Sulphur Nutrition of Tea - Global Review

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Introduction

Sulphur, as a secondary nutrient is vital for tea crop. Although, the importance of sulphur in tea crop nutrition was recognized long ago, it received little attention compared to other nutrients. This could be due to the fact that sulphur estimations in soil and plant are tedious. Quite often, sulphur needs were met through low analysis fertilizers like ammonium sulphate, single superphosphate and some organic sources. However, with increase in productivity of crop over time, removal of sulphur and increased use of high analysis fertilizers *viz.* urea, di-ammonium phosphate, and triple superphosphate *etc.* further hastened the depletion of sulphur from the soil. This review aims at consolidating the information available and help in identifying information gaps in our knowledge and suggest future lines of research.

Sulphur Deficiency in Tea

Sulphur deficiency of tea or "tea yellows" was first observed in Malawi tea plantations way back in 1930s. Subsequently, Forbes (1942) observed that any organic or inorganic fertilizer containing sulphur in available form cured "tea yellows" in Malawi.

Sulphur deficiency is characterized (Storey & Leach, 1933) as follows:

* Leaves are normal in size and texture but yellow mottling during early stage of deficiency.
* Leaves turn yellow, brittle and reduced in size. Scorching on margins and tips during intermediate stage of deficiency.
* All leave fall and only small leaf at the tip of shoot remain. Shortened internodes and axillary buds grow into small shoots with yellow leaves during later stage of deficiency.
* Bush totally defoliated death of terminal buds in the shoots and gradual dieback resulting in death of entire bush during extreme stage of deficiency.

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It was observed that sulphur deficiency could be aggravated at low temperature and under drought situation.

Table 1 gives the list of references in tea growing countries where S deficiency has been identified/ reported and also reports on effectiveness of sulphur containing nitrogenous fertilizers over pure nitrogen sources. Although tea is cultivated in more than thirty countries, reports on sulphur nutrition are very limited.

Sulphur content of tea

Plants usually take up Sulphur in SO_4^{2-} form. Sulphur content in the pluckable leaves is reported to be in the range of 0.08 - 0.37 % on dry weight basis (Stagg and Millin, 1975). Sulphur content varies between parts, clones, season and location. Table 2 shows variability of sulphur between different parts of the tea bush with maximum content in mature foliage and minimum in wood and twigs. Sulphur content varies with clones. Similarly, minor seasonal variation in S content was also observed under Indian conditions (Table 3). Sulphur content varied in different tea growing regions of India (Table 4). Sulphur content was found to be quite low in Kangra tea region of Himachal Pradesh, India. Low sulphur content in tea shoots is an indication of low sulphur status of the soils where tea is grown.

Forms of Sulphur and their Distribution in Tea Growing Soils

Total Sulphur vs. Available Sulphur

The total sulphur content of soils indicates the net reserves of this element, which may be converted into sulphate, the form most readily available to plant, by either chemical or biological action. Soils vary widely in their total sulphur content. Range of total sulphur and available sulphur in tea soils of China and India are shown in Table 5. Total sulphur content may not give clear indication of soil supplying capacity of sulphur to crop.

The organic sulphur is a part of organic matter and may be in the form of ester sulphates or carbon

Table 1: Reports on sulphur deficiency and use of sulphur containing Nitrogen fertilizers as sulphur sources

Region	Country	Cited reported on sulphur deficiency/tea yellows	Reports on use of sulphur containing nitrogenous fertilisers
Africa	Kenya	Eden (1953)	Eden (1953)
	Malwai	Storey & Leach (1933)	Forbes (1942)
	Tanzania	Eden (1953)	Eden (1953)
	Uganda	Hesse (1955)	N.A
	South Africa	Mkwalia (1992)	Mkwalia (1992)
Asia	India(North)	Kanwar & Takkar (1966) Sharma (1989); Barbora (1995); Nagendra Rao, T (1995)	Harler (1950), Gokhale (1956), Ranganathan & Swaminathan (1968)
	Sri Lanka	N.A	Watson & Wettasinghe (1982)
	Indonesia	Ishmyndji & Shin (1988)	Pronk (1955)
	Bangladesh	Islam (1989)	N.A
	Japa	N.A	Ishigaki (1974)
	Iran	N.A	Salardini(1978)
	Russia	N.A	Goletiani (1951)Urushadze (1954)
Oceania	Papua New Guinea	Sumbak (1983)	N.A

N.A : Information not available

Table 2: Sulphur content in different plant parts of South Indian tea clones

Plant Part	Sulphur % (Dry Matter Basis)			
	Upasi - 1 (B/4/41)	Upasi- 3 (B/5/63)	Upasi - 9 (B/6/61)	Upasi - 15 (SP/4/5)
Two & Bud	0.28	0.26	0.22	0.23
Mature foliage	0.34	0.33	0.33	0.33
Stem	0.15	0.13	0.13	0.12
Whole plant	0.22	0.20	0.20	0.19

Source: Planters Chronicle, December 1980

Table 3: Seasonal variation in nutrient content of tea shoots (two & bud) in Assam (India)

Month	Clone 19/29/13			Clone 3/77		
	S %	N:S ratio	P:S ratio	S%	N:S ratio	N:S ratio
July	0.28	13.6	1.6	0.24	17.6	1.8
September	0.32	14.5	1.7	0.28	18.9	1.9

Source : Science and Practice in Tea culture, Tea Research Association (TRA) Tocklai (1989)

Table 4 : Regional variation in sulphur content in harvested tea shoots in India

Region	Sulphur(%)	References
South India	0.22- 0.28	Bhat & Ranganathan (1980)
Assam	0.24-0.32	Barua (1989)
Himachal Pradesh	0.06-0.23	Sharma (1989)

Table 5: Sulphur status in tea growing soils

Country	Total Sulphur (ppm)	Available Sulphur (ppm)	References
China	24 - 835	3-222	Yong (1992)
North India South India	220 - 472 337 - 1318	10-144 14-371	Nagendra Rao & Shama (1997); (Nagendra Rao 1997)

bonded sulphur. Ester sulphates consist mainly of organic sulphates containing ester linkage such as choline sulphate, .phenolic sulphate and sulphated polysaccharides. Ester sulphate fraction is generally unavailable to plants but sulphur is released and made available after organic linkage is broken or organic sulphur gets mineralized. Drying soils breaks the linkage and consequently can have dramatic effects on soil test results. The fraction designated as "carbon bonded sulphur" has been proposed for determining the fraction of organic sulphur directly bonded to carbon in soils and fractions include cystine and methionine, which account for more than 95 per cent of sulphur in many organisms.

The common forms of inorganic sulphur in the soil are (a) Water soluble sulphates of Na, K, Mg and Ca, (b) Adsorbed sulphates on the surface of aluminium and iron oxides, clay minerals, (c) Non-sulphate sulphur (d) Sulphides, i.e., reduced forms of sulphur (negligible in well aerated soils).

Observations (Nagendra Rao, 1995) on distribution of sulphur fractions in tea growing soils of India indicated that Organic sulphur, especially carbon bonded sulphur fraction was the dominant form of sulphur in the surface soil horizons of India. South India had relatively higher quantities of all fractions compared to north India. Inorganic sulphur constitutes a small fraction particularly in north India (Table 6)Table 6: Distribution of various sulphur fractions in tea growing soil of India

Diagnostics

Selection of rapid, reliable sulphur extractant that can predict sulphur-supplying capacity is a prerequisite for any soil-testing programme. Various extractants have been used and the details are summarized in Table 7.

Inclusion of sulphur tests in tea advisory work is essential for balanced fertilization. Nagendra Rao and Chakravarty (1994), Nagendra Rao and Sharma (1997) have verified the advantage of using multi-elemental extractants in soil programmes of tea. Mehlich is one such multi-element extractant that could be useful for rapid extraction and helps in simultaneously analyzing nutrients like P, K, Ca, Mg, Cu, Fe, Mn and Zn from the soils besides sulphur.

Use of leaf analysis as a diagnostic tool for determining sulphur requirement of tea crop is not very common. Less than 0.05 percent sulphur content in third leaf of a tea shoot is categorised as below normal and more than 0.5 percent as above normal (Bonheure and Willson, 1992).

Sulphur Fertilization

Responses to sulphur fertilization:

Kanwar and Takkar (1966) studied the responses of tea crop to application of sulphur in tea soils of Dharamsala in erstwhile Punjab (now in Himachal Pradesh) and found that sulphur addition significantly increased tea yields when applied in the form of sulphate of ammonia on a sandy loam soils of pH 4.8. In other locations where the pH was higher, application of elemental sulphur was better. Grant and Shaxcn (1970) also reported that applied sulphur improved the soil status and using sulphate fertilisers could prevent sulphur deficiency in tea.

Table 6: Distribution of various sulphur fractions in tea growing soil of India

Sullphur fractions	Sulphur Content (ppm)	
	North India	South India
Total Organic Sulphur	204 - 430	315 - 1008
* Ester sulphate - S	15 - 204	28 - 581
* Carbon bonded - S	117 - 414	78 - 527
Total inorganic sulphur	8 - 134	16 - 310
* Adsorbed - S	2 - 96	2 - 254
* Water soluble - S	2 - 19	2 - 48
* Non - sulphate - S	1-19	3 - 28

Source: Nagendra Rao (1995)

Table 7: Extractants for available soil sulphur

Extractants compared	Composition	Location	Best Extractant (S)	Critical Level	References
1. Calcium Chloride 2. Olsen's extractant 3. Ammonium Acetate	0.15% $CaCl_2$ 0.5 M $NaHCO_3$ 1 NNH_4OAc	Himachal pradesh, India	Calcium Chloride	12.0 ppm	Sharma (1989)
1. *Morgan's reagent* 2. Potassium Phosphate	NaOAc + HOAc KH_2PO_4	Assam India	Morgan's	12.0 ppm	Bhowmick & Ghosh (1993)
1. Calciumchloride 2. Monocalcium Phosphate (MCP) 3. Monocalcium Phosphate (MCP)+ Acetic acid 4. Morgan's reagent 5. Mehlich III Extractant	-- $Ca(H_2PO_4)_2H_2O$ $Ca(H_2PO_4)_2H_2O$ + HOAc -- 0.15N NH_4F+ 0.25 N NH_4NO_3 +0.2 N *HOAc* + 0.013 N HNO_3 + 0.001 M EDTA	*India*	*Mehlich III*	14.0 ppm	*Nagendra Rao* & Sharma (1997)

Bhavanadan and Sunderalingam (1971) conducted some studies in the tea growing soils of South India where they use sulphate of ammonia, urea and CAN for the period 1961 to 1971 on tea crop and reported that sulphate of ammonia gave consistently higher yields than urea at the highest level (336 kg ha^{-1}). Otheino (1980) stressed the need of sulphur application to tea along with other fertilisers for better growth and yield. Watson and Wettasinghe *(1982)* studied the effect of three fertilizers viz. Sulphate of ammonia, urea and calcium ammonium nitrate on the leaf nutrient composition of tea grown in Sri Lanka and reported that *sulphate of ammonia gave* the highest yield. Response to sulphur application has been reported from *North-East India, Himachal* Pradesh and South India. Bhat and Ranganathan (1980) observed that tea bushes in South India absorbed 1kg of sulphur for each 100 kg of made tea. *According to them, a nominal yield level of 2000* kg of made tea absorbed 20 kg S ha^{-1} and to compensate for leaching and other limitations of sulphur availability, an application of 2 to 4 times the *quantity absorbed should be advocated. Sulphur* deficiency and/or response of tea to sulphur containing fertilizers has been reported from some tea growing countries (Sumbak, 1983). Natesan *et al.* (1989), *Verma* (1997) *also indicated the* importance of sulphur nutrition to tea crop.

Application of elemental sulphur @ 20 to 40 kg sulphur ha^{-1} was reported to increase tea yields significantly in Assam (Sinha *et. al.*, 1992). Gohain *et. al.* (1994) observed significant decrease in available sulphur in Assam soils following continuous application of Urea as nitrogen source. Krishnamurthy Rao (1988) concluded while comparing available sulphur status between unmanured vacant areas and area manured and planted to tea that there was no accumulation of sulphate sulphur in tea soils of south India on account of continuous use of ammonium sulphate. According to Mkwalia (1992), longterm studies in Malawi indicated that sulphur application did not enhance yield after 17-33 years, hence maintenance dose may be sufficient after adequate buildup of sulphur in the soils, although ammonium sulphate was a widely used sulphur source. Table 8 indicates the fact that response to sulphur sources varied considerably in different regions. Evaluation of sulphur sources is very important considering soil-climatic-economic situations.

Changes in Available Nutrients and pH due to Sulphur Application

Soil treatment with elemental sulphur, ammonium sulphate and single super phosphate showed some decrease in soil pH in the order mentioned in a tea growing soil of Himachal Pradesh when compared with gypsum treatment (Kanwar and Takkar, 1966). Raman (1963) observed that sulphur was responsible for effectively reducing soil pH and had favourable effect on growth of tea seedlings.

Influence of Sulphur Application on Tea Physiology and Metabolism

Increase in growth parameters of young tea like collar diameter, leaf area index (LAI) and bush volume was reported by Nagendra Rao (1995). Positive effects on chlorophyll content of the leaf were reported by Kanwar and Takkar (1966), Sharma (1989) from India, and Yong *et. al.* (1994), Wu and Ruan (1994) from China. Yong (1933a) reported increased rate of photosynthesis with S application and the rate increased in the order of K_2SO_4> $MgSO_4$ > $(NH_4)_2$ SO_4> Sulphur. Takeo (1979) reported that amino acid content of new shoots increased when sulphate of ammonia was applied, during late spring-early summer. Sharma (1989), Yong (1993b) and Nagendra Rao (1995) observed increased content of sulphur containing amino acids in tea leaves with sulphur application. Increased theanine and aspartic acid in tea due to sulphur application was reported by Yong *et. al.* (1994), Wu and Ruan (1994).

Table 8 Tea crop response to sulphur application through various sources

Region/ Country	Cropping Stage	Sulphur Dose (kg ha^{-1})	%Yield increses over control	Sources of sulphur	References
Himachal pradesh (India)	Young Tea	50	64 57 51 20 1	Elemental S Iron Pyrites Alum Gypsum SOA + SSP	Sharma & Nagendra Rao (1995)
Himachal pradesh	Mature Tea	200	132	Iron Pyrites	Sharma (1989)
Tocklai Assam (India)	Mature Tea	20	20 18 17 15 7	Gypsum SOA Iron Pyrites Alum Elemental S	Barbora (1995)
UPASI (South India)	Mature Tea	624*	4*	SOA	Natesan & Ranganathan (1986)
Mimosa (Malawi)	Mature Tea	25	13	SOA	Mkwalia (1992)

* For two years

Quality

Sulphur has been considered so far as a nutrient for growth and yield. Recent reports indicate the fact that sulphur plays a crucial role in improving made tea quality also.

According to Yong *et al.* (1994), sulphur application reduced polyphenol oxidase (Catechin Oxidase) activity and polyphenol metabolism which is considered good for green tea. Under pot experiments, Yong (1993b) reported increased caffeine content in tea leaves. Nagendra Rao (1995) reported similar positive effects on field plucked-made tea of Himachal Pradesh and observed positive effect of sulphur on Methionine in tea shoots and positive correlation of methionine with caffeine reinforced involvement of sulphur in caffeine biosynthesis. Theaflavins (TF), Thearubigins (TR) and colour were found positively influenced by sulphur application in orthodox Kangra tea (Nagendra Rao, 1995) Similar results were also obtained in Assam and confirmed by tasters' scores (Barbora, 1995); Ali *et. al.*, (1997). Nagendra Rao (1995) further observed that the quality of rainy season flush was usually poor compared to first or post rainy season flushes. With the application of sulphur quality of rainy season flush could also be improved to some extent. The positive effect of sulphur on aroma compounds like Linalool, Geraniol, β-Ionone was also reported (Wu and Ruan, 1994)

Conclusions

With the change in fertilizer use from low analysis sulphur containing fertilizers to high analysis sulphur free fertilizers input of sulphur through various sources will be diminishing from the soil system over the years. Tea is normally grown in light textured soils in high rainfall zones where sulphur losses are considerable over time. Hence, inherent soil sulphur status as well as nutrient losses from the system along with crop demand need to be considered while calculating sulphur requirement of crop in order to maintain proper balance between addition and removal from the system for sustainable crop productivity.

Future lines of research:

1. Survey and monitoring of sulphur status in tea soils must be done regularly on regional basis.
2. Sulphur use efficiency of various sulphur fertilisers in each region must be properly established.
3. Sulphur sources must be evaluated through yield assessment and economics on regional basis.
4. Nutrient budgeting in soils needs to be done on regular basis.
5. Interaction of sulphur with other nutrients on longterm basis must be studied properly.
6. Introduction of multi-element extractants and new procedures must be introduced in routine soil test labs to evaluate sulphur requirements rapidly, precisely and in cost effective manner. Critical levels of sulphur in soils and plants need to be established.
7. Specific roles of sulphur metabolites as well as their metabolic pathways on quality of made teas need to be thoroughly understood.

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