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FOREWORD

To minimize the gap between the demand and supply of cereals, oilseeds and pulses, intensive efforts are being made to increase their production. As ever-increasing population and urbanization cannot allow increase in the land area under the cultivation, yield *per se* need to be improved further. With the improvement of crop productivity through the adoption of high-yielding varieties and multiple cropping systems, fertilizer use has become more and more important to increase crops yield and quality. The shift towards the large scale use of high analysis fertilisers, nutrients other than N,P and K have shoot-up into prominence.

All crops need at least sixteen nutrients for their growth. S is now recognized as the fourth major plant nutrient after nitrogen, phosphorus and potassium and is a proven "yield & quality" nutrient. Sulfur deficiencies are becoming widespread and crop removals are on the increase. Deficiencies have been reported from several states of India. A number of commonly available and used fertilizers contain 12-24% S which can be as useful as NPK on S deficient soils, is quiet often ignored. Giving due recognition to the sulfur component of different sources and putting it to work in S deficient areas will contribute towards higher agricultural production through balanced and efficient use of all applied nutrients. Research addressing improving sulfur use efficiency of rice cultivars has also been overshadowed by other major nutrients like nitrogen and phosphorous.

This research bulletin has focused on the current status of sulfur in our soils and the management options to alleviate the field problems for sustainable rice based cropping systems. The information would be of great use and hope that will benefit scientists, extension workers, and the students. I congratulate the authors for their efforts in bringing out valuable information in the form of this bulletin.

(V. RAVINDRA BABU)
Project Director (A)

Contents

1. Introduction

Rice (*Oryza sativa* L.) is grown under a range of hydrological regimes from the unflooded rainfed, through the rainfed and irrigated flooded, to the deep water and floating cultivation systems. It is the staple food for a large proportion of the world's population. The geographic range of worldwide rice production is from the equator to the temperate areas of northern Japan and southern Australia and from sea level to attributes of more than 2500 m.

The anaerobic soil environment created by flood irrigation of lowland rice creates a unique and challenging environment for the efficient management of soil and fertilizer nutrients. Supplying required essential nutrients in adequate rates, sources, application methods, and application times are important factors that influence the productivity and sustainability of rice. While the soils, climate, cultivars and degree of mechanization may vary considerably among the rice producing regions of the world, the basic principles governing efficient nutrient use of by rice are relatively constant.

In rice growing areas several crop combinations (cropping systems) are in practice based on agro-ecological conditions, market and domestic needs and facilities available with farmers, Rice based cropping system is a major cropping system practiced in India, which include the rotation of crops involving rice, pulses, oil seeds, cotton, sugarcane, green manures, vegetables, etc., and is the most predominant of the 30 major cropping systems identified in India (Yadav and Prasad, 1998). In the era of shrinking resource base of land, water and energy, resource-use efficiency is an important aspect for considering the suitability of a cropping system (Yadav, 2002).

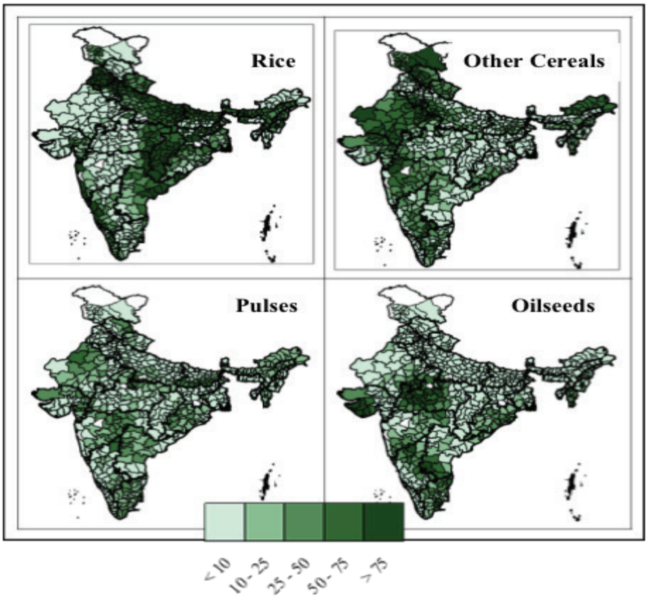


Fig. 1: Rice Based Cropping Systems in India (Source: @2014 Global Water Forum)

Our aim is to provide a comprehensive view describing the nutritional problems, nutrient use efficiencies, and the production strategies used for efficient nutrient use and production of lowland rice.

Sulfur was initially called brimstone. Free sulfur ‘gandhaka’ was known in India 3000 years ago. It was used in fumigation, medicines and bleaching by Aryans, Greeks and Romans. In 1777, Lavoisier was the first to recognize the basic nature of sulfur. Sulfur represents the ninth and least abundant essential macronutrient in plants, preceded by C, O, H, N, K, Ca, Mg and P. Sulfur is essential to life. It is a minor constituent of fats, body fluids, and skeletal minerals and a constituent of insulin and certain antibiotics.

Plant nutrients in soil whether naturally endowed or artificially maintained are major determinant of success or failure of a crop production system. Among the essential elements sulfur is the yield+quality nutrient and very much beneficial for increasing the production, quality of rice (Tandon 1991). Sulfur is a constituent of essential amino acids (cysteine, methionine, and cystine) involved in chlorophyll production and is thus required for protein synthesis, and plant function and structure. It is also a constituent of coenzymes required in protein synthesis. It is contained in the plant hormones thiamine and biotine, both of which are involved in carbohydrate metabolism. S is also involved in some oxidation-reduction reactions. It is less mobile in the plant than N, so that deficiency tends to appear first on young leaves. S deficiency affects human nutrition by causing a reduction in cysteine and methionine content in rice. The nitrogen metabolism is greatly influenced by sulfur. At inadequate uptake of sulfur, synthesis of proteins and oils is suppressed, and consequently, the absorbed nitrate that is accumulated as non-protein elements may result not only in loss of yield, but also may impair the quality of crop produce. The various results reveal that nitrogen, a vital major plant nutrient element, depends on sulfur, among other important nutrient elements including phosphorus. Application of sulfur is inevitable, particularly when nitrogen application is raised for higher production. A proportion of sulfur to nitrogen of 1:2 to 1:3, depending upon the oilseed or cereal crops, is likely to boost and sustain the yield as well as quality of crops.

Sulfur cycling has important implications because it is a source of S for crops, and yet the S being cycled out can be a major drain on the S economy of crop production systems. The most obvious illustration of S cycling is the soil - plant - rain (through-fall) pathway. Another pathway is the atmosphere-plant-soil route. This is called dry deposition and is important in industrial and residential areas where fossil fuels are burned. In the tropics, burning of vegetation is relatively more important. Areas that have a marked wet-dry rainfall pattern giving rise to savanna-type vegetation that is regularly burned no doubt lose much of the S that accrues to them in rainfall in this way. Large areas of the tropics are so affected. Burning is generally done in the dry season. Thus there is little likelihood that S volatilized by agricultural burning will be redeposited on land from which it came. A disproportionate quantity will accrue to downwind locations and to nearby areas where soils are moist and vegetation is green (Fox and Blair, 1987).

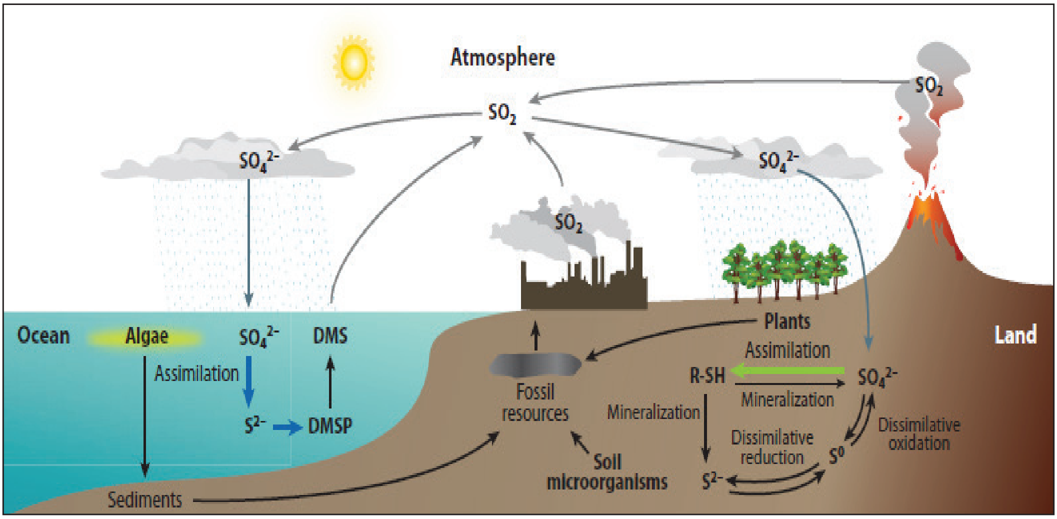


Fig. 2: Sulfur cycle in nature (Source: Hideki. et. al., 2011)

Sulfur deficiency has been reported from nearly all rice producing regions of the world including Indonesia, Brazil, India, Bangladesh, Thailand and USA. Available information suggests that in general a significant percentage of tropical soils of Asia have low total resources of Sulfur because of low quantities of organic matter and its rapid mineralization as well as leaching losses. This deficiency in tropics cause not only reduction in yield but also in the amount of methionine, cysteine, and cystine types of S containing essential amino-acids in cereals, oilseeds and pulses that will be disastrous for cereal consuming countries.

Major attention towards S deficiency was drawn during the sixties when 75 per cent of the ground nut growing soils of Ludhiana were found deficient in S (Kanwar 1963). Sulfur deficiencies have been reported from the red *chalka* soils (Alfisols) of the Hyderabad region (Saharan *e.t al.,* 1989) and coastal sandy soils of Guntur and Prakasam (Jamuna *et al.,* 1984). Sulfur deficiency is generally observed in light textured, low organic matter containing soils which are prone to leaching. A soil is considered deficient if the tests are less than 10 mg/kg soil extractable with 0.15% Ca $Cl_{2.}$

Causes of Sulfur deficiency

Sulfur deficiency is accentuated in soils of the tropics by intensive agricultural practices, less use of organic manures, removal of crop residues and leaching of sulfur by heavy rains (Yadvinder Singh *et al.* 2005). Also caused by absence of Sulfate containing fertilizers (In the decade, the N:S ratio in applied nutrients increased to 20 and P_2O_5 : S ratio to 8 against the desired ratio of 5-7:1 and 3:1 respectively), low sulfur content in irrigation water, rain water and soil condition. Sulfur deficiency is common in crop rotations including pulses and oil seeds.

Major causes of S deficiency increases are due to

- Increases in net depletion of soil S, not only by the removal of grain, but also by the removal of stover/straw from the field.
- Low level of fertilizer use on pulses and oilseeds that have a higher requirement of S than cereals per unit of grain production. These crops occupy almost 27% of the gross cropped area.
- Depletion of soil S due to higher S removals as compared to S additions, resulting in severe deficit in many soils and cropping systems. At present, S uptake by crops is twice the amount of S added through fertilizers.
- A fertilizer use pattern dominated by S-free fertilizers, such as urea, DAP, MOP and S-free NP/NPK complex fertilizers. Such a product pattern not only excludes S, but accentuates its depletion resulting from the luxuriant crop produced with NPK.
- Possibility of leaching losses of soil S with the spread of flood irrigation to large areas, and in areas receiving heavy rainfall.

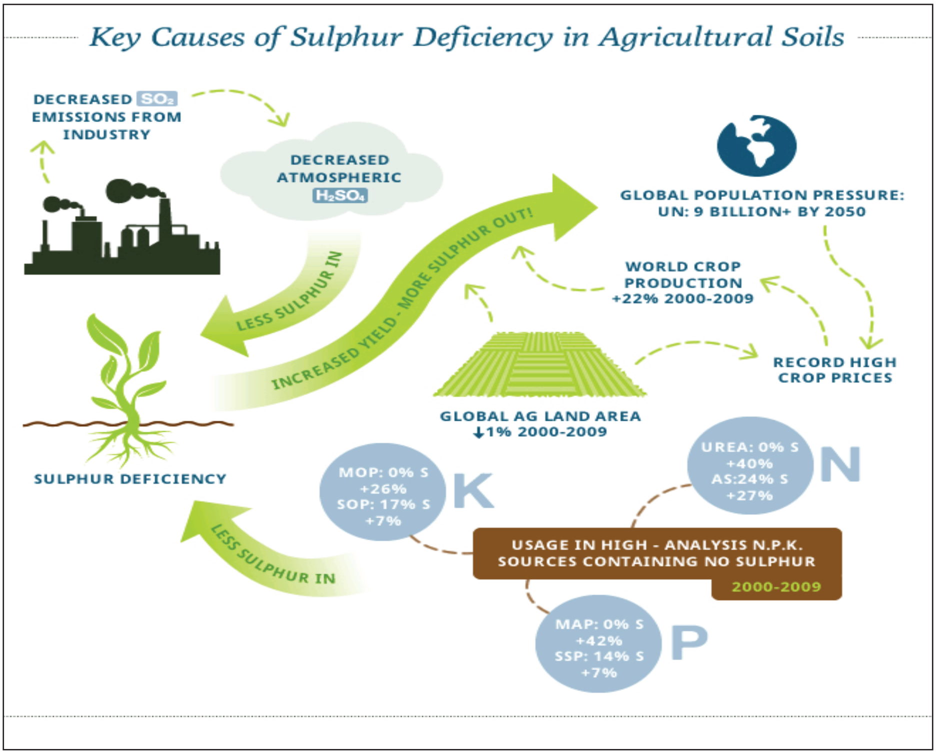


Fig. 3: Causes of Sulfur deficiency (Source-@ 2012 Sulvaris)

2. Sources of Sulfur

Sources of sulfur in soil are sulfides, sulfates and organic combinations with C and N. Sulfur in soil exists in 4 forms viz., total sulfur, organic sulfur, non-sulfate sulfur and available sulfur. The variation in sulfur fractions in soils is attributed to the differences in parent material, climatic conditions, nature and quality of organic matter.

The lithosphere contains about 0.06 per cent sulfur. During the process of weathering, much of the sulfur in pyrites and other metallic sulfides is transformed to sulfate and either accumulates or is lost by leaching.

Organic sulfur in soils is an important reserve supply of the element for plant growth. As organic matter is decomposed, the sulfur is released mainly as sulfate, which is the principal source of sulfur for higher plants. Fallowing accelerates the decomposition of soil organic matter, and has been shown to temporarily increase available sulfur and plant growth on sulfur-deficient soils (Commonwealth Scientific and Industrial Research Organization, 1954).

In poorly drained soils, large quantities of inorganic S may be present in reduced forms, mainly sulfides. Sulfides are usually found in subsoils below the water table. Re-oxidation of sulfide to sulfate under aerobic conditions can result in the formation of acid-sulfate soils (Fleming and Alexander, 1961). The losses of H_2S from productive rice soils may be more due to increased losses at night as a result of the nocturnal decline in the degree of oxidation of the rhizosphere, surface soil, and floodwater.

In addition, as rice cropping is intensified and larger areas are brought under controlled irrigation, many rice wetland soils are being maintained in anoxic states for longer periods. This potentially increases the degree of soil reduction and thus gaseous S emissions. The loss of S may be further increased by the use of waste water which is high in carbon to irrigate rice fields, as is occurring near some large cities. The planned or incidental application of sulfate may also increase gaseous S losses, especially where more reducing management practices are used.

Atmosphere

Most of the fuels contain varying levels of Sulfur. When these fuels burn sulfur dioxide is released into the atmosphere and may be deposited in the soil by rainfall or absorbed by soils and plants. Sulfur dioxide being heavier than air settles out of atmosphere over relatively short distances from the centre of the industrial belt. The concentration of sulfur in the atmosphere may be directly related to the sulfur nutrition of plants, Most of the atmospheric sulfur is in the form of SO_2. SO_2 can be adsorbed through the leaves of plants. Since the root medium was not isolated from the atmosphere there was a possibility that SO_2 was adsorbed by the root medium and after oxidation to sulfate taken up by the plant.

Irrigation Water

Sulfur is present in irrigation water as sulfate-sulfur and is an important source for crops. Well water vary in sulfur content depending on the source of rock through which they pass. The river water contains lowest amount of sulfur near their sources and increases as the flow is supplemented by drainage water from cultivated and fertilized areas.

Rain water

The S in rainfall is often assumed to be largely in the sulfate form and is generally higher in industrialized countries and near industrial centres, volcanoes, swamps and seas (Blair *et al* 1978) in 1987 that the observations in Korea showed that in rainfall is inversely related to the amount of precipitation. S in rainfall declines along a transect from the coast as shown in northern Queensland (Probert 1976).

Crop Residues

Crop residues are used as animal feed, for thatching of homes, and as a source of domestic and industrial fuel. A large portion of unused crop residues are burnt in the fields primarily to clear the left-over straw and stubbles after the harvest , which results in loss of plant nutrients like N, P, K and S. Crop residues contain 0-2 kg S/ha. When they are added back to the soil, the removed S and other nutrients are returned back to the soil. Therefore, appropriate management of crop residues assumes a great significance.

Manures

Organic manure provides all the nutrients that are required by plants but in limited quantities. Manure has always supplied sufur to crops, but its contribution is often overlooked. The amount varies from 0.45% to 0.70% on dry weight basis. Thus animal manures are generally required in large quantities due to their low nutrient content. Animal manures (Farm Yard Manure / compost) are the oldest sources of plant nutrients used by farmers and poultry manure is richer than cattle manure.

Fertilizers

The incidental addition of sulfur in fertilizers has been and will continue to be an important source of sulfur for crop production, Mehring and Bennett (1950) summarized the data showing the sulfur content of fertilizers, manures, and soil amendments. Normal super phosphate contains an average of about 12 per cent sulfur. Since super phosphate is the source of phosphorus in many mixed fertilizers, most mixed fertilizers contain a considerable content of sulfur as sulfate.

Elemental sulfur is often added to the soil in insecticides and fungicides. Under favorable conditions in the soil, elemental sulfur is oxidized to sulfate by microorganisms. It is unlikely that the sulfur would be oxidized in time to benefit the immediate crop but the succeeding crops may be benefited by residual sulfate. It is possible that elemental sulfur may enter into the nutrition of some plants by being absorbed directly through the leaves like lesion.

3. Sulfur transformations

The soil environment is a primary component of the global bio-geo-chemical S cycle, acting as a source and sink of various S species. The global cycling involving inorganic as well as organic compounds of S occur through a variety of mineralization and redox reactions. The broad range of oxidation states of sulfur (-2 to +6) allows S to move freely between the lithosphere, hydrosphere and atmosphere.

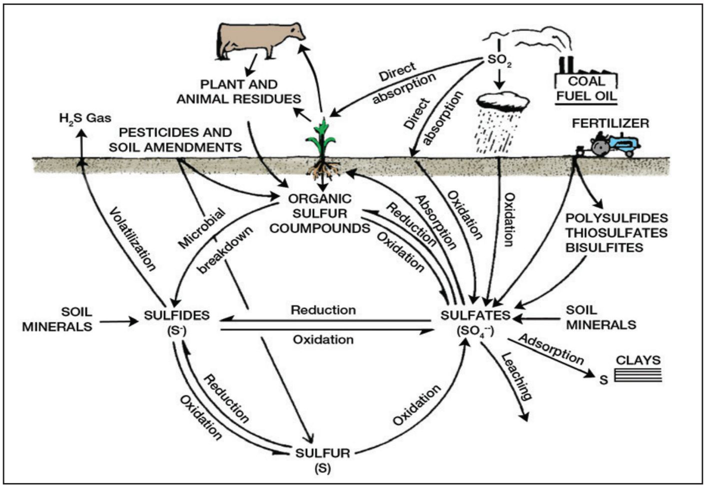


Fig. 4: sulfur cycle in soils (Source: Kovar and Grant 2011)

In soils, S occurs in inorganic and organic forms and is cycled between these forms via mobilization, mineralization, and immobilization, oxidation, reduction and volatilization processes. Ninety-five percent or more of the total sulfur in soils is in organic forms though inorganic S predominates only where S occurs as pyrite and other base metal sulfides, gypsum and elemental sulfur in limited areas where saline, acid sulfate, gypsiferous and in other soils dominated by sulfur-containing minerals are located. Soil sulfur pool is extremely dynamic wherein the inorganic sulfur forms are immobilized to organic sulfur, different organosulfur forms are interconverted, and immobilized sulfur is simultaneously mineralized to yield plant available inorganic sulfur.

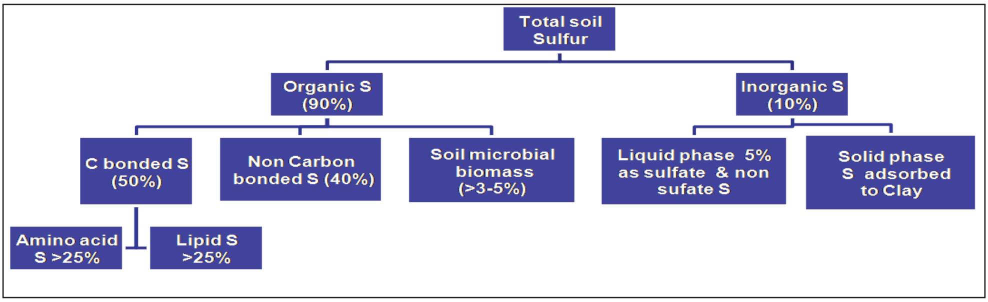


Fig. 5: Forms of soil sulfur (Source: Anandam et al, 2011)

Mineralization - the breakdown of organic containing sulfur compounds to form mineral sulfate

Mineralization is the process by which organic S is decomposed and released as inorganic S. The mineralization of S present in organic forms is strictly a microbiological process with two pathways being used for mineralization of organic S. The pathways are (a) the biochemical process in which there is extracellular hydrolysis of organic S due to catalysis by exoenzymes like sulfatases. Organic S in the ester fraction, are usually mineralized through this process. In the other mechanism termed the biological process, the release of S from organic materials is due to the oxidation of C by soil organisms. Sulfate is released as a by product of the decomposition of organic matter. C-bonded organic S is thought to be mineralized mainly through this process.

Table 1: Carbon/Sulfur Ratios of Plant Residues as Indicators of Mineralization and Immobilization Processes

C:S Ratio = <200	C:S Ratio = 200–400	C:S Ratio = >400
Mineralization >> Immobilization	Mineralization = Immobilization	Immobilization > Mineralization
Net gain of inorganic sulfur	Neither a gain nor a loss of inorganic sulfur	Net loss of inorganic sulfur

Source: Ramesh and DeLaune, 2008

Arylsulphatases belongs to the sulfatase family of enzymes and are responsible for the hydrolysis of aromatic ester sulfates in the soil ($R–O–SO_3$) to phenols (R–OH) and sulfate (SO_4). Actinobacteria and Pseudomonads have been identified as the main groups of bacteria that secrete arylsulfatases into the external environment for S mineralization. Low SO4 concentrations in the soil solution associated with poor S availability for both plants and soil microorganisms stimulate the production of sulfatases. Arylsulfatase activity is considered as a key functional marker of S mineralization in soil and is reported to vary from 7-340 µg p-nitrophenol/ g soil under field moist conditions to 2-361 µg p-nitrophenol/ g soil under air dried conditions. In a study conducted at IIRR, arysulfatase activity was determined in the rhizosphere of rice after application of different sulfur fertilizers with dosages varying from 0-60 kg S/ha.

Table 2: Effect of S sources & dosages on rhizosphere arylsulfatase activity of rice

Treatments	Arylsulfatase activity µg p-nitrophenol/ g soil		
	At tillering	At panicle initiation	At harvest
Main – S fertilizers			
Single super phosphate	319.61	295.84	341.96
Ammonium sulfate	334.91	357.6	340.24
Potassium sulfate	329.79	416.55	421.24
Zinc sulfate	326.94	377.14	595.97
Magnesium sulfate	326.58	381.55	375.44
CD (0.05)	NS	9.20	18.79
CV (%)	11.37	2.99	5.38
Sub plots – S levels			
No sulfur	348.87	376.15	268.80
15 kg S/ha	318.09	409.70	396.75
30 kg S/ha	335.54	334.80	540.32
45 kg S/ha	306.15	343.07	426.92
60 kg S/ha	332.92	364.96	442.44
Expt. Mean	327.57	365.73	414.97
CD (0.05)			
Sub	NS	12.72	38.67
Main x Sub	70.62	27.04	79.59
CV (%)	13.11	4.71	12.63

Arylsulfatase activity indicative of sulfur mineralization, was influenced by crop stage, sulfur source and the quantity of sulfur applied as fertilizer. Generally the activity was observed to be higher at panicle initiation and harvest stages than at tillering stage perhaps due to the availability of readily available sulfur in soil immediately after fertilization. Arylsulfatase activity during panicle initiation and at maturity was highest with potassium sulfate and Zinc sulfate probably because they are highly water soluble source of sulfur which releases sulfate immediately after application which could lead to immobilization of inorganic sulfate. The highest activities at all the three crop stages was observed under 0 and 15 kg S application indicating that mineralization of organic sulfur occurs when less sulfur is applied to soils.

Immobilization - the conversion of mineral sulfate to organic sulfur compounds

Sulfur immobilization is a process in which inorganic S, mainly sulfate, is incorporated into organic compounds through biological reactions. During the microbial assimilation of inorganic S added to soil, SO_4 is transformed to low molecular weight organic S compounds resulting in the immobilization of S in soil microbial biomass. Between 1 and 5% of the soil organic S can be accounted by microbiological biomass where organic S exists in form of proteins and amino acids in microbial cells. The S concentration of most soil microorganisms ranges between 1 and 10 µg/g, the C:S ratio between 57:1 and 85:1 and the N:S ratio is about 10:1. The microbiological biomass is relatively labile and thought to be the most active pool for S turnover in soil. At IIRR, increase in the quantity of sulfur applied resulted in higher populations of bacteria fungi and actinomycetes which could represent that a significant portion of sulfur is captured in the microbial biomass.

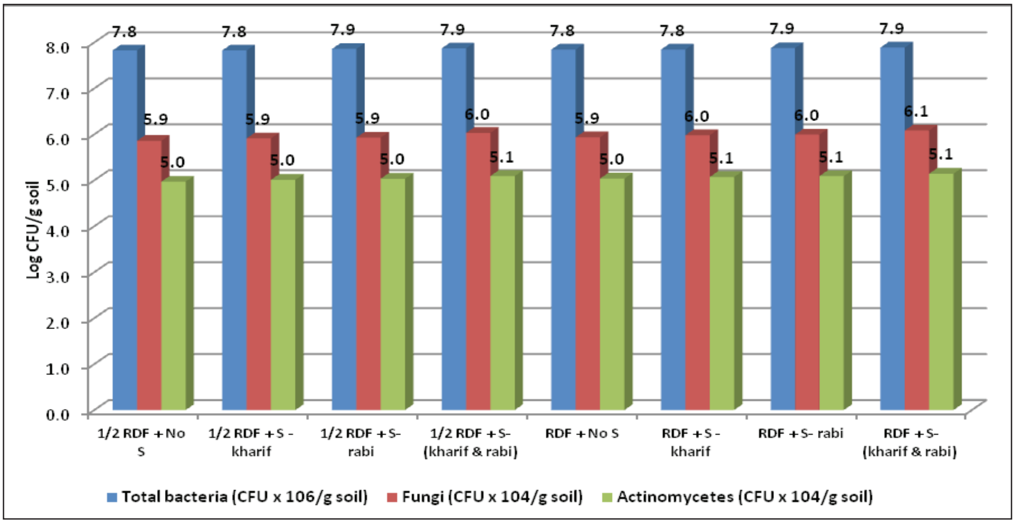


Fig. 6: Effect of NPK and S fertilization on soil microbial populations

Oxidation - the conversion of inorganic sulfur compounds of lower oxidation state to a higher state

Sulfur oxidation involves the oxidation of reduced sulfur compounds such as sulfide (H_2S), inorganic sulfur (S^0) and thiosulfate. Aerobes, facultative organisms and anaerobes contribute to sulfur oxidation. Elemental sulfur is commonly used as S fertilizer in agricultural systems. The elemental S is oxidized to sulphite by the soil microbial population. This conversion is necessary to render the S plant available with the rate of oxidation being a major factor influencing the effectiveness of elemental S fertilizer. Oxidation of S occurs readily in some soils, but chemical, physical and biological factors limit oxidation rates in other soils.

Table 3: Sulfur oxidising bacteria in soils

Aerobic sulfur oxidizing bacteria		
Autotrophic	**Mixotrophic**	**Heterotrophic**
Thiobacillus thioparus	*T. intermedius*	*T. perometabolis*
Halothiobacillus neapolitanus	*Paracoccus versutus*	*Beggiatoa spp*
Thermithiobacillus tepidarius	*T. organoparus*	*Burkholderia spp*
Acidithiobacillus sp	*Pseudomonas spp*	*Alcaligenus spp*
Thiobacillus denitrificans	**Anaerobic sulfur oxidizing bacteria**	
Starkeya novella	**Photolithotrophs**	
Thiobacillus thermophilic	*Chromatium spp*	*Oscillatoria sp*
Sulfobacillus thermosulfidooxidans	*Chlorobium spp*	*Lyngbya spp*
Acidianus brierleri	*Ectothiorhodospira spp*	*Aphanothece*
Beggiatoa alba	*Rhodopseudomonas spp*	*Chloroflexus aurantiacus*
Sulfobacillus acidocaldarius	**Chemolithotrophs**	
Thermothrix thiopara	*Thiobacillus denitrificans*	*Thermothrix thiopara*
Acidothiobacillus thiooxidans	*Microcoleus spp*	*Phormidium spp*

(Source: Anandham et. al., 2011)

In an experiment conducted at IIRR, in the rice black gram system, the sulfur oxidizer population was found to be positively stimulated by the both NPK and sulfur fertilizer application.

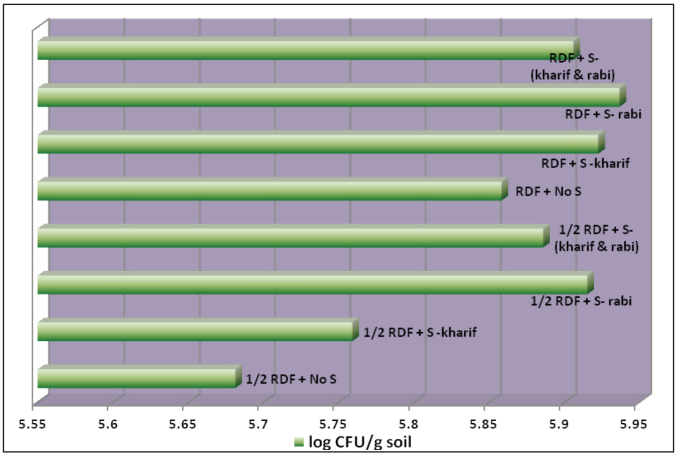


Fig. 7: Sulfur oxidizing population in rice- Bengal gram system

Reduction - the conversion of inorganic sulfur compounds of higher oxidation state to a lower state

Two types of sulfate reduction that occur are a) the assimilatory or biosynthetic S reduction where the microbes reduces sulfur for nutritional needs and the second type is the dissimilatory or respiratory pathway in which sulfate serves as terminal electron acceptor and is termed as anaerobic respiration. Sulfate is reduced to hydrogen sulfide by *Desulfovibrio* and *Desulfatomaculum* in this pathway. Elemental sulfur is also reduced to H_2S by some anaerobic members of the Bacteria and Archaea. Among the Bacteria are *Desulfuromonas acetoxidans, Desulfovibrio gigas*, while *Pyrococcus furiosus, Pyrodictium*, and *Acidianus* reduce S among the Archaea. Two fungi, *Rhodotorula* and *Trichosporon*, have also been found to be able to reduce S^0 to H_2S.

Sulfur volatilization

The decomposition of organic S compounds in poorly drained soils and sediments lead to the formation of volatile S compounds which include mercaptans and alkyl sulfides such as dimethyl sulfide. While some volatile S compounds cause unpleasant odours and inhibit certain processes in soil, some S volatiles are also involved in plant growth promotion.

Table 4: Sulfur Gases Produced in Soils by the Microbial Degradation of Organic Matter

Volatile Sulfur Compounds	Biochemical Precursors
H_2S (hydrogen sulfide)	Proteins, polypeptides, cystine, cysteine, glutathione
CH_3SH (methyl mercaptan)	Methionine, methionine sulfoxide, methionine sulfone, S-methyl cysteine
CH_3SCH_3 (dimethyl sulfide)	Methionine, methionine sulfoxide, methionine sulfone, S-methyl cysteine, homocysteine
CH_3SSCH_3 (dimethyl disulfide)	Methionine, methionine sulfoxide, methionine sulfone, S-methyl cysteine
CS_2 (carbon disulfide)	Cysteine, cystine, homocysteine, lanthionine, djenkolic acid
COS (carbonyl sulfide)	Lanthionine

(Source: Ramesh and DeLaune, 2008)

Sulfur transformations in wet rice cultivation

Rice field soils represent anaerobic freshwater habitats where anaerobic processes such as denitrification, ferric iron reduction, sulfate reduction and methanogenesis are the terminal steps in the degradation of organic matter. In rice field soil the highest in situ sulfate reduction rates and highest cell numbers of sulfate reducers occur in or near oxygenated zones. The rice plants also provide the soil with organic material especially root exudates consisting of many substances (acetate, lactate, etc.) that are typical electron donors for sulfate reducers. Therefore, a stimulating effect of the rice roots on the sulfate-reducing community is not only due to the indirect provision of electron acceptors but also due to a direct supply of easily degradable electron donors. Low redox potential of rice soils causes reduction of sulfate to sulfides, some of which are toxic (H_2S), and others low in solubility (FeS, ZnS). In addition, the slower mineralization of organically bound sulfur decreases availability of sulfur to rice in submerged soils.

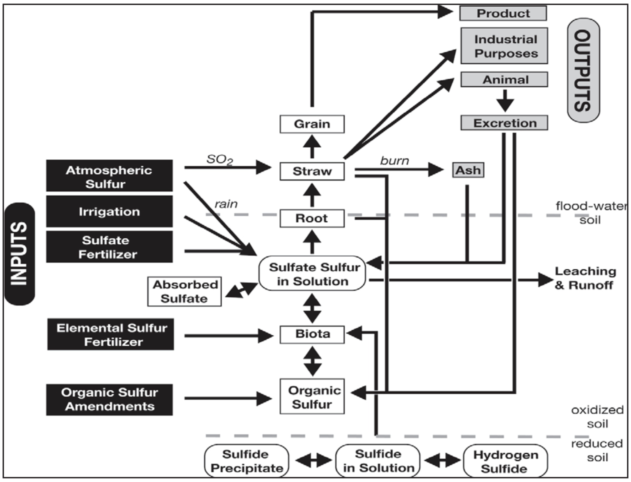


Fig. 8: Sulfur cycling in paddy field (Source: Bell, 2008)

The rice ecosystem provides a unique soil profile which supports a variety of sulfur cycling microorganisms involved in both sulfur mineralization and inorganic transformations.

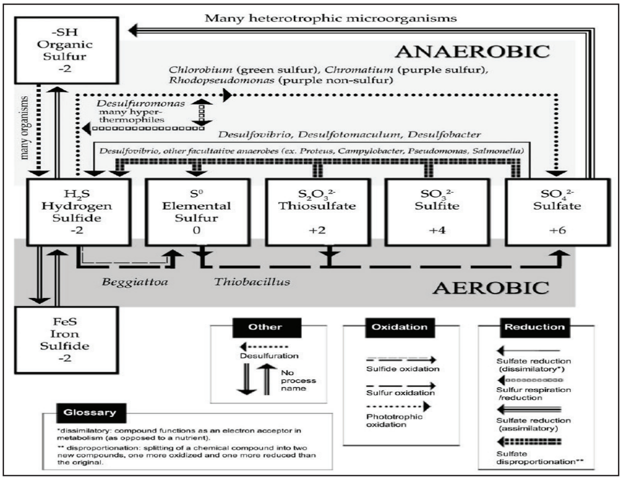


Fig. 9: Microorganisms involved in sulfur cycling in rice soils (Source: Brian et al, 2005)

Role of sulfur cycling microorganisms in plant sulfur nutrition and growth promotion

Plant growth is dependent on bacteria, saprophytic, and mycorrhizal fungi which facilitate the cycling and mobilization of sulfur. In addition S cycling microorganisms also act as plant growth promoting microorganisms facilitation plant growth by various mechanisms.

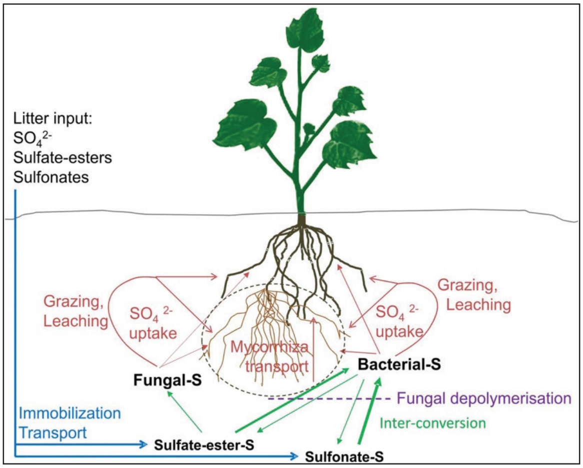


Fig. 10: Mobilization of organic S by micro organisms for plant nutrition

(Source: Mariea and Achim, 2014)

Mobilization of organic S for plant uptake

Sulfate-esters and sulfonates are utilized by *Variovorax*, *Polaromonas*, *Acidovorax*, and *Rhodococcus* with arylsulfatase enzyme complex to release SO$_4$. AM fungi are also stimulated by organo-S mobilizing bacterial metabolites to expand their hyphal networks, increasing the area of soil and volume of S available to the plant. Additionally, inoculation with AM fungi has been shown to increase both percentage root colonization and the magnitude of the sulfonate mobilizing bacterial community (Mariea and Achim, 2014). Growth promotion of A*rabi*dopsis and tomato were observed when inoculated with aryl sulfonate utilizing strain of *Pseudomonas putida* S313R.

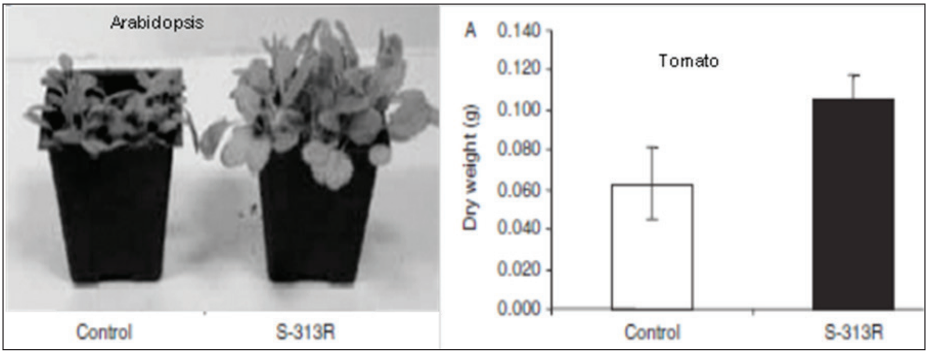


Fig. 11: Plant growth promotion by inoculation of sulfur cycling bacteria (Source: Keartesz et al 2007)

Sulfur oxidation and plant growth promotion

Thiobacilli play an important role in sulfur oxidation in soil. Sulfur oxidation is the most important step of sulfur cycle, which improves soil fertility due to the formation of sulfate, which can be used by the plants, while the acidity produced by oxidation helps to solubilize plant nutrients. Inoculation of sulfur oxidizing bacteria along with *Rhizobium* has been found to be very useful for legume crops which have high sulfur requirements. In a field trial Thiobacillus pellets (LCH) @ 60 kg/ha applied along with other sulfur oxidizing bacteria (SWA5, SWA4, NCIM, SGA6) coinoculated along with *Rhizobium* enhanced the groundnut plant biomass by 76% over uninoculated control.

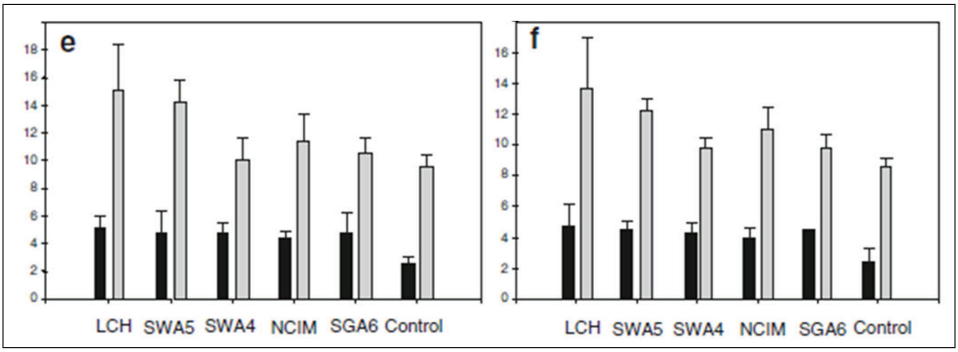


Fig. 12: Growth promotion of groundnut by inoculation with Thiobaciallus (Source: Anandham et al., 2011)

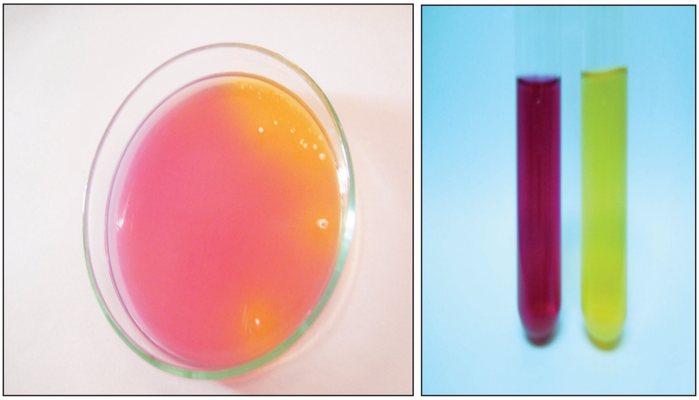


Fig. 13: Isolation of acid producing sulfur oxidizing bacteria

Rock phosphate bioacidulation and plant growth promotion

The sulfuric acid produced during oxidation of elemental S to sulfate by S oxidizing bacteria like Acidothiobacillus help in increasing the solubility of phosphate rocks and has been observed to improve the release of bioavailable P from low reactive rock phosphates. Anandam et al, 2011 observed that *Halothiobacillus* has higher capacity to release P from rock phosphate when incubated with thiosulfate after 45 days of incubation.

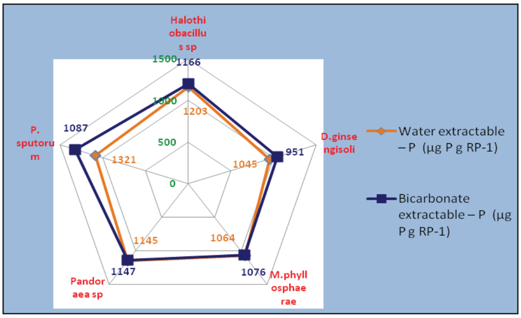


Fig:14. Water and bicarbonate extractable – P released from Rock phosphate by bacteria (Source: Adapted from Anandam et al., 2011)

Sulfur containing volatiles and plant growth promotion

Bacillus sp-B55 emits a S-containing volatile compound - dimethyl disulfide DMDS that enhances the availability of reduced S to wild type tobacco plants growing in S-deficient conditions and 35S-etr1 mutant plants with impaired S uptake/assimilation/metabolism by a newly uncovered mechanism of plant growth promotion by enhancing S availability and reducing the need for energy-demanding S assimilation (Dorothea *et al.,* 2013).

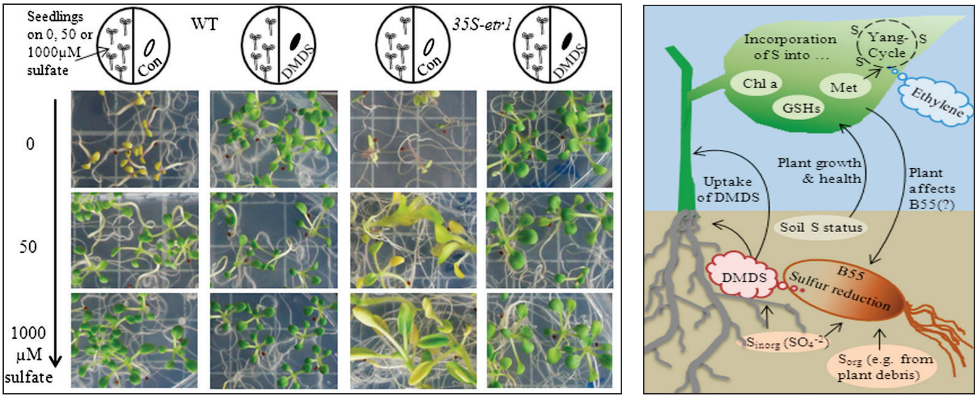


Fig15: Plant growth promotion by sulfur containing volatiles of bacteria

Inoculation practices, therefore, have huge potential to sustainably increase crop yield in areas where S is becoming a limiting factor to growth.

S transformations in upland soils

In upland agricultural systems (oxic soils), the major transformations of S are mineralization, immobilization, and oxidation. Such transformations often result in losses or gains of S in the soil-plant system through processes such as leaching and S gas evolution and absorption. As a result, the S load in adjacent hydrospheric and atmospheric systems is altered. S transformations can be greatly affected by small changes in the environment which, in turn, can cause large shifts in the size of the S pools.

4. Sulfur Retention and release phenomenon in soils

The mechanism of retention and release of S from soil is an important factor in S nutrition of plants. Sulfur retention in soils is the maintenance of S on site through several mechanisms, of which the two primary S retention mechanisms are immobilization and adsorption. Retained S can move within the soil and undergo transformations, but it is not lost from the system. While organic sulfur compounds formed during immobilization are largely immobile, inorganic sulfur is more mobile and sulfate (SO_4^{2-}) is the most mobile S species in soil. The quantities of mobile and immobile fractions and the time that each remains mobile or immobile determine the degree of retention or movement of S and are dependent on S pool characteristics and processes are site-specific because in some soils initial retention of SO_4^{2-} may be by adsorption, followed later by a portion of that adsorbed pool being transformed to organic S constituents, while in others SO_4 may be immobilized quickly through microbial assimilation.

The inorganic SO_4^{2-} in soil solution is termed soluble SO_4^{2-} and though highly mobile can be retained physically in soil by the short- or long-term by adsorption. The sulfate adsorption describes the solid and liquid phase interaction affecting the availability of sulfur to plants and leaching of SO_4^{2-} and associated cations. The release and fixation of SO_4^{2-} are also reflected by the SO_4^{2-} adsorption behavior of soils. Adsorbed SO_4^{2-} sometimes is called insoluble SO_4^{2-} because it cannot be desorbed with just water. Sulfate adsorption can be nonspecific or specific. In nonspecific adsorption, SO_4 is held within the double diffuse layer as a counter ion to positively charged surfaces on organic matter, layer silicates, or oxide- and hydrous oxide-dominated surfaces. Because only electrostatic attraction is involved in nonspecific adsorption, desorption can be achieved relatively easily-either by increasing solution pH or by exchange with other anions that have a greater or equal affinity for adsorption. In specific adsorption, SO_4^{2-} bonds to the metal oxide within the inner Helmholtz layer by displacing an H_2O or OH molecule or occasionally other anions. Specific adsorption results in a greater adsorption capacity than would occur by nonspecific adsorption alone, and specifically adsorbed anions are held more tightly. Specific adsorption is believed to be the predominant mechanism of SO_4^{2-} adsorption in soils. Most specific adsorption occurs in soils with high levels of free iron and aluminium oxides and hydroxides. These adsorption and desorption kinetics is an important factor in S nutrition of plants as it affects sulfate availability to plants.

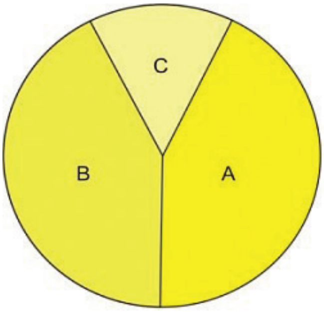
Soils, which have been exposed to high sulfur loading, and have a relatively small sulfate retention capacity may show, more release than adsorption. Sulfate adsorption on kaolinite is mostly reversible (> 50%) but sulfate adsorbed on to Fe and Al oxides is essentially irreversible (50%). The Alfisols and Ultisols of Jharkhand are characterized by low soil pH and high Fe and Al oxides concentration which absorb large amounts of sulfur and then release it in a speed which does not match the plant absorption. For understanding the adsorption these Alfisols and Ultisols for better management of fertilizer sulfur, the relationship between a dissolved and adsorped sulfate was studied (Brajendra and Shukla, 2003) using various model equations are used such as the Longmeir, Freundich and Temkin.

The basic data of sulfate adsorbtion on different soils from these soils were fitted into different linear adsorption equation to describe the adsorption behavior of sulfate. Out of various adsorption isotherms equations used, as the adsorption data did not confirm to the Langmiur isotherm over the entire range of equilibrium sulfate concentrations, adsorption of sulfate is described using Frendlich and Temin models and the adsorption parameter and regression equation of sulfur for these soils in Freundlich isotherm model which best predicts the retention and release of sulfate is presented below.

Soil Samples	1/n	K	Regression eqn.	R^2
1	0.609	1.076	Y=0.609x + 0.8371	0.94
2	0.678	1.240	Y= 0.648x +0.7857	0.94
3	0.739	1.400	Y= 0.739x + 0.67	0.96
4	0.592	1.200	Y= 0.5926x + 0.8187	0.93
5	0.610	1.320	Y= 0.6145 + 0.7226	0.91
6	0.611	1.281	Y= 0.6114x+0.7547	0.88
7	0.527	1.012	Y=0.5278x+0.9863	0.84
8	0.397	1.017	Y= 0.3976x+0.983	0.85
9	0.570	1.119	Y=0.5739x+0.8263	0.93
10	0.550	1.181	Y=0.556x+0.8343	0.95

5. Status of Sulfur in India

Total S in Indian soils varies from 19 to 9750 ppm in the surface layer. In most of the normal agricultural soils, the plough layer has 50-300 ppm Sulfur. The deficiency or sufficiency depends on the input-output relationship. Sulfur content in Indian soils, area of deficiency forms and factors affecting them have been reported by Tandon (1991) and Saharam (1992).



A = 45% districts having more than 40% soil samples deficient in S

B = 40% districts having 20-40% soil samples deficient in S

C = 15% districts having less than 20% soil samples deficient in S

Fig:16. Distribution of 240 districts according to the extent of sulfur deficiency

(Source: TSI- Sulfur in Indian Agriculture)

Soils particularly prone to S deficiency include the following types:

- Allophane soils with low organic matter status.
- Highly weathered soils containing large amounts of Fe oxides.
- Sandy soils, which are easily leachable (increased leaching of SO_4^{-2} beyond rooting zone due to increased irrigation to the crop with increase in use of phosphate fertilizers which facilitates adsorption of SO_4^{-2}.

Soil Sulfur status map of IIRR farm

This study emphasizes our current research based knowledge of S management with regard to efficiency and sustainability of lowland rice production and identifies where additional research needed to bridge information gaps. The available sulfur content of the experimental plots of Directorate of Rice Research Farm, Rajendranagar was analyzed block wise and a Soil Available Sulfur Status Map was prepared.

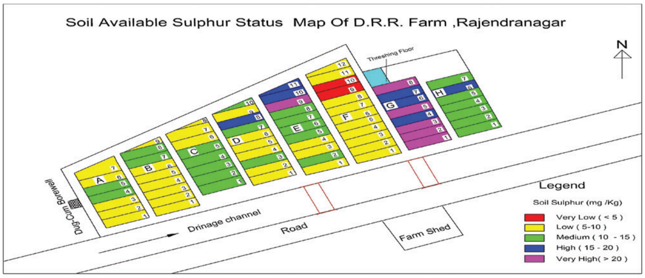


Fig. 18: GIS based soil sulfur status map of IIRR Farm

Table 5: Current status of the extent of S deficiency in Districts of India

State	Distribution of S-deficient Districts*		
	Less than 20% samples deficient	**20-40% samples deficient**	**More than 40% samples deficient**
Andhra Pradesh	Karimnagar, Guntur, Prakasam, Medak, Vijayanagaram, Srikakulam, Anantapur, East Godavari, West Godavari	Ranga Reddy, Warangal, Visakhapatnam	Adilabad, Cuddapah, Nalgonda, Chittoor, Ranga Reddy, Mehboobnagar, *Karimnagar, Medak*
Assam	All tea growing areas		
Bihar	Muzaffarpur, Bhagalpur, Jehanabad, Munger, *Madhubani, Dharbanga, Vaishali*	Samastipur, Gopalganj, Gaya, Patna, Dharbanga, Aurangabad, *Saharsa,* W. Champaran, Bhojpur, Nalanda, Rohtas	Laxmipur, Nawada, *Samastipur*
Chhattisgarh	Bilaspur, Durg	Raipur	Rajnandgaon
Gujarat	Surendranagar, Rajkot	Ahmedabad, *Bharuch,* Bhavnagar, Jamnagar, Kheda, Kutch, Surat, Vadodara, Valsad, Banaskantha	Amreli, Bharuch, Junagadh, Mehsana, Panchmahal, Sabarkantha
Haryana	Rohtak, Rewari, Kurukshetra, Sirsa	Gurgaon, Jind, Karnal, Kaithal, Mohindergarh, Bhiwani, *Panipat, Sonepat*	Ambala, Faridabad, Hisar
Himachal Pradesh	Saproon valley	Hamirpur, Kangra, Una, Shimla	*Kangra*
Jharkhand		Palamau, Dumka	Ranchi, West Singhbhum, East Singhbhum, *Dumka, Lohardaga*
Karnataka	*Kolar*, Bangalore, Dharwad Coffee growing areas	Shimoga, Malprabha area, *Dharwad*	Dakshin Kannada, Uttar Kannada, Malnad area
Kerala	Thiruvananthapuram, Quilon, Calicut, Kasargod	Thrissur	Idduki, Palghat, *Thrissur, Kollam, Thiruvananthapuram*

State	Distribution of S-deficient Districts*		
	Less than 20% samples deficient	**20-40% samples deficient**	**More than 40% samples deficient**
Madhya Pradesh	Narsinghpur, Mandla, Betul	Bhopal, Jabalpur, Bhind, Guna, Satna, Sagar, Ratlam, *Gwalior, Morena*	Dewas, Ujjain, Seoni, Mandsaur, Dhar, Khandwa, Morena, Vidisha, Balaghat, Bhind, Gwalior, Sidhi, Sehore, Indore, Chhindwara
Maharashtra	Dhule, Ratnagiri, Pune*Latur, Jalgaon, Wardha, Kolhapur, Osmanabad, Satara, Solapur*	Aurangabad, Chandrapur, Bhandara, Raigad, Nanded, Kolhapur, Osmanabad, Parbhani, *Nasik, Sangli,Ahmednagar*	Ahmednagar, *Ratnagiri*
Orissa	Keonjhar, Phulbani,*Balasore*	Sambalpur, Balasore, Puri, Dhenkanal, Cuttack,*Kalahandi, Kuardah*	Kalahandi, Bargarh, Sambalpur, *Dhenkenal*
Punjab	Ferozepur, Faridkot, Patiala, Bhatinda	Sangrur, Kapurthala Jalandhar	Ropar, Ludhiana, Amritsar, Hoshiarpur
Rajasthan	Jaipur, Jodhpur, Nagaur, Bikaner	Bharatpur, Sri Ganganagar, Udaipur, Kota, Jhunjhunu	Chittorgarh, Alwar, holpur, Banswara *Dausa, Sri Ganganagar, Tonk, Jaipur*
Tamil Nadu	Thanjavur, Ramanathapuram, Tuticorin	Coimbatore, Erode, Nilgiris, Dharmapuri, Tiruchirapalli, Dindigul, Kanya Kumari	Madurai, South Arcot, Vellore, Salem, Cuddalore
Uttar Pradesh	Jalaun, Farukhhabad, Meerut, Ghaziabad	Allahabad, Sitapur, Jhansi, Hamirpur, Lalitpur, Aligarh, Bulandshahar, Fatehabad, Firozabad, Mainpuri, Agra, Moradabad, *JP Nagar*	Lucknow, Hardoi, Varanasi, Kanpur, Gazipur, Mirzapur, Banda, Ballia, Pratapgarh, Faizabad, *Rai Bareilly, Unnao, Bhadohi, Fatehpur, Sonebhadra, Aligarh, Jhansi, Gorakhpur*
Uttarakhand	U.S. Nagar, Almora		Haridwar, *New Tehri*
West Bengal	Howrah, *N 24-Parganas*	Birbhum, Burdhwan, Bankura, *Murshidabad, Hoogly*	*Jalpaiguri, Nadia, Purulia, Midnapore*

(Source: Practical Sulfur Guide –HLS Tandon and D.L.Messick 2007)

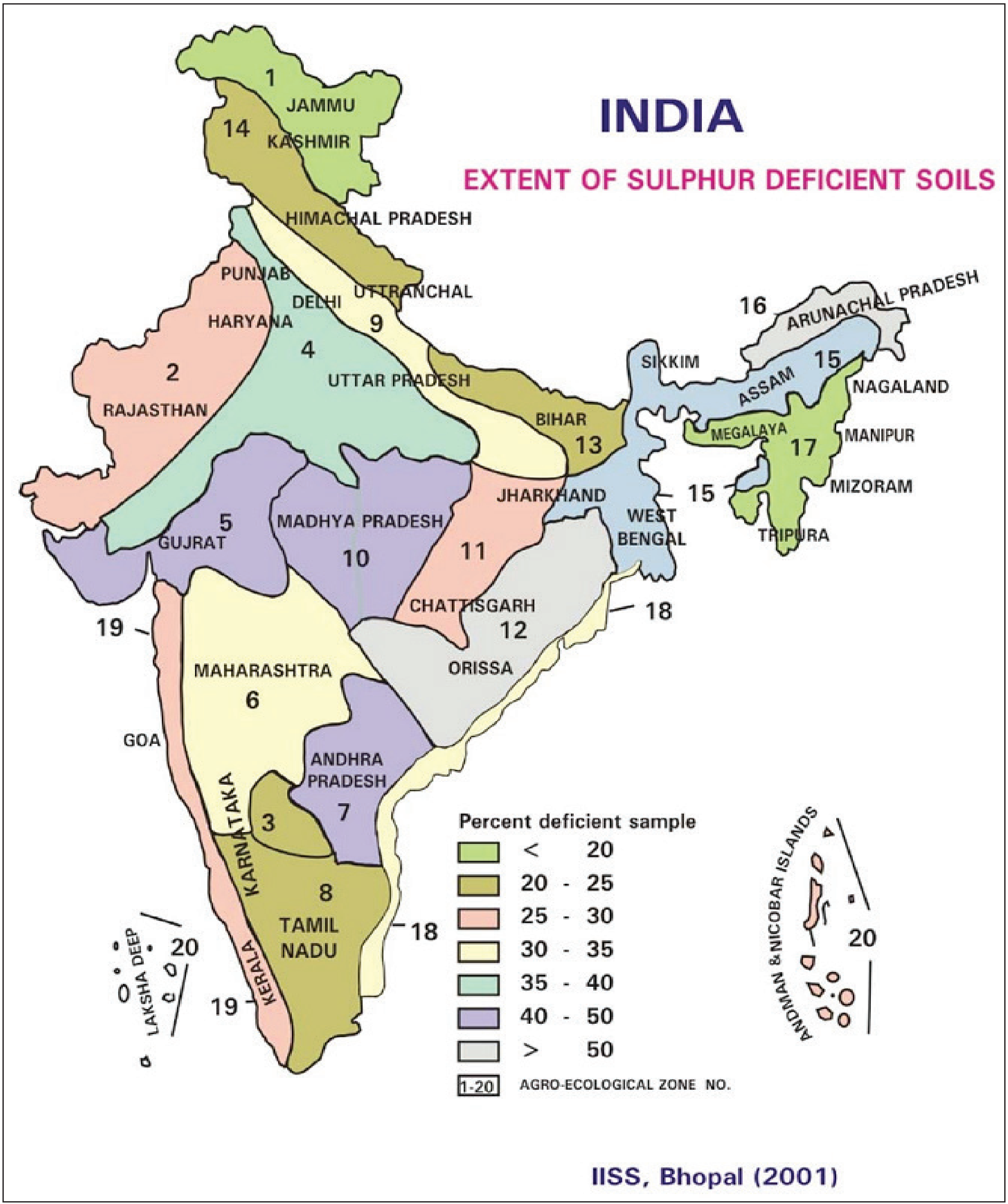


Fig. 17: GIS-based Soil Fertility Map of India showing Deficiency of Sulfur

6. Sulfur deficiency in crops

- The most striking feature of sulfur-deficient plants is the stunted chlorotic growth. Stems of sulfur-deficient plants are shorter and thinner than normal, and they are inclined to be woody (Ergle and Eaton, 1951).
- Leaf area is much reduced. Accompanying the general depressed growth, a deficiency of sulfur reduces fruiting,
- Chlorosis may involve the whole plant or it may be severe only on the younger leaves. Plants resemble those which are deficient in nitrogen, except that they do not develop characteristic leaf patterns, as is usual with nitrogen deficiency.
- Anthocyanin pigmentation develops in some plants with severe sulfur deficiency. Typical chlorosis appeared when a small amount of sulfur was added and the plants grew a little.
- Sulfur has been reported to increase root systems of plants, Although sulfur applications may stimulate root growth, the proportion of roots to tops may actually be reduced because of a relatively greater growth of tops.
- Sulfur deficiency has been shown to decrease numbers and weights of nodules on legumes (Duley, 1916; Miller, 1921; Anderson and Spencer, 1950). Some consider this a reflection of reduced growth and consequent reduced demand for nitrogen by the host plant and both cereals and grasses in Alberta (Alberta Advisory Fertilizer Committee, 1956) have been found only moderately responsive to applications of sulfur at low nitrogen levels, but very responsive when these nutrients were added in combination.

Sulfur Deficiency impact on crop growth

- Reduced plant height and stunted growth (but plants are not as dark-colored as in P or K deficiency)
- Reduced number of tillers
- Fewer and shorter panicles,
- Reduced number of spikelets per panicle;
- Delayed plant development and maturity by 1-2 weeks;
- Yellowish seedlings in nursery beds with retarded growth;
- High seedling mortality after transplanting;
- S-deficient rice plants have less resistance to adverse conditions (e.g., cold).

Signs of S deficiency in rice results in

- Yellowing or pale green whole plant;chlorotic young leaves with necrotic tips;
- Lower leaves do not show necrosis;
- Reduced plant height;
- Reduced number of tillers and spikelets;
- Fewer and shorter panicles;
- Effect on yield is more pronounced when S deficiency occurs during vegetative growth

Fig.19: Reduced plant height & tillering; Chlorosis of young leaves & necrosis of tips; Rice field showing S deficiency symptoms (Source: Dobermann and Fairhurst. 2000)

Sulfur deficiency in other cereals

Wheat: General yellowing of the plant and more prominent between imterveins.

Maize: Younger, upper leaves with inter-veinal yellowing. In Later stages, reddening at the base of the stem and along the leaf margins

Sorghum: Young leaves are shorter and more erect than usual and pale green.

Fig. 20: Deficiency in wheat, barley, maize and sorghum

Sulfur deficiency in oil seed crops

Sunflower: Plants are markedly smaller with shorter internodes than normal. Number and size of leaves remain small. Leaves and inflorescence (flowers) become pale.

Groundnut: Young plants are smaller than normal, pale and more erect from the petiole than normal plants giving the trifoliate leaves a V shaped appearance. Older leaves may remain green. In new leaves area around the main vein may be pale. Nodulation and pod formation is restricted and maturity of seeds is delayed.

Rapeseed and mustard: leaves are cupped and a reddening of the underside of leaves and stem is visible. Flowers abort prematurely resulting in poor pod formation. Reduces seed oil content and lowers the economic yield.

Sesame: Growth is retarded leaves are smaller and fully emerged leaves first turn pale and then golden yellow. Number flowers, pods, oil content and yield are reduced.

Soybean: Pale yellowish green new leaves. Reduced size of leaves and internodes. Chlorosis starts from leaf margins and spreads inwards. Severe deficiency results in whole plant yellowing and premature leaf fall, reduced flowering and fruiting.

Linseed: Yellowing, curling and premature drying of tips of young terminal leaves. Chlorosis gradually spreads on old leaves. The stem remains slender with poor branching. Number of floral buds is reduced and most of these fail to open.

Fig. 21: Sunflower, Groundnut, Soybean under S deficiency and sufficiency

Sulfur deficiency in Pulses

Blackgram: Chlorosis starts from the tips of young leaves and spreads along the margin. The leaves which emerge after onset of S deficiency are severly chlorotic. Stems become thin and woody with bushy appearance of the plants.

Green gram: Stunded and bushy plants with poor branching. Reduced flowers and shrunken pods.

Horsegram: Pale leaves with inter-veinal chlorosis of leaflets of young leaves. Under severe deficiency, symptoms spread from young to middle leaves.

Cowpea: Stunted plants with reduced internodes. New leaves are pale, chlorotic and fail to expand. Flowering is delayed, number of pods are reduced and hence the yield.

Chickpea: Plants are chlorotic, erect. Young leaves wither and dry prematurely. Nodulation, N fixation and seed setting are severly restricted.

Pigeon pea: Young and middle leaves turn yellow, branching, leaf size and flowering are suppressed. Flowers lack normal yellow color and shed early. Pod formation and seed development are retarded.

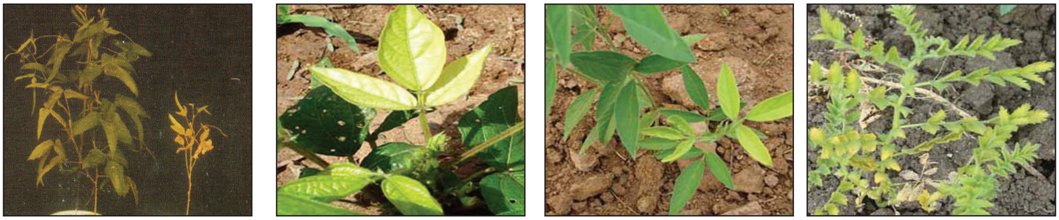


Fig. 22: Blackgram, Greengram, Redgram, Chickpea under S deficiency and sufficiency

7. Sulfur toxicity in crops

S toxicity occurs in well-drained sandy and degraded paddy soils with low active Fe status, in poorly drained organic soils, acid- sulfate soils. Soils prone to sulfide toxicity and Fe toxicity are similar in containing a large amount of active Fe, small CEC, and small concentration of exchangeable bases. Implications of release of H_2S (at Eh of < -50 mV at pH 7.0) in low active Fe containing soils leading to sulfide toxicity in rice culture are that S may become deficient, Fe, Zn, and Cu may become immobilized as sulfide precipitates which affect the nutrient availability and concentration of K, Mg, Ca, Mn, and Si content in plant tissue may be reduced. H_2S toxicity can occur when the concentration > 0.07 mg/l in the soil solution.

Sulfide-toxicity symptoms

- An excessive concentration of hydrogen sulfide (H_2S) in the soil results in reduced nutrient uptake because of a decrease in root respiration.
- The intensity of sulfide toxicity, therefore, depends on the strength of root oxidizing power, H_2S concentration in the soil solution, and root health.
- *Interveinal chlorosis of emerging leaves. Coarse, sparse, and blackened roots,* leaf symptoms of sulfide toxicity are similar to those of chlorosis caused by Fe deficiency
- Freshly uprooted rice hills often have poorly developed root systems with many black roots (stains of Fe sulfide). In contrast, healthy roots are covered with a uniform and smooth orange-brown coating of Fe3+ oxides and hydroxides.
- No critical levels have been established. The toxicity depends on the concentration of sulfide in the soil solution relative to the oxidation power of rice roots. H_2S toxicity can occur when the concentration of H_2S is >0.07 mg per L in the soil solution.
- Deficiency of K (regulates root oxidizing power) and unbalanced crop nutrient status and excessive application of sulfate in fertilizers or urban or industrial sewage on poorly drained, strongly reducing soils.

Fig. 23: Sulfur toxicity

Management of sulfide toxicity

- Mid season drainage to remove accumulated H_2S and Fe^{2+}. Drain the field at the mid tillering stage (25–30 DAT/DAS), and maintain floodwater-free (but moist) conditions for about 7–10 days to oxidize sulfates and improve oxygen supply to roots during tillering. Apply K, P, lime and Mg fertilizers, and Fe (salts, oxides) in low-Fe soils to increase immobilization of H_2S as FeS. Avoid large quantities of organic matter application particularly those which have high BD like sewage sludge, urban wastes etc in poorly drained soils and rich in Fe content
- Growing rice varieties that tolerate sulfide toxicity because of their greater capacity to release O_2 from roots through better aerenchyma tissue.
- Dry ploughing the field after harvest to increase S and Fe oxidation during the fallow period.

8. Sulfur requirement in rice based cropping systems

S is important throughout the growth cycle of the crops. Plant tissues must contain sufficient concentrations of sulfur, only then the plants can produce carbohydrates, proteins, oils and vitamins to their full potential (Tandon and Messick 2007)

Cereals: 3-4 kg/ (1-6 range); **Pulses:** 8 kg(5-13 range); **Oilseeds:** 12 kg (5-20 range)

Sulfur uptake and use by rice

Sulfur is important in rice nutrition for the synthesis of amino acids and proteins, which account for approximately 90% of organic S in the plant. The sulfur requirement of rice varies according to the nitrogen supply. When S becomes limiting, addition of N does not change the yield or protein level of plants. Sulfur is required early in the growth of rice plants. If it is limiting during early growth, then tiller number and therefore final yield will be reduced. Although the concentration of sulfur in rice grain is higher than in rice straw, there is less re-mobilization of S to the grain than for phosphorus.

Table 6. The optimal ranges and critical levels of S in plant tissue

Growth stage	Plant part	Optimum (%)	Critical level for deficiency (%)
Tillering	Y leaf		<0.16
Tillering	Shoot	0.15-0.30	< 0.11
Flowering	Flag leaf	0.10-0.15	< 0.10
Flowering	Shoot		< 0.07
Maturity	Shoot		< 0.06

9. Sulfur availability indices

Useful tools for the diagnosis of S deficiency are soil as well as plant analysis which are apparently and possibly complementary. However, often plant analysis do not reveal a deficiency until it is too late for a corrective S fertilizer application.

Soil analysis

As a mean of evaluating the S status of soils different soil testing methods, which include the extraction of different S binding forms, S released during incubation experiments or microbial growth have been suggested (Jones, 1986). However, the concentration of inorganic S in soils varies throughout the year (Ghani *et al.,* 1991) and is the result of changes between the balance between the activity of the microbial biomass, leaching and surface run off, fertilizer, plant senescence and atmospheric inputs and uptake of the crop. Therefore any analytical value on (SO_4) Inconsistencies between soil tests for S and crop performances have been reported widely and seasonal effects on the availability of S to plants and the leaching of SO_4^{2-} restrict the usefulness of soil analysis to identify S responsive sites (Robson *et. al.,* 1995). Soil tests for S are not reliable unless they include inorganic S as well as some of the mineralizable organic S fraction (ester sulfates), (Dobermann and Fairhurst 2000).

Critical soil levels for occurrence of S deficiency:

- <5 mg S kg-^{1} 0.05 M HCI
- <6 mg S kg-^{1} 0.25 M KCI heated at 40 °C for 3 hours, and
- < 9 mg S kg-^{1} 0.01 M Ca $(H_2P0_4)2$

Plant tissue analysis

It offers a better tool than soil testing for the prediction of the need of S application (Zhao *et. al.,* 1996) and several diagnostic indices have been suggested, but without general consensus as to which index gives the best results. The use of plant analyses instead of soil analyses for diagnosing S deficiency in soils is based on the condition that each essential element should be present in the plant just sufficient for unrestricted plant growth.

Table 7: Critical levels of S in some crops of rice based cropping systems

Crop	% S concentration in dry matter		
	Deficient	Moderately Sufficient	Sufficient
Rice, Wheat, Maize, Millets	0.10-0.20	0.20-0.30	Above 0.30
Groundnut, Mustard, Soybean, Cowpea, Brinjal, French bean, Cucumber	0.10.-0.25	0.25-0.40	Above 0.40
Sunflower, Linseed	0.25-0.35	0.35-0.55	Above 0.55
Horsegram, Pea, Chickpea	0.15-0.45	0.45-0.75	Above 0.75
Potato, Cauliflower, Spinach	0.30-0.40	0.40-0.75	Above 0.75

10. Sulfur Fertilizers

More than 60 fertilizers contain sulfur and useful in agricultural applications. S fertilizer applications have worldwide shown little historic growth, because the value of S as a component of multi-nutrient fertilizers was not recognized.

Elemental Sulfur based products is commonly used as a fertilizer in S-deficient agricultural systems, but can also be a soil pollutant in the form of wind-blown dust from stockpiles. The elemental S is oxidized to sulfate by the soil microbial population to render the S plant available, with the rate of oxidation being a major factor influencing the effectiveness of elemental S fertilizer. Oxidation of S occurs readily in some soils, but chemical, physical, and biological factors limit oxidation rates in other soils (Janzen and Bettany, 1987). Temperature and moisture affect microbial activity and consequently oxidation rate. Very slow rates are observed in cold, dry soils. Decreasing the particle size of the elemental S results in higher oxidation rates due to the increased surface area.

Sulfur is applied in fertilizers as either sulfate or elemental sulfur. Rice plants take up S from solution as sulfate (as mentioned above, there is some evidence that some marsh plants can take up sulfide, but if this is true of rice it is most likely a minor pathway). Consequently, elemental sulfur must be converted to sulfate before it is available; the inhibition of oxidation of elemental sulfur to sulfate will decrease the availability of fertilizer sulfur to the plant. Also, the reduction of sulfate to sulfide will reduce the availability of the sulfur, particularly if the sulfides are precipitated. To be effective, S-containing fertilizers must be placed in a zone of high oxidation-reduction potential such as the oxidized soil layer at the soil-water interface or within the root rhizosphere. Application 3-4 weeks ahead of planting crop is required to allow adequate time for transformation.

A wide range of elemental S products are available, varying in S content from 63-100% containing pure S, some bentonite, some N or micronutrient combinations.

Single Super Phosphate : It is a grey to brownish color powder containing 16% water soluble P_2O_5, 12% sulfur, 21% calcium and around 4% phosphoric acid by weight. It is relatively cheaper source of P and S as compared to DAP and Gypsum unless the area is close to gypsum mines so that transportation costs are competitive. When SSP is added to soil it dissolves in water and several reactions occur in soil depending on the pH. In most soils, reaction products are held largely in top soil except sandy soils. Both Phosphate and Sulfate ions are absorbed by acid soils in similar manner. Sulfate ions get converted to SO_3, SO_2, S and ultimately to H_2S under highly reduced conditions.

Mineral Gypsum ($CaSO_4 . 2H_2O$): It is a white, yellowish or occasionally brown opaque solid material, contains 13-18.6% S which is readily available to plants and 16-23.2% calcium and slightly soluble in water. It is one of the most efficient and desirable source of sulfur and its efficiency depends on crop type, soil characteristics and method of application. It is a popular amendment for alkali soil reclamation and source of S for groundnut crop.

Phosphogypsum: It is a byproduct of chemical industry during manufacture of wet process phosphoric acid. It is high grade gypsum containing some quantities of phosphorus in addition to Sulfur and Calcium. The sole bottleneck in it's large scale use is, it is being bulky requiring huge handling and freight expenses.

Iron pyrites (Fe S_2): Is a mineral containing Iron and Sulfur, normally occurring in igneous and metamorphic rocks and found as a sedimentary deposit. It occurs in various physical forms such as crystalline, massive and powdery varieties. It immediately reacts with air and water to form sulfuric acid and iron sulfate. Oxidation of pyrite in soil is brought about primarily through chemical action and microbial agents like *Thiobacillus ferroxidans.* If pyrite is applied with organic manure, it forms metal complexes which oxidize faster, presumably due to microbial action in which the micro-organisms can utilize organic part of these complexes and precipitate iron thus liberating Sulfur.

Ammonium Phosphate Sulfate: It is composed of 60% ammonium sulfate and 40% ammonium phosphate. It contains 16-20% N, 20% $P_2 O_5$ and 15% S. It is a light grey granular fertilizer, excellent in keeping quality. Water solubility is complete and leaves an acidic effect in soil because of the ammoniacal nitrogen and accompanying sulfate anion.

Potassium Sulfate: A preferred source where soil salinity is a problem, where chloride accumulates in the soil through irrigation water and when heavy rates of Potassium are applied. It contains 50 % K_2O and 18% sulfur, dissolves in soil solution well. The sulfate ions are held relatively weakly by soil surfaces, particularly in high pH soils.

Study was taken up using different sources and levels of S application on rice (2007-2009). The data are presented in Fig. 24 & 25 and the salient findings are given below

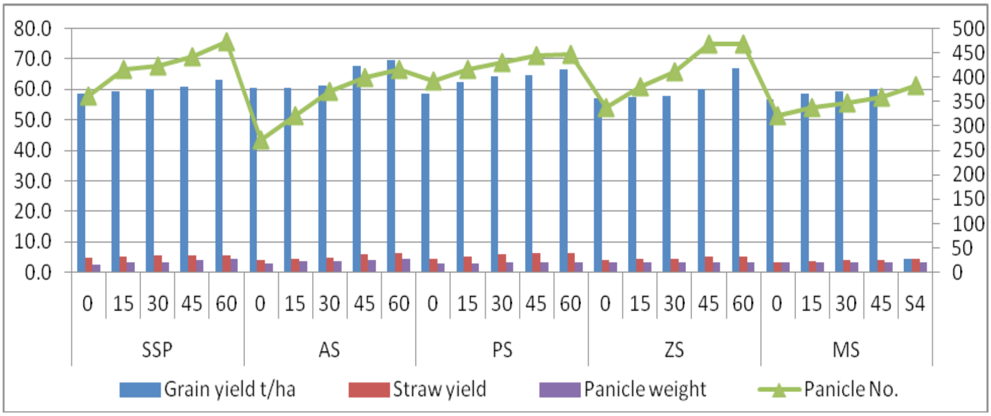


Fig. 24: Yield attributes and yield of rice influenced by S sources and levels.

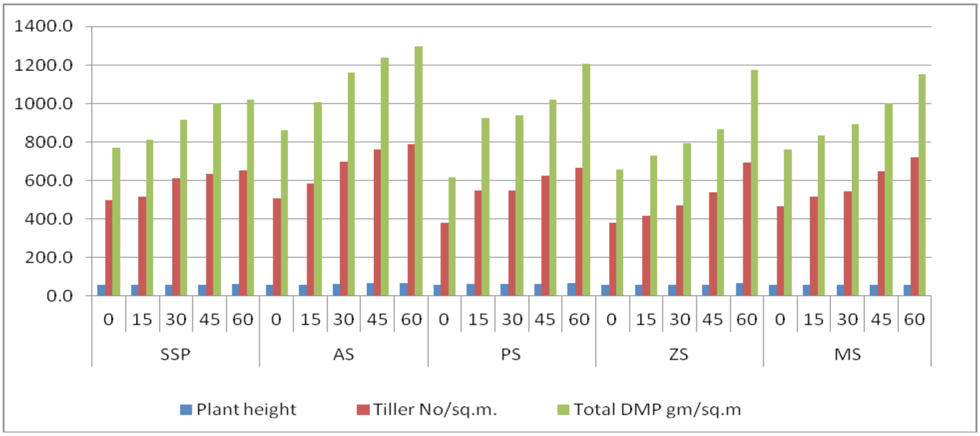


Fig. 25: Growth parameters of rice influenced by S sources and levels.

- Increasing sulfur level upto 45 kg/ha increased grain straw yields and harvest index. Among the five S sources, ferrous sulfate recorded maximum and significantly highest performance in terms of grain yield followed by elemental sulfur and gypsum. progressive increase in grain and straw yields due to S application could be attributed to the important role of sulfur in the synthesis of proteins and vitamins and enhanced photosynthetic activity of plant. Harvest Index (HI) was higher under higher sulfur levels in case of elemental S, ammonium phosphate sulfate and superphosphate. In case of gypsum, harvest index was maximum with 15 kg S/ha. In case of ferrous sulfate, harvest index was maximum with 45 kg/ha, which may be attributed to photosynthetic production and its partition to sink. The yield attributes viz., productive tiller number per unit area and panicle weight supported grain and straw yields. Application of balanced fertilizer dose (including S) in defiant soil promoted the supply of assimilates from the source to sink would resulted in the production of more number of filled grains per panicle and panicle weight.
- The growth characteristics viz., plant height and total tillers per hill were significantly influenced by the sources of nutrients. Plant height was not significantly influenced by S levels or interactions of S sources and levels. In the present study, increasing the S levels increased the total no. of tillers. Maximum tiller no was observed in ferrous sulfate applied plots. Earlier the tillers emerge after transplanting more they contribute towards the yield and proliferation of tillers after transplanting is important for increasing the yield. Dry matter production of root and shoot at tillering atage was analysed and showed significant difference with S sources, S levels and their interaction. Ferrous sulfate has resulted in significantly higher root dry matter production, shoot dry matter followed by elemental S. Dry matter production increased progressively with increasing S levels upto 45 kg/ha. The lowest amount of dmp was recorded by Ammonium phosphatesulfate.

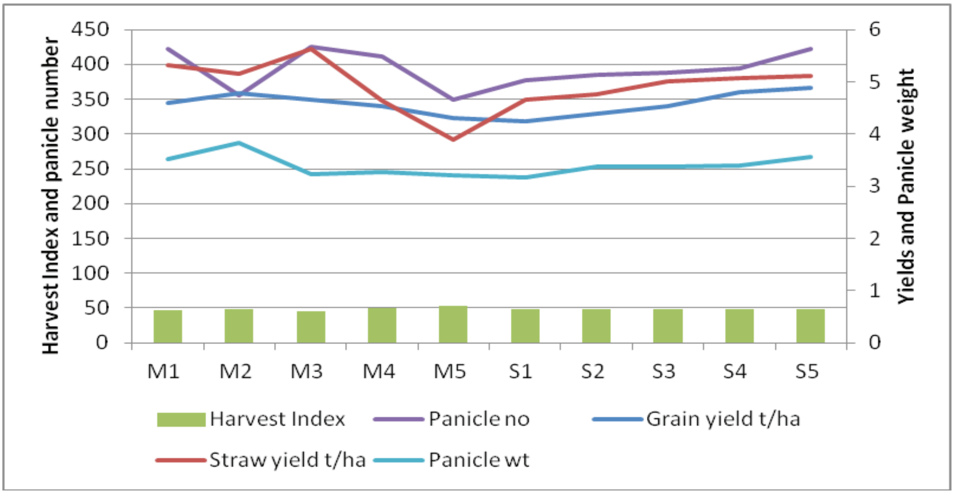


Fig. 26: Influence of S sources and levels on Rice yield and yield attributes

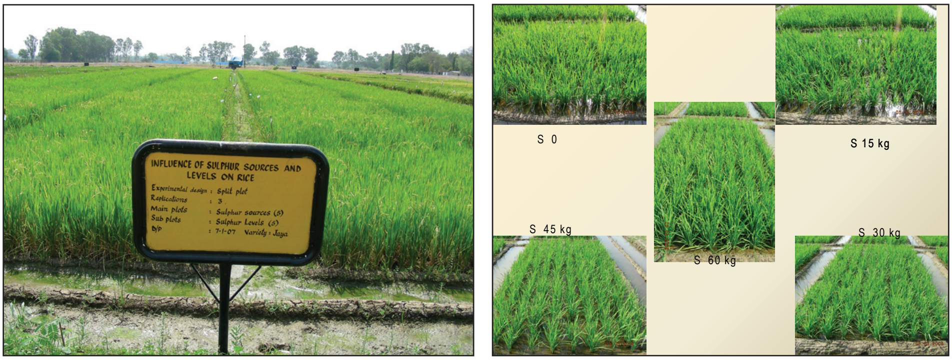


Fig.27. Rice field experiment in deficient soil under different levels & sources of S

11. Time of application

S fertilizer application should be tuned based on the initial soil S status and the soil properties that influence S availability during the course of the growing season. Routine soil testing for S is not a guideline. Soil properties like drainage, texture, oxidation status and field histories are used for finding out the necessity of S fertilization. If initial soil S availability is low, the fertilizers should be applied at seeding or by the 5 leaf stage i.e., beginning of rapid plant growth and tillering. In highly permissible soils or reduced soils, to prevent late season deficiency application during reproductive growth phase i.e., panicle initiation or early boot stage is necessary.

12. High Sulfur Use Efficient Cultivars

In the context of Indian agriculture, majority of the farmers donot use amendments to ameliorate soil constraints –they face such difficulties in obtaining fertilizers to meet the nutritional needs of their crops. Under prevailing conditions, the most appropriate strategy is to develop cultivars of rice that are adapted to deficient environments where Sulfur deficiency is the major factor limiting yields. Selection of cultivars of rice that acquire more S, or that have better use efficiency of S, is a strategy for adaptation to deficient environments. The effects of sulfur deprivation in rice were analyzed by measuring changes in photosynthesis, carbohydrate metabolism, and antioxidants. The ability to respond to S-deficiency stress varies between crops and this is a target for the genetic improvement of S-utilization efficiency. Improved capture of resources, the accumulation of greater reserves of S and improved mechanisms for the remobilization of these reserves are required.

The existence of considerable genotypic variations, techniques and selection criterion could enhance the feasibility of breeding crop cultivars for improved mineral nutrient use efficiency (Fageria and Baligar, 1994; Graham, 1984). Identification of cultivars with greater tolerance to suboptimal soil nutrient levels offer considerable promise for increasing the crop production potential of marginal low fertility lands throughout the world (Duncan and Carrow,1999). Breeding cultivars for high tolerance to low levels of nutrient supply will have a better chance of improving NUE. The potential for breeding improved cultivars with superior NUE largely depends upon: (i) the genetic variability present in the species/cultivar for that particular trait(s) that govern NUE and, (ii) development of methodology to accurately quantify the physiological parameters that reflect efficient NUE (Duncan and Carrow, 1999).


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Fig. 28: Field trials of Screening for S use efficiency

Identification of heritable traits (physiological, and biochemical) that relate to the NUE of grain yields or productivity in general appears to be the most formidable barrier for genetic improvement of plants for high NUE. Conventional plant breeding has enhanced N use efficiency in rice cultivars (Fischer 1998), most efficient and most inefficient nutrient efficiency ratios (NER) in different species and cultivars/genotypes within species have been reported (Baligar *et al.* 1997). Efforts are being made to identify S use efficient varieties/ genotypes by evaluating several genotypes/ varieties under minimum and optimum S conditions.

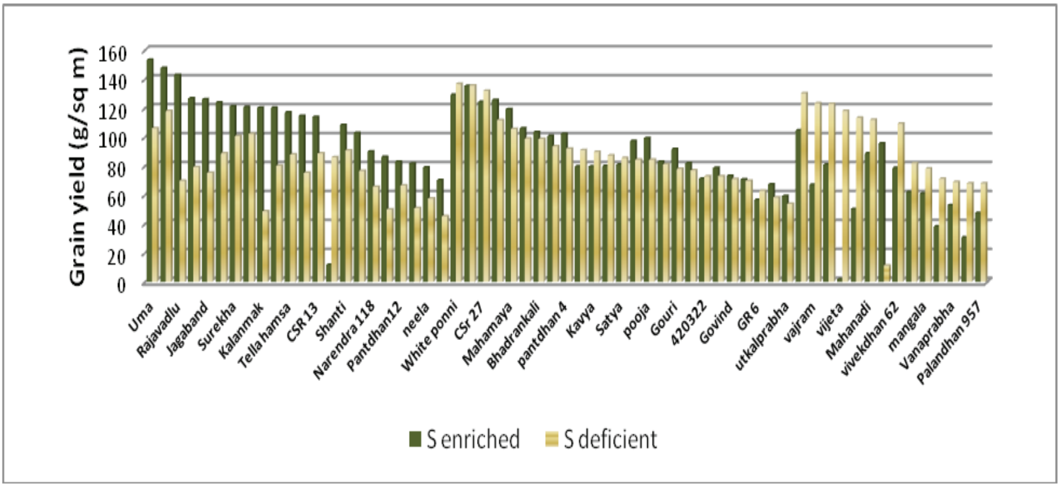
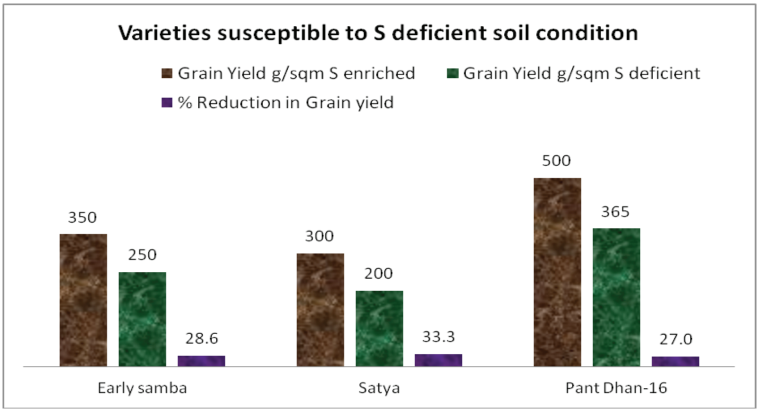


Fig. 29: Grain yields of different genotypes under S stress, S sufficient condition

At IIRR, the test varieties Vijetha, Mahanadi, Chaitanya, Uma, Jaishree, Krishna, Karjat 4, Pooja, Karjat 184, Kalanamak, Deepti, CSR 27, White Ponni, Karisma, Lunishree, Bhadrakali, Orugallu, Pantdhan 4, PR 114, Mahalakshmi, Kavya, CSR 10, Remya, Pantdhan 11, Gouri, Poornima, Danteswari, Govind, PR 106, GR 6, Rasi, Utkal Prabha, were found to be tolerant to sulfur deficient soil condition of <10 ppm. Some of these possess desirable traits, e.g. the superior yield and responsiveness to inputs and the general hardiness, drought and acid-soil tolerance. The cultivars, Narendra usardhan 3, Rajavadlu, Renjini, Jagabandhu, Surekha, IR 64, Kalanamak, GR 4, Tellahamsa, CSR 13, Ranjit, Shanti, Pantdhan 16, Narendra 118, Karjat 3, Pantdhan 12, Krishnaveni, Neela, GR 9 were highly responsive to S application in S deficient soil condition; Early Samba, Satya, Pantdhan16 and Samba Mahsuri were susceptible to S deficient condition. (Fig.30.)



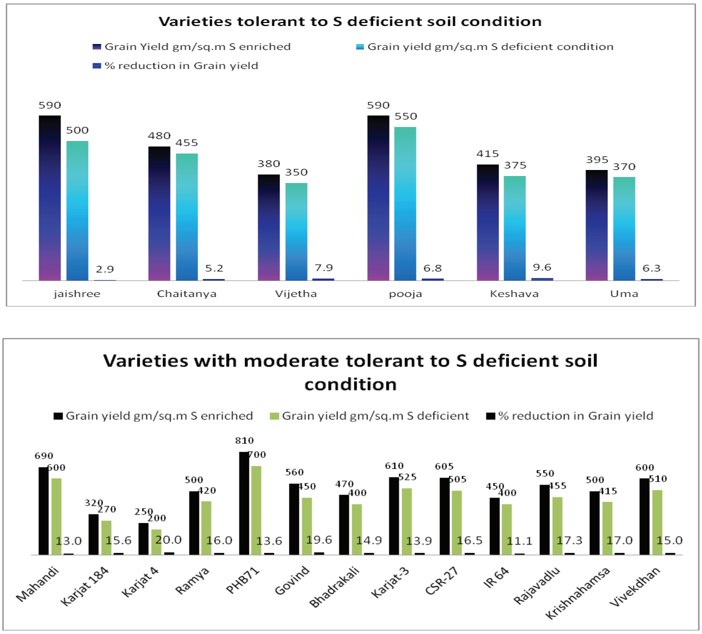


Fig. 30: Cultivars yield performance under S deficient soil condition

The improved varieties viz., PHB71, Vivekdhan, VLDhan221, Mahamaya, Govind, Karjat3, CSR27, Poornima, Rajavadlu, GR4, Krishnahamsa, Pantdhan16, Remya, Bhadrakali and IR64 – High S use efficiency interms of grain yield under deficient native sulfur content. In the long term, however, an integrated approach, in which genetic tolerance and plant-nutrient management seems to be more practical and sustainable.

Sulfur nutrition in Cropping systems

Diversification of rice cropping system with alternative crops, such as oilseed, pulse, and forage crops, furnishes producers with a range of agronomic and economic options. Many traditional cropping systems include an upland crop in rotation with rice, especially when there is insufficient water for an additional rice crop. These upland crops are grown for many and often multiple uses, including human and animal feed, fuel, fibre, and green manure for improved physical and chemical soil fertility. With intensification of rice cultivation, often associated with improved irrigation, many of these traditional multiple cropping systems have been replaced by multiple rice crop systems. Recently there has been more interest in using green manure crops in rice culture, especially as legumes show greater prospects for multiple use in more sustainable farming systems. We must take into account, the effect on rice production, in terms of a possible reduction in cropping intensity and the benefits of improved soil fertility, as well as the changes in nutrient demands of these multiple cropping systems. The sulfur requirements of many of these upland crops, especially the legumes, are higher than for rice, but the sulfur dynamics of these systems with regard to their residue and soil, particularly hydrological, management is not well known and needs further clarification.

Crop diversification also improves management of pests and diseases through manipulation of host factors such as crop and cultivar selection; interruption of pest and disease cycles through crop rotation, fungicide application, and removal of weeds and volunteer crop plants; and modification of the microenvironment within the crop canopy using tillage practices and stand density.

Fig:31. Rice, Blackgram and Sunflower crops in the cropping system in deficient &, sufficient soil S

Yield formation and Quality

Total S requirement mainly differs between crop species and the development stage of plants. In general, S demand of Cruciferae and Liliaceae is highest and lowest of small grains, while Leguminaceae range in between. According to Walker and Booth (1992) an oilseed rape crop removes between 20 and 30 kg S/ha, while cereals remove about 10 to 15 kg S/ha. S applications on S deficient soils increased crop yield by 17% in Rice 32% in Groundnut; 25% in Soybean; 20% in Sunflower; 30% in Mustard ; 22% in Pigeonpea; 25% in Wheat; 20% in

Greengram; 16% in Linseed. Results of the study conducted at DRR in deficient soils showed that Recommended Fertilizer Dose (RFD)of rice has given significantly higher grain yield and sulfur application @ 45 kg/ha in *Kharif* has given maximum yield of rice-blackgram system. Sulfur application in *rabi*season or both *Kharif* and *Rabi* seasons has resulted in maximum yield of rice-sunflower system. Rice equivalent yield was maximum with RFD and S application in *Kharif* followed by S application in both *Kharif* and *Rabi* recorded higher yields. Interactions were significant. Gross returns obtained were high with RFD + S application in both *Kharif* and *Rabi*. Net returns were high with RFD+ S application during *Kharif* season.

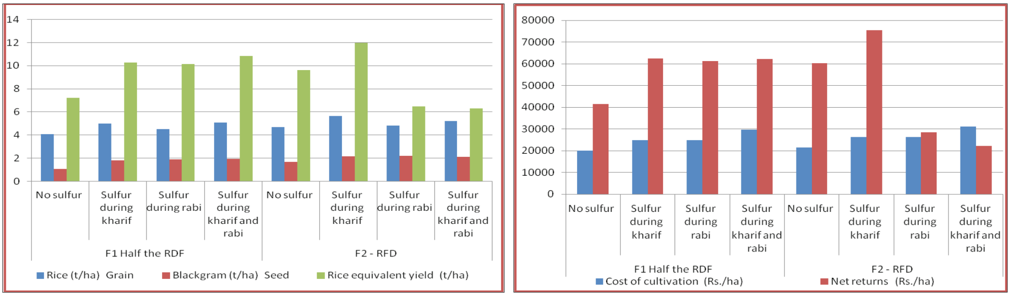


Fig. 32: Yield and Economics of Rice-Blackgram System (kharif 2008- rabi 2008-09)

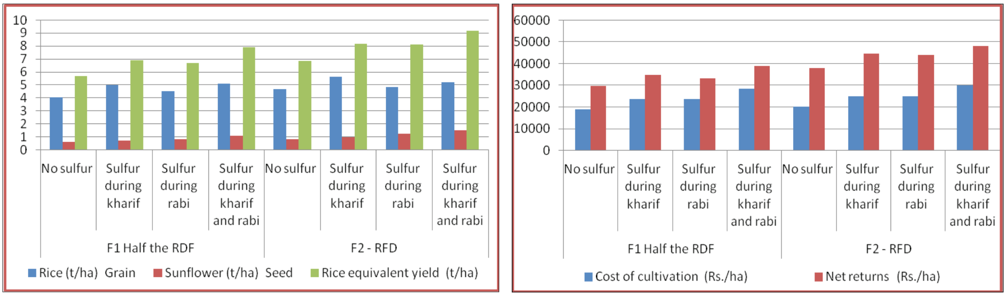


Fig:33. Yield and Economics of Rice-Sunflower System (kharif 2008- rabi 2008-09)

13. Sulfur impact on yield and post harvest quality of rice based cropping system

S nutrition of a crop often has a strong influence on food quality because of its essential role in the synthesis of amino acids, proteins and some secondary metabolites (Zhao *et al.,* 1997). For processing quality of cereal grains, the nutritional quality of legumes, sufficient S supply is required. Results of the experiments conducted at DRR showed that, Post harvest processing qualities like Hulling%, Brokens %, Head Rice Recovery% were not influenced by Sulfur schedules. The Milling %, Polished rice % were significantly improved by S application (Fig. 34).

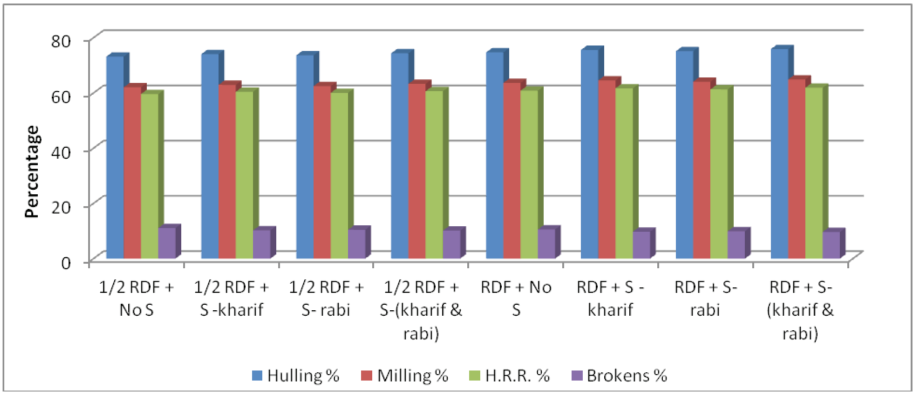


Fig. 34: Post harvest processing characters of Paddy

Sulfur improves crop quality in many ways by Increasing the oil content of seeds; Increasing protein percentage in plants and harvested produce; Improving nutritional quality of forages by providing a balanced N:S ratio; Improving starch content of tubers; Improving baking quality of wheat; Increasing sugar recovery in sugarcane; Enhancing marketability of copra (coconut kernel).

Application of S increases the methnionine content of rice to the tune of 1.7 to 2.5% (Wallilhan and Sharpless 1974). S deficiency affect significantly grain quality due to reduced cysteine and methionine content. Dikshit and Palimal 1989 reported that S application of 60 ppm increased sugar, starch contents, rice: husk ratio of paddy grain significantly. Protein and Amino acid contents of paddy were increased by S application @ 30 kg/ha. (Mac Ritche and Gupta 1993). Suwahart *et al.,*1997 examined the effect of Sulfur fertilizer on cooking and eating qualities of grains of Know Dauk Moli 105 aromatic rice and found increase in aroma, softness, whiteness and stickness of boiled milled rice. The results of experiments at DRR showed that the cooking quality parameters indicated no significant increase in water uptake, Kernal length after cooking and Volume expansion ratio etc. of milled rice due to sulfur application. Several workers (Singh and Sreedevi, 1997; Choudhari *et al.,* 1998) have reported response of N and S fertilizers on yields and quality of aromatic rice.

Protein content

It was observed that the protein contents of rice grain were significantly increased due to the application of different rates of sulfur. The highest protein content (8.70%) was obtained by the application of 20-kg sulfur. But the lowest protein content (7.86%) was due to application of no sulfur. Alameen (1999) also showed that sulfur application increased protein content in the rice grain. From the observation it revealed on application of sulfur protein content increased in rice grain. Reports on application of S through pyrites @ 600 kg/ha increased crude protein content of rice variety Saket-4. Application of S decreased N:S ratio significantly and increased amino acid content Jain 1992, Pritchand and Brock 1994.

Results of the field experiments at DRR and Paddy grain analysis showed that the content of nitrogen and protein were influenced by Nitrogen and S schedules. Recommended Fertilizer Schedule along with S recorded significantly high N content and Protein contents. The N content ranged from 0.86 to 0.93% and Protein content 5.14 to 5.52%. Phosphorus, Potassium and Sulfur contents were influenced by S schedules with highest being observed in Recommended Fertilizer Schedule along with S applied plots. Zinc content of paddy grain was not altered by Nitrogen or Sulfur.

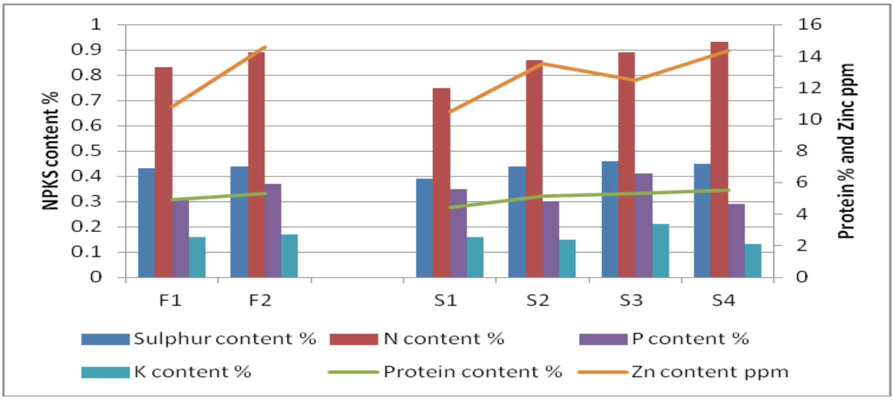


Fig: 35. Nutritional quality of Paddy grain

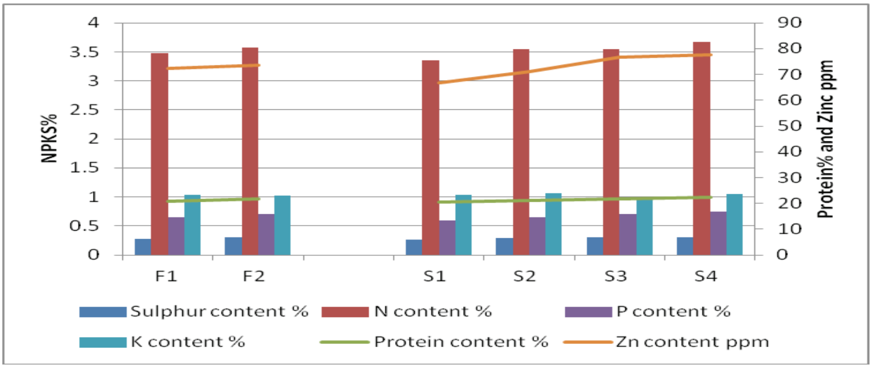


Fig. 36: Nutritional quality of Sunflower seed

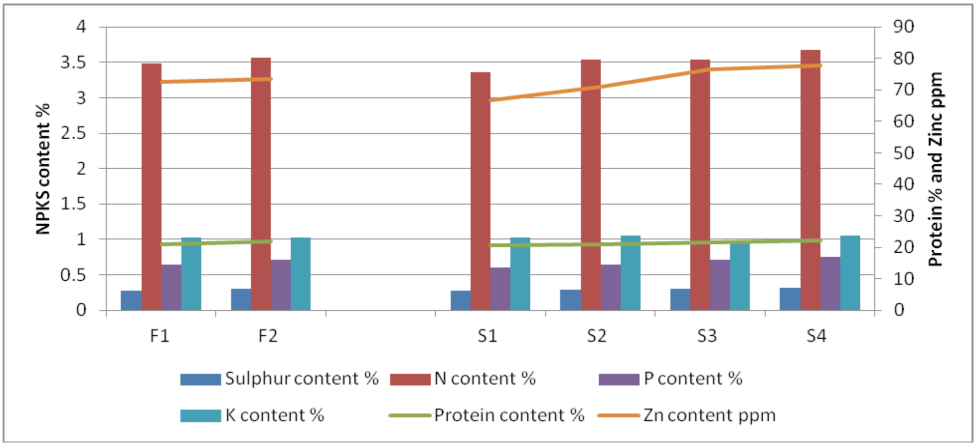


Fig. 37: Nutritional quality of Blackgram seed

Amino acid analysis showed lysine to be the first limiting essential amino acid in cereal proteins, but lysine content was highest in oats and rice among cereal proteins (Eggum, 1979). In contrast, tuber proteins are adequate in lysine but deficient in sulfur amino acids cysteine and methionine particularly at high protein levels (Food and Nutrition Research Institute, 1980).

Rice has the highest protein digestibility among the staples. Utilizable protein was comparable in brown rice, wheat, maize, rye, oats and potato but was lower in sorghum and higher in millet. Rice has the highest energy digestibility, probably in part because of its low dietary fibre and tannin content.

Rice hulls, Brown rice, Golden rice, White rice, Cooked rice

14. Role of Sulfur based herbicides in weed control

Weeds are one of the major pests of agricultural crops. The presence in and around agricultural fields inflict enormous losses which must be borne by all of us. On country basis such losses in crop yields have been estimated at 30-35 % in rice, 15-30 % in wheat and 18-85 % each in maize, sorghum pulses and oilseeds. But as the farmers adopt some kind of weeding in their fields, it still leaves us with a conservative estimate of at least 10 % reduction in crop yields. Increased herbicide use has saved farmers of undue, repeated intercultivators and hoeing and has helped the farmers in getting satisfactory weed control where physical methods often fail. Now, we were > 150 herbicides in common use for selective and non-selective weed control in different areas.

Echinochloa, Paspalum, Cyperus and Marselia weeds

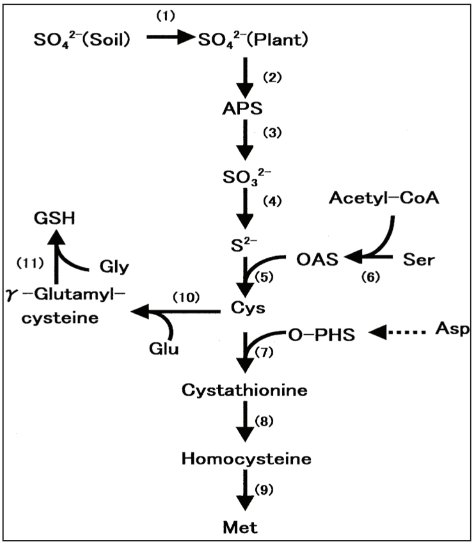
A wide variety of herbicides have been developed and used for weed control and these act by disrupting essential biochemical or physiological plants processes and safeners protect crops from herbicide action mainly by enhancing herbicide detoxification. The biochemical modes of action of the herbicides include disorganising the photosynthetic apparatus of susceptible plants or disturbing the normal course of respiration or interfere with phytoharmones and plant growth.

S-containing herbicides are often rapidly oxidized to sulfoxide and afterwards more slowly to sulfones. Sulfoxidation can occur in soil and water mediated chemical or biologically (López *et al.,* 1994; Hsieh *et al.,* 1998; Ankumah *et al.,* 1995). This oxidation is so rapid and complete that sulfoxides are often the compounds found in soil shortly after application of the parent sulfide compound. Furthermore, in some cases, sulfoxides and sulfones are suspected to have the herbicidal activity (Campbell & Penner, 1985). The important group of five chemical families are sulphonyl ureas, imidazolinones, pyrimidinyl-oxybenzoates, triazolopyrimidines and sulphony laminocarbonyl-triazolinones.

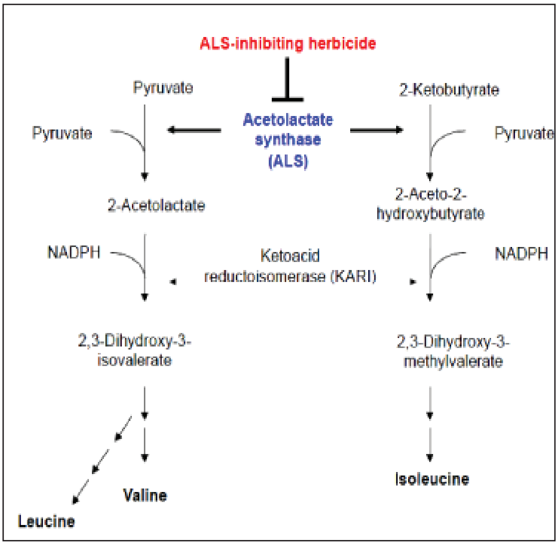
Sulfonylureas are also known as ALS inhibitors can move in both the xylem and phloem to areas of new growth and can be taken up through plant foliage and roots. AHAS/ALS is the first enzyme that is common to the biosynthesis of the branched-chain amino acids isoleucine, valine, and leucine. Inhibition of ALS leads to the starvation of the plant for these amino acids, and it is this starvation that is thought to be the primary mechanism by which ALS-inhibiting herbicides cause plant death. But other secondary effects of ALS inhibition, such as buildup of 2-ketobutyrate, disruption of protein synthesis, and disruption of photosynthate transport, have also been implicated in the mechanism of plant death in 7-20 days.

Representative sulfonyl urea Herbicides are

S. No.	Common Name
1	Chlorimuron-ethyl
2	Chlorsulfuron
3	Halosulfuron-methyl
4	Metsulfuron-methyl
5	Nicosulfuron
6	Primisulfuron-methyl
7	Prosulfuron
8	Rimsulfuron
9	Sulfometuron-methyl
10	Thifensulfuron-methyl
11	Tribenuron-methyl



Sulfur assimilation pathway in plants



ALS Activity in susceptible plants

15. Influence of Sulfur nutrition on insect pests in rice based cropping systems

Sulfur plays an important role as a constituent of many plant processes and it also plays an important role in imparting resistance to some of the insect pests. Application of sulfur fertilizers to the soil increases the sulfur content of rice plants and there by minimizes the insect pest numbers feeding on it. Rice crop is prone to stress throughout the crop growth period due to different pests such as insects, diseases and weeds. Insect pests attack the crop throughout the growth period and cause significant yield losses. There are more than 100 insect species recorded as feeding on rice plant. About 20-25 of them reached the status of pests causing economic losses under farmers' field situations. Among them stem borers, planthoppers, leafhoppers, leaf folders, gall midge, rice hispa, gundi bug, case worm, army worm, cut worm, mealy bugs and rice thrips are the most important.

Fig. 38: BPH, WBPH, Galmidge, Leaf folder and YSB in paddy

Among the pulses, Black gram is the major protein rich, but attacked by several insect pests like borers, sucking pests and flower feeders. The borers include g**ram pod borer, *Helicoverpa armigera*, s****potted pod borer,** *Maruca testulalis,* s**piny pod borer,** *Etiella zinckenella,* b**lue butterfly,** *Lampides boeticus,* g**rass blue butterfly:** *Euchrysops cnejus,* sucking pests include bean Aphids, *Aphis craccivora,* *l*eaf **hopper,** *Empoasca kerri,* p**od bugs,** *Riptortus pedestris,* *l***ab lab bug or stink bug,** *Coptosoma cribraria,* w**hitefly,** *Bemisia tabaci, f*lower feeders like blister beetle, *Mylabris phalerata,* (Fig. 39).

Fig. 39: Aphids, white flies, spotted pod borer, blister beetle and blue butterfly

Among oil seeds, Sunflower crop is seriously affected by the insect pests, attacking at different stages of crop growth. the important insect pests aretobacco caterpillar, Spodoptera litura, bihar hairy caterpillar, Spilosoma oblique, American pod borer Helicoverpa armigera, cut worm Agrotis ipsilon, jassids, Amrasca biguttula bigittula, white flies, mealy bugs and thrips. (Fig. 40).

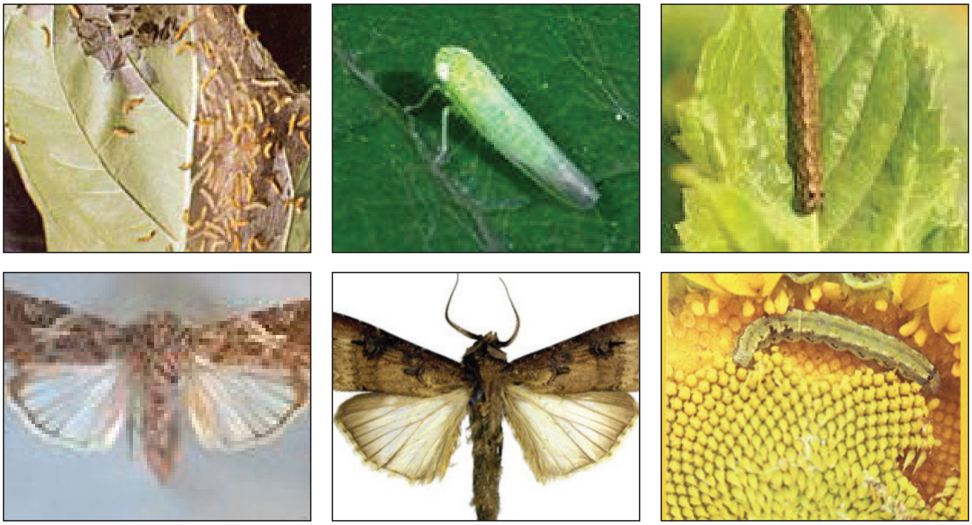


Fig. 40: Bihar hairy caterpillar, sunflower jassid, Spodoptera Larva and Moth, Agrotis ipslon, Heliothis armigera

Nutrient and Insect pest interaction

Results of the earlier studies revealed that, Sulfur, Zinc and Potassium nutrient contents of rice foliage and incidence of brown planthopper (BPH) had a significantly negative relationship. Zinc and sulfur content in foliage was positively correlated with leaf folder incidence (Dash *et al.*, 2007). Whereas phosphorus showed significantly positive correlations (r=0.6279) with BPH only and nitrogen showed positive correlation with both BPH and leaf folder.

Table 8: Nutrient influence on Insect Pest Incidence

Plant nutrient	**Correlation Coefficient r**	
	BPH (no/hill)	**LF (%DL)**
Nitrogen	0.7390**	0.727**
Phosphorus	0.6279**	0.3423
Potassium	-0.3275	-0.1184
Zinc	-0.2690	0.0349
Sulfur	-0.2689	0.0101

*** significant at 1% level*

Sulfur use in Insect Pest Control

Application of sulfur powder has positive effect on tolerance of rice seedlings to BPH. Application of sulfur powder @15g/seedling box with 15 days old and 45 days old rice seedlings increased days to withering of seedlings by BPH, reduced the number of eggs per seedling, lowered honeydew excretion and reduced feeding preference. (Kang *et al.,* 1989). Sujatha *et al.,* 1987 in their study on influence of mineral nutrition on insect pest incidence of different rice cultivars reported the relationship between chemical composition and resistance of 11 rice varieties to BPH revealed positive correlation between sulfur content of rice plant and resistance to BPH (no/hill). In their findings, phenol, silica, phosphorus, potassium, calcium, sulfur and iron contents were positively correlated with resistance, while the protein, nitrogen, zinc and manganese contents were negatively correlated with resistance. Results of the experiments on impact of Sulfur and other major nutrient fertilizers on Rice Insectpest incidence showed that application of elemental sulfur to rice fields decreased the pest incidence viz., leaf folder and BPH. When DAP, elemental sulfur containing fertilizer i.e. sulfur enhanced diammonium phosphate (SEF 12) and SSP were applied to the soil, differential response in the pest incidence to soil applied sulfate and elemental sulfur were observed. Less leaf folder and BPH damage were observed in elemental sulfur applied plots (Zhuzhang *et al.,* 2010).

Experiments were conducted at Indian Institute of Rice Research to find out and quantify the iimpact of Sulfur application on insect pest incidence and control in deficient soil conditions in rice based cropping systems. Pest incidence was observed in the experimental field at DRR with and without sulfur fertilization. The incidence of insect pests was generally low in the vegetative stage (45-50DAT). The dead heart incidence ranged from 0-1.7%. There was no leaf folder and gall midge damage. Whorl maggot incidence ranged from 0.6 to 2.0%. The incidence was more in the plots which received recommended fertilizer dose compared to those that received ½ the dose. Stem borer damage was moderate at the time of pre-harvesting stage with 10 to 13.4% white ears. Plots with recommended fertilizer dose recorded more number of white ears (12%) than those with ½ the recommended dose (10%). Plots with sulfur application had less number of white ears (10%) compared to those without sulfur application (12%). Among the interactions, plots with recommended fertilizer and without sulfur application recorded more no of white ears (13.4%) compared to other interactions.

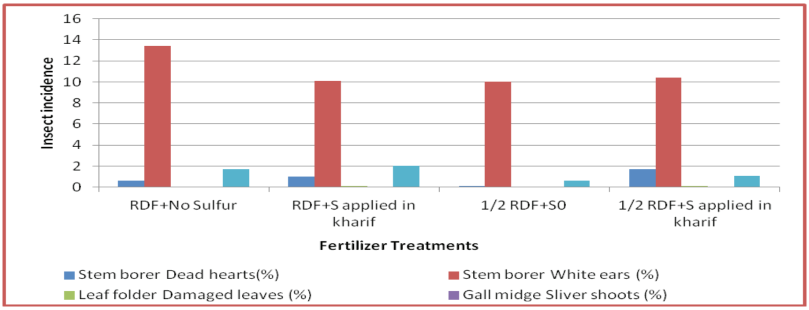


Fig. 41: Incidence of insect pests in the sulfur plots

16. Influence of Sulfur nutrition on diseases in rice based cropping systems

Among 70 diseases that are reported rice, bacterial leaf blight (*Xanthomonas oryzae* pv. *oryzae*), blast (*Magnaporthe grisea* (anamorph: *Pyricularia grisea*), sheath blight (*Rhizoctonia solani* Kuhn (Teleomorph: *Thanetophorus cucumeris* (Frank) Donk), rice tungro (RTSV, RTBV) and false smut (*Ustilaginoidea virens*) are the major diseases and cause substantial quantitative and qualitative losses especially in endemic areas. Besides, foot rot or bakanae (*Fusarium moniliforme* (Teleomorph: *Gibberella fujikuroi*), sheath rot (*Sarocladium oryzae*), brown spot (*Helminthosporium oryzae (synonym: Drechslera oryzae; Teleomorph: Cochliobolus miyabeanus)* and stem rot (*Sclerotium oryzae*) are also noticed to have majour concern. Similarly sunflower is attacked by many diseases, which reduce the yield and quality significantly under optimal conditions. The major diseases limiting sunflower cultivation in India are Alternaria leaf blight, downy mildew, sunflower necrosis and rust. During the last 3 years, powdery mildew caused by *Erysiphe cichoracearum* has become a serious problem on sunflower in south India (Karuna *et, al.,* 2013). Another crop in rice based cropping system is black gram and the black gram diseases responsible for an estimated yield loss of 20 to 30 percent (Singh, 1995). Among the foliar fungal diseases, powdery mildew, *Cercospora* leaf spot and rust are the more prevalent diseases and the yield losses caused by foliar disease are proportional to the disease severity depending on the stage of infection, genotypes and environmental conditions.

Fig. 42: Bakanae, leaf blast, brown spot and bacterial leaf blight infected rice

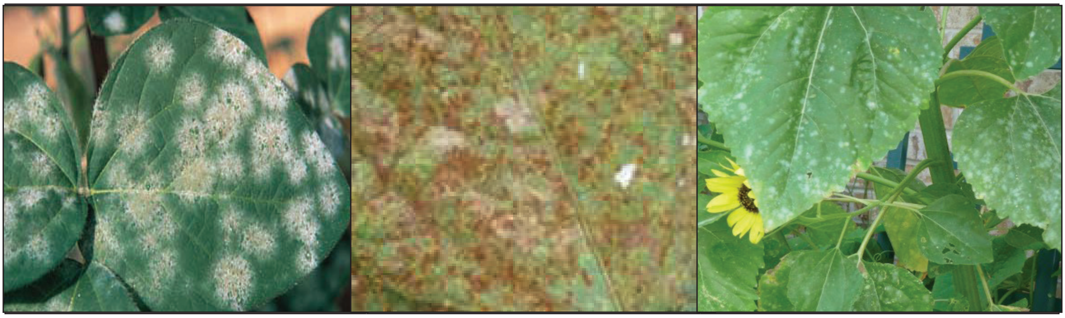


Fig. 43: Powdery mildew and rust diseases on black gram and powdery mildew on sunflower

The nutrition of a plant determines in large measure its resistance or susceptibility to disease and the ability of pathogens to cause severe disease. Nutrients interact as part of the environmental component (Figure 1) and plant nutrition, although frequently not recognized, always has been a component of disease control. Cultural practices that influence disease such as crop sequence, organic amendment, liming for pH adjustment, tillage, and irrigation all supply nutrients to the plant directly or make them more or less available for plant uptake through altered microbial activity. In contrast, many pathogens can alter the availability of nutrients in the rhizosphere or infection court to predispose plants to more severe infection (Huber and Graham 1999). Many plant diseases have been effectively controlled by integrating the effects of specific mineral nutrients, and the cultural practices which influence them, with genetic resistance, sanitation, and chemical controls. Mineral nutrients are directly involved in all mechanisms of defense as integral components of cells, substrates, enzymes and electron carriers; or as activators, inhibitors, and regulators of metabolism. Mineral fertilization may off-set the reduced absorption (root rots), translocation (vascular wilts) or distribution (leaf spots, rots) effects of disease by providing a greater abundance of nutrients for uptake or by inhibiting virulence and survival of the pathogens (Huber DM, Graham RD (1999).

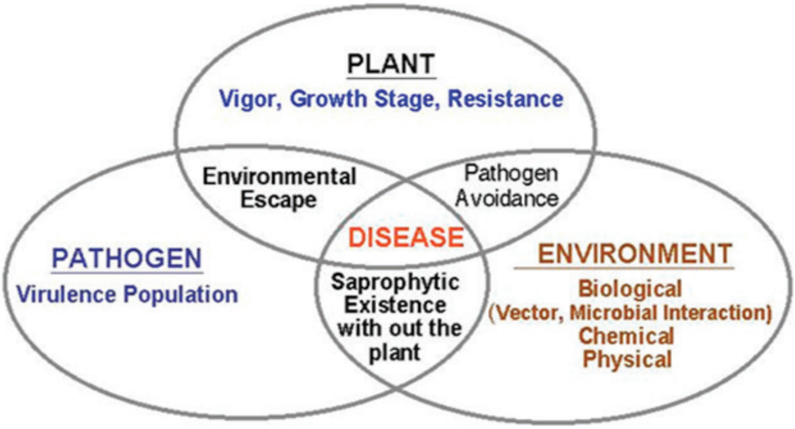


Fig. 44: A schematic representation of the interacting components involved in plant disease

The effect of mineral nutrients on disease incidence or severity has been determined by:

- Observing the effect of nutrient fertilization on disease severity,
- Comparing mineral concentrations in resistant and susceptible cultivars or tissues,
- Correlating conditions influencing mineral availability with disease incidence or severity

A particular element may reduce some pathogens but increase others, and have an opposite effect with modification of the environment, rate or time of application. These differences provide an opportunity to manage various diseases by integrating them with specific cultural or management practices. The flexibility in most disease-nutrient interactions permits a much broader utilization of this cultural control in reducing disease severity than is presently practiced. The severity of most diseases can be greatly reduced and the chemical, biological, or genetic control of many plant pathogens enhanced by proper nutrition. Balanced nutrition for the specific crop is important and there is little advantage in starving a plant into a non-productive state just for disease suppression.

Limited information is available on the influence of sulfur nutrition on dynamics of rice diseases in deficient soils. However emphasis has been put forth for efficient and sustainable management of diseases in rice-based cropping systems at Indian Institute of Rice Research. The study revealed that, the disease incidence of rice was influenced by S application. Brown spot, sheath rot were relatively low in plots applied with Sulfur by 10%. The bacterial leaf blight incidence was less in half the Recommended Dose of Fertilizers (RDF) + Sulfur applied plots, than RDF without S applied plots

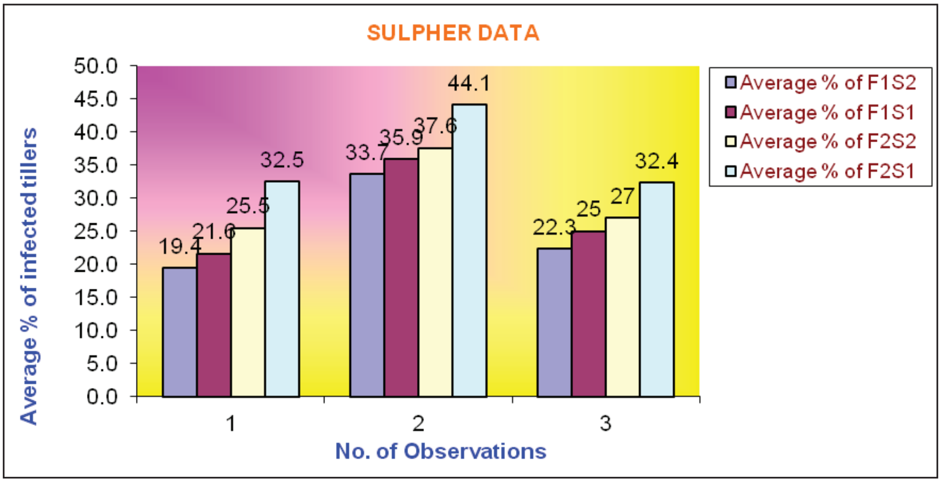


Fig. 45: Influence of sulfur nutrition on bacterial leaf blight of rice

Sulfur fungicides in disease control

Sulfur has unquestionably been one of the most important and certainly one of the earliest fungicides ever used. Use of sulfur in plant disease control is classified as inorganic sulfur and organic sulfur. Inorganic sulfur is used in the form of elemental Sulfur or as lime sulfur. Elemental sulfur can be either used as dust or wettable sulfur, later being more widely used in plant disease control. Sulfur is best known for its effectiveness against powdery mildew of many plants, but also effective against certain rusts, leaf blights and fruit diseases. Sulfur fungicides emit sufficient vapour to prevent the growth of the fungal spores at a distance from the area of deposition which is an added advantage in sulfur fungicides as compared to other fungitoxicants.

Mode of Action of Sulfur on diseases

- Elemental sulfur may enter fungal cell wall and disrupt reactions in metabolism of the pathogen
- May also be direct toxic effects to Pathogens
- Initially found as foliar reactions, later as increased S levels in soil pathogens

Table 10: Some of the sulfur fungicides used for controlling diseases in the rice based cropping systems

Disease	Fungicide recommended	Reference
Rice		
Blast- (*Pyricularia grisea*)	Thiovit 80WP	UsmanGhazanfar et al 2009
Brown spot- (*Helminthosporium oryzae)*	ThiovitJet80WG	Azher Mustafa et al 2013
	Sulfex Gold 80% WDG	Azher Mustafa et al 2013
	Kumulus80%WG	Azher Mustafa et al 2013
	sulfur-coated urea or urea super granules and neem cake + urea	Vidhyasekaran et al., 1983; Viswanathan andKandiannan, 1990
Sheath rot (*Sarocladium oryzae*),	Mancozeb75 WP	Viswanath and Narayanaswamy, 1993
Blackgram		
Powdery mildews *Erysiphe polygoni*	Wettable sulfur, Sulfur dust	Pande et al 2009
Rust - *Uromyces phaseoli typical* (Syn: *U. appendiculatus*)	Mancozeb 75 WP	Pande et al 2009
Anthracnose - *Colletotrichum lindemuthianum*	Mancozeb75 WP	Pande et al 2009
Sunflower		
Powdery mildew- (*Erysiphe cichoracearum*)	Wettable sulfur 80 WP; Mancozeb 75 WP	Akhileshwari et al 2012
Rust- (*Puccinia helianthi*)	▪ Zineb 80 WP; ▪ Mancozeb 75 WP	Rashid, K. Y. 1997
Alternaria leaf spot: *Alternaria helianthi Hansf.*	▪ Mancozeb 75 WP; ▪ Zineb 80 WP; ▪ Mancozeb 75 WP	Basappa and Santha Lakshmi Prasad, 2005.

17. Conclusions

- Nutrient management slogan has to be NPKS rather than NPK: No more neglect of plant nutrient sulfur has to be a slogan while prioritizing nutrient management options.
- The various results reveal that nitrogen, a vital major plant nutrient element, depends on sulfur, among other important nutrient elements including phosphorus. Application of sulfur is inevitable, particularly when nitrogen application is raised for higher production.
- A proportion of sulfur to nitrogen of 1:2 to 1:3 depending upon the oilseed or cereal crops, is likely to boost and sustain the yield as well as quality of crops in terms of the free fatty acid contents and proportion of saturated to unsaturated fatty acids.
- Along with Recommended Fertilizer Dose of *kharif* rice, Sulfur application @45 kg/ha in *kharif* season is required to achieve higher rice yield, blackgram yield, rice equivalent yield and profits in rice-blackgram cropping system.
- For rice-sunflower system, recommended Fertilizer Dose of *kharif* rice along with sulfur application @45 kg/ha each in both *kharif* and *rabi* seasons is required to achieve higher rice yield, sunflower yield, rice equivalent yield and profits
- Significantly higher yield benefits with 45 and 60 kg/ha were recorded and 45 kg/ha was found as the economic optimum dose in S deficient soils.
- Among different chemical fertilizer sources, phosphogypsum, gypsum and ammonium phosphate sulfate were efficient sources.
- The improved Varieties viz., PHB71, Vivekdhan, VL Dhan 221, Mahamaya, Govind, Karjat3, CSR27, Poornima, Rajavadlu, GR4, Krishnahamsa, Pantdhan16, Remya, Bhadrakali, IR64, Early samba and Satya have exhibited high S use efficiency
- Soil arylsulfatase activity, an indicator of organic sulfur mineralization and soil microbial populations and sulfur oxidizer populations is affected by sources and quantity of sulfur fertilizers applied.
- Farmers should not rely exclusively on a single management practice but rather integrate a combination of practices to develop a consistent long-term strategy for pest and disease management that is suited to their production system and location.

18. Future thrust

- Tailoring genotypes to yield better under nutrient, other abiotic and biotic stresses is a very important future strategy to realize full potential from the deficient soils.
- Integrating Sulfur completely with balanced fertilization schedule for different crops and cropping systems has to be accomplished.
- Studies on evaluation of various organic sources as S carriers and development of appropriate strategies for their effective use.
- Strong extension efforts are needed to advocate the use of required S along with soil testing backup for its accelerated use.
- Data on S deficient areas, response yardsticks and S content of fertilizers should be displayed at fertilizer sale points.
- Considering the importance of organic S in plant nutrition, a better understanding of the role(s) of arylsulfatases in S mobilization in agricultural soils is critical and need to be focussed upon.
- In addition, as very little is known about specific microbial genera or species that play an important role in the soil organosulfur, these microbes need to be identified and characterized for their exploitation as bioinoculants for agriculture.

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