming and credit for mitigating greenhouse gases Current Science 109 (7), 1223.

Mukherjee I, Das SK and Kumar A. 2012. A Fast Method for Determination of Flubendiamide in Vegetables by Liquid Chromatography. Pesticide Research Journal 24 (2): 159-162.

Das SK, Avasthe RK, Singh R and Babu S. 2014. Biochar as carbon negative in carbon credit under changing climate. Current Science 107 (7): 1090-1091.

Das SK and Mukherjee I. 2011. Effect of light and pH on persistence of flubendiamide. Bull Environ Contam Toxicol, 87: 292–296.

Das SK and Mukherjee I. 2012. Effect of moisture and organic manure on persistence of flubendiamide in soil. Bulletin of Environmental Contamination Toxicology 88: 515–520.

Das SK, Mukherjee I and Das SK. 2012. Dissipation of flubendiamide in/on Okra [*Abelmoschus esculenta* (L.) Moench] Fruits. Bulletin of Environmental Contamination Toxicology 88: 381–384.

Das SK and Mukherjee I. 2012. Flubendiamide transport through packed soil columns. Bulletin of Environmental Contamination Toxicology 88: 229–233.

Das SK and Mukherjee I. 2014. Influence of microbial community on degradation of flubendiamide in two Indian soils. Environmental Monitoring & Assessment, 186: 3213–3219.

Das SK, Mukherjee I and Kumar A. 2015. Effect of soil type and organic manure on adsorption–desorption of flubendiamide. Environmental Monitoring & Assessment 187:403. DOI 10.1007/s 10661-015-4623-2.

Das SK. 2014. Role of micronutrient in rice cultivation and management strategy in organic agriculture-A reappraisal. Agricultural Sciences 5 (09): 765.

Das SK. 2014. Recent developments in clean up techniques of pesticide residue analysis for toxicology study: a critical review. Universal Journal of Agricultural Research 2 (6): 198-202.

Das SK, 2017. Nanoparticles advanced characterization techniques: A view point. Journal of Atoms and Molecules 7 (4): 1091-1098.

Das SK, Mukherjee I, Das SK. 2017. Metsulfuron-methyl Herbicide on Dehydrogenase and Acid Phosphatase Enzyme Activity on Three Different Soils. International Journal of Bio-Resource & Stress Management 8 (2): 236-241.

Das SK, Roy A and Barman H. 2016. Fungi toxic efficiency of some plant volatile essential oils against plant pathogenic fungi African Journal of Microbiology Research 10 (37), 1581-1585.

Mukherjee I, Das SK, Kumar A. 2016. Degradation of flubendiamide as affected by elevated CO2, temperature, and carbon mineralization rate in soil. Environmental Science and Pollution Research 23 (19), 19931-19939.

Das SK, Mukherjee I and Roy A. 2016. Alachlor and Metribuzin Herbicide on N_2-fixing Bacteria in a Sandy Loam soil. International Journal of Bio-Resource & Stress Management 7 (2): 334-338.

Barman H, Roy A, Das SK, Singh NU, Dangi DK, Tripathi AK. 2016. Antifungal properties of some selected plant extracts against leaf blight (*Alternaria alternata*) in tomato. Research on Crops 17 (1): 151-156.

Das SK, Avasthe RK, Singh M. 2015. Buckwheat: the natural enhancer in rhizosphere phosphorus. Current Science 109 (10): 1763.