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Influence of potassium solubilizing bacteria on crop productivity and quality of tea (*Camellia sinensis*)

B. Bagyalakshmi^{1*}, P. Ponmurugan¹ and S. Marimuthu²

¹Department of Biotechnology, K. S. Rangasamy College of Technology, Tiruchengode -637 215, Namakkal District, Tamil Nadu, India.

²R&D Centre, Parry Agro Industries, Valparai – 642125, Tamil Nadu, India.

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A field experiment was conducted to study the efficacy of indigenous potassium solubilizing bacteria (KSB) in combination with various dosages of potash fertilizers along with recommended dose of nitrogen (N) and phosphorus (P) fertilizers in tea plants. Soil and leaf samples were drawn from the respective plots and they were subjected for the analysis of various parameters related to nutrients and quality aspects. Among various treatments, plants treated with N₁₀₀ P₁₀₀ K₇₅ + KSB concentration formulation was found to be the best in terms of high chlorophyll, carotenoid, N, P and K contents in the crop shoots followed by other treatments. Significantly higher yield of the green leaf was achieved by the same treatment. K content in soil and also in crop shoots was greatly improved due to the application of KSB along with possible reduced doses of potash source. On the other hand, N₁₀₀ P₁₀₀ K₂₅ + KSB formulation and untreated control plots have exhibited least green leaf yield and nutrient status of soil and crop shoots. The biochemical parameters, total polyphenols, catechins, amino acids and sugars were significantly at higher level in plants after imposing treatments in combination with KSB. Biometric parameters such as plucking surface of the tea bush canopy, plucking points per unit area, internodal length, leaf moisture and dry matter contents were analyzed and found to be high in tea plants treated with N₁₀₀ P₁₀₀ K₇₅ + KSB combination. Banji content was significantly reduced invariably in all the treatments except the untreated control plots. Evaluation of KSB population in soil revealed that wherever KSB was incorporated, there was a significant increase in population level and has coincided with dehydrogenase enzyme activity. The flush shoots of tea comprising of three leaves and a bud were subjected to manufacture black tea, and it was revealed that almost all the tea quality parameters such as theaflavin, thearubigin, highly polymerized substances, total liquor colour, caffeine, briskness, colour and flavour indexes were greatly improved in KSB treated plants, which in turn improve the quality as well. This finding confirms that the influence of indigenous potassium solubilizing bacteria upon potassium nutrient exhibited improvement in the productivity and nutrient uptake in plants and retained in soil including quality parameters in tea plantations.

Key words: Tea, potassium solubilizing bacteria, biofertilizer, nutrient status, crop productivity, tea quality.

INTRODUCTION

Tea (*Camellia sinensis*) is an important commercial crop in many subtropical and tropical areas of the world. Tea, owing to its favorable benefits on human health, currently enjoys a great popularity among other beverages worldwide (Liang et al., 2007). The crop shoots are plucked at

regular intervals (10 to 15 days) and removed a certain amount of various elements from the plant-soil system.

Essential nutrients have to be supplemented through various sources of fertilizer for higher productivity and maintenance of soil health. Next to nitrogen (N), potassium (K) is another major essential nutrient and it is being taken up by the crop plants in quite large quantities similar to or more than nitrogen. It has been reported that potassium and magnesium are required in large quantities, and they are both involved in almost all

*Corresponding author. E-mail: bagyalakshmi09@gmail.com.
Tel: +91 4288 274741 – 44. Fax: +91 4288 274745.

biological reactions in crop plants (Sedagathoor et al., 2009). Potassium promotes root growth, stronger stem, and increases resistance to cold and water stress. It directly connects with improvement of the quality of crop, reduces pest and disease incidence by enhancing crop resistance as well. Although K is not a constituent of any organic molecule or plant structure, it is involved in numerous biochemical and physiological processes and pivotal role to plant growth, yield, quality and stress (Cakmak, 2005). In tea plantations, both seedlings and clones of tea are being cultivated under diverse soil types, areas with abundant rainfall and various agro climatic conditions. Due to perennial habitat of the tea plant and continuous application of inorganic NPK fertilizers (5-6 splits), the tea plantation soils are highly weathered, low in base status and are generally acidic in reaction.

There is a mutual relationship between soil microflora and minerals possessed in soil environment and these interactions have been extensively studied to produce technologies such as bio mineralization, bioremediation and bio hydrometallurgy (Rawlings, 2002).

Moreover, quality of made tea depends on organic and inorganic composition of harvested shoots, which are changed into the substances, these are responsible for taste, flavor and colour of made tea. The nutrients absorbed by crop shoots may influence the quality attributes in made tea. In which, potassium is the major nutrient element which influences on the quality of marketable tea (Venkatesan et al., 2006). Also, the important quality components of black tea were shown to be improved with increased K application in Chinese cultivation practices (Ruan and Hardter, 2001).

In this regard, supplement of balanced nutrition of tea is of particular importance to secure good harvested fresh leaves as a prerequisite for tea of superior quality. In recent years, the tea plantation mainly depends on synthetic inorganic source of fertilizers for higher yield and productivity. Deep dependency of such inorganic fertilizer remains demand, in future, is simultaneously harmful to soil health and environment. There are reports available for application of plant growth promoting bacteria and metals/minerals solubilizing bacteria to enhance the productivity and reduce banji contents, without affecting the quality of black tea (Mandal, 2007).

Experiments were conducted to evaluate the potential of potassium solubilizing bacteria (KSB) in soils planted with egg plant which revealed that KSB enhanced the plant growth and soil nutrient level significantly (Han and Lee, 2005). Similarly, *Frateruria aurantia* belonging to the family Pseudomonaceae obtained from the agricultural soils of Coimbatore region of Tamil Nadu, India was solubilized with K considerably, and this promoted the crop yield (Ramarethinam and Chandra, 2006). This solubilization effect is generally due to the production of certain organic acids and enzymes by KSB. In addition, they are also known to produce amino acids, vitamins and growth promoting substances like indole-3-acetic acid (IAA) and

gibberellic acid (GA₃) which help in better growth of the plants (Ponmurugan and Gopi, 2006). To keep this in mind, a study was undertaken to assess the influence of indigenous KSB in combination with various doses of potash fertilizers and the recommended dosage of nitrogen and phosphorus (P) fertilizers for improving yield potential and quality of tea.

MATERIALS AND METHODS

Selection of indigenous KSB strain for field application

The indigenous potassium solubilizing bacteria (*Pseudomonas putida*) strain obtained from tea estate of Valparai, Tamil Nadu, India was selected based on prior knowledge of their higher potassium solubilization rate and production of phytohormones (Bagyalakshmi et al., 2009). The selected KSB strain was formulated using talcum powder as carrier for field application with prior mixing with farm yard manure. This bioformulation was incubated for a week for rapid multiplication of KSB, and maintained population level as 1×10^9 cfu/g before field application. The bio-preparation was applied in soil around the tea bush by placement method (at a depth of 10 cm) at the rate of half kg/bush. The NK fertilizers were applied as per the recommendation by UPASI Tea Research Institution, Valparai, India, in four equal splits during April, May, September and November by broadcasting every year, avoiding very wet and dry periods. Pretreatment yield of the experimental blocks was recorded for three months before the start of the experiment. Applications of KSB bioformulation were carried out twice a year during April/May and September/October for a period of four years.

Field experiment

A field trial was conducted at Parry Agro Tea Industries, Valparai, Tamil Nadu, India during 2008 to 2011 located in the Western Ghats of Southern India (10°30'N, 77°0'E, altitude 1050 m above mean sea level). The field was planted with a drought resistant clone UPASI-9. Experimental plots were laid out as randomized block design and plot size consisted of 20 bushes, and each was replicated three times. There were 8 treatments namely,

1. N₁₀₀P₁₀₀K₁₀₀ + KSB
2. N₁₀₀P₁₀₀K₇₅ + KSB
3. N₁₀₀P₁₀₀K₅₀ + KSB
4. N₁₀₀P₁₀₀K₂₅ + KSB
5. N₁₀₀P₁₀₀K₁₀₀ + KSB + VC
6. N₅₀P₅₀K₅₀ + KSB + VC
7. N₁₀₀P₁₀₀K₁₀₀ alone
8. Control (N₀P₀K₀)

Urea, rock phosphate and Muriate of Potash (MOP) were used as NPK sources of nutrients respectively as per the recommendations of UPASI. Moreover, vermicompost was also applied along with NPK for better efficiency, and regular culture practices other than manuring were followed as per the standard procedure (Verma and Palani, 1997).

Yield assessment

Green leaf yield was recorded at every harvesting regularly, during the course of the experimental period. Yield and yield attributes, particularly the percentage of banji occurrence was monitored. The

green leaf yield was expressed into made tea as per the reference of Ponmurugan and Baby (2007).

Productivity index (PI) in response to soil application of KSB bioformulation was calculated according to the method of Sharma and Satyanarayana (1990).

Soil analysis

The soil samples were collected periodically and subjected to analyse various physicochemical parameters such as soil pH, EC, total organic carbon (Walkley and Black, 1934), nitrogen (AOAC, 1990), available phosphorus (Jackson, 1973), exchangeable potassium (Murphy and Riley, 1962) and calcium, sodium and magnesium (Bhargava and Raghupathi, 2001). Population level of KSB in the experimental plots were enumerated by pour plate technique using Aleksandrov media (Aleksandrov et al., 1967). Total microbial activity of KSB (soil dehydrogenase) treated soil samples were estimated by following titrimetry method by Dubey and Maheshwari (2009).

Biochemical constituents of green leaves

Crop shoots consisting of three leaves and a bud from each replicated plot were subjected to analyse various nutrient uptake and quality parameters.

Total chlorophyll and carotenoids (Wellburn, 1994), sugars (Dubois et al., 1956), nitrogen (AOAC, 1990), proteins (Lowry et al., 1951), amino acids (Moore and Stein, 1948), polyphenols (Dev Choudhury and Goswami, 1983) and catechins (Swain and Hillis, 1959) were estimated.

Study of tea bush architecture

Biometric observations of bushes were monitored by assessing plucking surface of the bush, number of active plucking points containing three leaves and a bud, internodal length (average 1 to 3 internodes), fresh and dry weight of leaves, were studied by the method adopted by Balasubramanian et al. (2010).

Tea quality constituents

A weight of 2.5 kg of flush shoots containing three leaves and a bud was collected and manufactured the black tea in the crush, tear, curl (CTC) miniature unit, and subsequently theaflavins (TF), thearubigins (TR), highly polymerized substance (Thanraj and Shesadari, 1990), and caffeine (Ronald and Ronald, 1991) were analysed. For determining the quality, organoleptic evaluation (liquor colour, briskness, colour and flavor indexes) of made tea were assessed with professional tea taster's to accomplish the market value realization of the product (Willet, 1987). The flavor index was calculated from the flavor profile, which is the ratio of sum of VFC Group II to that of VFC group I (Obanda and Owuor, 1995).

Statistical analysis

The data were analysed using SPSS 14.0 version of statistical software package (SPSS, Inc. Chicago, IL). Data obtained were subjected to analysis of variance (ANOVA) and the significant means were segregated by critical difference (CD) at various levels of significance. The standard error (SE) and coefficient of variance (CV) were also calculated (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Nutrient status of tea plantation soil

The results of tea soil nutrient analysis after imposing various doses of NPK and KSB application was outlined in Table 1. It showed that the tea soils were acidic with a pH range of 4.7 to 5.4. The initial pH measured was 5.4 before imposing treatments. Further, EC ranged between 0.2 and 0.3 dSm⁻¹ in KSB treated soils. The total organic carbon was increased from 5.2% to varying levels (6.8 to 8.2 %). Moreover, it was significantly increased in soil (8.2%) treated with N₁₀₀P₁₀₀K₇₅ + KSB combination. NPK contents were also increased significantly ($P < 0.05$) in the same treatment. But concentration of calcium was found to be low in N₁₀₀P₁₀₀K₇₅ + KSB treatment which was recorded as 164.8 mg/kg soil dry weight. Available magnesium and sodium concentration of soil samples determined between 91 to 156 and 20.8 to 37.3 mg/kg soil dry weight, respectively. Exchangeable K content in soil samples was determined between 97.8 and 141.3 mg/kg soil dry weight which increased in KSB treated plots. Apart from the control plot, soil samples collected from N₁₀₀P₁₀₀K₁₀₀ alone treated plots had registered least potassium content (116.2 mg/kg) and this was supported by Ranganathan and Natesan (1987).

The observation and maintenance of high acidic pH in the KSB treated soils revealed the influence of bioinoculant like KSB. The aforementioned experiment results showed that the tea plants are well known to grow better in acidic soil environment (Pandey and Palani, 1996). The increased content of magnesium in soil also had its importance in plant growth. Magnesium is the central metal constituent of chlorophyll molecule that regulates photosynthesis activity and acts as an enzyme activation system (Ma et al., 2005).

Tea canopy architectural analysis

The treatments where N₁₀₀P₁₀₀K₇₅ along with KSB combination were given, was the most efficient in enhancing the tea bush canopy architecture when compared to other treatments (Table 2). Plucking surface of the bushes determined between 4892.7 and 8614 cm². It was moderate in plants treated with different dosages of NPK along with KSB and vermicompost combinations which ranged between 6954 and 7935.7 cm². The untreated control bushes registered the plucking surface of an average of 4892.7 cm² harvestable shoots. The area of area of plucking surface coincided with the number of plucking points in the bushes due to various treatments. There was a strong positive correlation between the results of plucking points per unit area and the observation of internodal length, leaf moisture and dry matter contents. However, these were found to be superior were plants treated with N₁₀₀P₁₀₀K₇₅ along with KSB, followed by N₁₀₀P₁₀₀K₁₀₀ along with KSB and

Table 1. Effect of KSB on nutrient status of tea plantation soils.

Treatment details	Soil reaction (pH) #	Electrical conductivity (dSm ⁻¹)	Organic carbon (%)	Nitrogen (%)	Phosphorus (mg/kg)	Potassium (mg/kg)	Calcium (mg/kg) #	Magnesium (mg/kg)	Sodium (mg/kg)
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB	5.1 ± 0.2 ^e	0.2 ± 0.04 ^a	7.8 ± 0.1 ^b	2.2 ± 0.1 ^c	12.7 ± 0.7 ^g	129.6 ± 2.5 ^d	253.7 ± 11.2 ^c	142.8 ± 9.0 ^e	32.3 ± 1.0 ^e
N ₁₀₀ P ₁₀₀ K ₇₅ + KSB	4.7 ± 0.2 ^a	0.3 ± 0.02 ^b	8.2 ± 0.1 ^f	2.7 ± 0.1 ^f	13.5 ± 0.9 ^h	141.3 ± 3.6 ^f	164.8 ± 12.2 ^a	156.0 ± 8.0 ^f	37.3 ± 0.9 ^g
N ₁₀₀ P ₁₀₀ K ₅₀ + KSB	4.9 ± 0.2 ^c	0.2 ± 0.04 ^a	7.6 ± 0.1 ^e	2.5 ± 0.1 ^e	11.4 ± 0.6 ^f	125.6 ± 6.4 ^d	375.3 ± 10.4 ^f	136.3 ± 5.7 ^d	34.3 ± 1.1 ^f
N ₁₀₀ P ₁₀₀ K ₂₅ + KSB	5.4 ± 0.2 ^f	0.2 ± 0.01 ^a	6.8 ± 0.2 ^b	2.2 ± 0.2 ^c	10.6 ± 0.7 ^c	120.3 ± 5.0 ^c	384.0 ± 11.4 ^g	124.8 ± 7.1 ^c	31.3 ± 1.0 ^d
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB+VC	4.8 ± 0.1 ^b	0.3 ± 0.04 ^b	7.6 ± 0.1 ^e	2.4 ± 0.1 ^d	10.7 ± 0.4 ^e	134.3 ± 6.4 ^e	196.3 ± 13.1 ^b	151.3 ± 10.1 ^f	29.6 ± 0.8 ^c
N ₅₀ P ₅₀ K ₅₀ + KSB+VC	5.3 ± 0.1 ^d	0.2 ± 0.02 ^a	7.2 ± 0.2 ^d	2.2 ± 0.1 ^c	10.8 ± 0.9 ^d	121.3 ± 3.7 ^c	324.7 ± 14.0 ^d	104.0 ± 11.8 ^b	24.7 ± 0.9 ^b
N ₁₀₀ P ₁₀₀ K ₁₀₀ alone	4.8 ± 0.1 ^b	0.2 ± 0.02 ^a	7.1 ± 0.1 ^c	2.0 ± 0.1 ^b	10.6 ± 0.7 ^b	116.2 ± 9.9 ^b	313.3 ± 13.1 ^e	140.7 ± 11.0 ^e	31.8 ± 1.2 ^d
Control (N ₀ P ₀ K ₀)	5.3 ± 0.2 ^d	0.2 ± 0.02 ^a	5.2 ± 0.2 ^a	1.4 ± 0.2 ^a	10.4 ± 0.7 ^a	97.8 ± 2.3 ^a	420.3 ± 14.4 ^h	91.0 ± 7.6 ^a	20.8 ± 0.9 ^a
SE ±	0.13	0.02	0.12	0.08	0.59	4.60	8.97	7.56	0.83
CD at P = 0.05	0.39	0.06	0.27	0.19	1.26	9.68	18.86	21.77	1.76

VC = Vermicompost. KSB = Potassium solubilizing bacteria. Values are mean of three replications. Standard deviations followed by the same letter are not significantly different (*P* < 0.05) as determined by Duncan’s multiple range test. A higher alphabet indicates the improvements obtained due to treatment. # A lower alphabet indicates the improvement obtained due to treatment.

Table 2. Evaluation of KSB on canopy architectural analysis of tea bush.

Treatment details	Plucking surface (cm ²)	Plucking points (per sq. ft.)	Leaf moisture (%)	Internodal length (cm)	Dry matter (%)
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB	8262.7 ± 85.9 ^f	117.4 ± 8.0 ^f	72.5 ± 0.5 ^e	4.9 ± 0.2 ^e	21.8 ± 0.8 ^e
N ₁₀₀ P ₁₀₀ K ₇₅ + KSB	8614.0 ± 86.7 ^g	122.9 ± 9.2 ^g	75.1 ± 0.2 ^g	5.3 ± 0.1 ^f	23.6 ± 1.3 ^g
N ₁₀₀ P ₁₀₀ K ₅₀ + KSB	7242.0 ± 89.6 ^d	113.4 ± 5.4 ^e	70.4 ± 1.0 ^e	4.8 ± 0.1 ^e	22.7 ± 1.1 ^f
N ₁₀₀ P ₁₀₀ K ₂₅ + KSB	6942.7 ± 73.5 ^d	101.4 ± 6.8 ^c	68.4 ± 1.0 ^d	3.6 ± 0.1 ^b	21.3 ± 0.9 ^e
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB + VC	7935.7 ± 75.8 ^e	116.0 ± 6.9 ^f	73.5 ± 1.0 ^f	4.6 ± 0.1 ^d	22.4 ± 1.3 ^f
N ₅₀ P ₅₀ K ₅₀ + KSB + VC	6954.0 ± 58.9 ^d	111.8 ± 7.1 ^d	68.7 ± 0.6 ^d	4.1 ± 0.1 ^c	20.6 ± 0.6 ^d
N ₁₀₀ P ₁₀₀ K ₁₀₀ alone	6681.0 ± 10.5 ^c	110.3 ± 6.1 ^d	72.7 ± 1.0 ^f	4.8 ± 0.1 ^e	22.6 ± 1.2 ^f
Control (N ₀ P ₀ K ₀)	4892.7 ± 10.7 ^b	90.07 ± 8.4 ^b	65.4 ± 0.8 ^c	3.6 ± 0.1 ^b	17.5 ± 0.7 ^c
SE ±	52.78	4.18	0.63	0.08	0.78
CD at P = 0.05	151.9	12.05	1.83	0.24	2.26
CV %	0.93	4.70	1.10	2.31	4.52

Values are mean of three replications. Standard deviations followed by the same letter are not significantly different (*P* < 0.05) as determined by Duncan’s multiple range test. VC = Vermicompost. KSB = Potassium solubilizing bacteria. A higher alphabet indicates the improvements obtained due to treatment.

Table 3. Estimation of biochemical parameters in tea crop shoots treated with KSB.

Treatment details	Biochemical constituents (%)									
	Chlorophyll*	Carotenoid*	Sugar	Nitrogen	Protein	Amino acids	Catechin	polyphenol	Potassium	Phosphorous
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB	1.7 ± 0.9 ^e	0.3 ± 0.3 ^e	7.1 ± 0.8 ^d	6.0 ± 0.1 ^f	10.6 ± 0.4 ^e	1.6 ± 0.1 ^d	19.2 ± 0.9 ^d	27.0 ± 1.3 ^d	2.1 ± 0.2 ^d	0.5 ± 0.1 ^c
N ₁₀₀ P ₁₀₀ K ₇₅ + KSB	1.8 ± 0.2 ^f	0.4 ± 0.1 ^f	7.4 ± 0.6 ^f	6.2 ± 0.3 ^e	11.4 ± 0.6 ^f	1.6 ± 0.2 ^e	19.5 ± 0.6 ^e	28.2 ± 0.3 ^e	2.7 ± 0.4 ^f	0.7 ± 0.2 ^f
N ₁₀₀ P ₁₀₀ K ₅₀ + KSB	1.4 ± 0.1 ^b	0.2 ± 0.2 ^c	6.2 ± 0.3 ^b	5.8 ± 0.1 ^c	10.2 ± 0.7 ^c	1.6 ± 0.1 ^c	18.7 ± 0.7 ^c	26.3 ± 1.1 ^c	1.9 ± 0.1 ^b	0.5 ± 0.1 ^b
N ₁₀₀ P ₁₀₀ K ₂₅ + KSB	1.5 ± 0.1 ^c	0.2 ± 0.1 ^b	6.7 ± 0.1 ^c	5.6 ± 0.2 ^b	10.0 ± 0.4 ^d	1.5 ± 0.1 ^b	18.7 ± 0.8 ^c	26.8 ± 1.1 ^c	1.8 ± 0.1 ^a	0.5 ± 0.1 ^a
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB+VC	1.7 ± 0.1 ^e	0.3 ± 0.1 ^d	7.1 ± 0.1 ^d	6.0 ± 0.1 ^f	11.4 ± 0.7 ^f	1.7 ± 0.3 ^f	18.5 ± 0.3 ^b	28.2 ± 1.1 ^e	2.2 ± 0.2 ^e	0.6 ± 0.2 ^e
N ₅₀ P ₅₀ K ₅₀ + KSB+VC	1.6 ± 0.1 ^d	0.2 ± 0.2 ^b	6.3 ± 0.1 ^b	5.9 ± 0.1 ^d	10.7 ± 1.1 ^e	1.6 ± 0.1 ^d	18.5 ± 0.8 ^b	26.8 ± 0.9 ^c	1.9 ± 0.1 ^b	0.5 ± 0.1 ^c
N ₁₀₀ P ₁₀₀ K ₁₀₀ alone	1.7 ± 0.2 ^e	0.2 ± 0.1 ^c	7.3 ± 0.1 ^e	5.7 ± 0.5 ^b	10.5 ± 0.9 ^d	1.6 ± 0.1 ^c	18.6 ± 0.9 ^c	26.9 ± 0.2 ^c	2.0 ± 0.3 ^c	0.6 ± 0.1 ^e
Control (N ₀ P ₀ K ₀)	0.9 ± 0.1 ^a	0.2 ± 0.1 ^a	5.5 ± 0.1 ^a	4.7 ± 0.1 ^a	8.6 ± 0.6 ^a	1.5 ± 0.1 ^a	17.4 ± 0.9 ^a	24.5 ± 1.0 ^b	1.8 ± 0.1 ^a	0.4 ± 0.2 ^a
SE ±	0.10	0.07	0.29	0.12	0.19	0.07	0.60	0.80	0.19	0.04
CD at P = 0.05	0.30	0.21	0.85	0.37	0.57	0.21	1.74	2.30	0.56	0.14

Values are mean of three replications. Standard deviations followed by the same letter are not significantly different ($P < 0.05$) as determined by Duncan's multiple range test. * mg/g fresh weight of leaves. VC = Vermicompost. KSB = Potassium solubilizing bacteria. A higher alphabet indicates the improvements obtained due to treatment.

N₁₀₀P₁₀₀K₁₀₀ with KSB and vermicompost. The dry matter content was recorded between 22.6 and 23.6% in trial plots and the same was 17.5% in untreated control plots. The application of KSB in soils showed improvement in tea plant growth and also reduced banji content. Similarly, the increasing level on nutrients in soil had increased the yield by improving the yield components like plucking points; plucking surface was reported by Balasubramanian et al. (2010).

Biochemical parameters of tea crop shoots

Combined application of KSB formulation with NPK fertilizers resulted in significant increase in chlorophyll, carotenoid and catechins contents when compared to control plot. Chlorophyll is a major green pigment found in green leaves and is undoubtedly determining the photosynthetic efficiency and productivity of plants. Notably K also played an important role in the synthesis of chlorophyll by taking part in various enzyme

activities (Senthurpandian et al. 2008). Since K is found to influence the total chlorophyll and carotenoid contents of the leaves it may also directly and / or indirectly improve crop yield through increased photosynthesis. Similar kind of results was also reported (Jayaganesh et al., 2011). Increase in N, P and K uptake by the plants might be due to the activity of KSB. The results are on par with the findings. (Venkatesan et al. 2005 and 2006). High chlorophyll and carotenoid (1.8 and 0.4 mg/g fresh weight, respectively) contents were recorded by N₁₀₀P₁₀₀K₇₅ along with KSB combination (Table 3). Among the nutrient parameters, P and K contents had shown tremendous increase in the case of N₁₀₀P₁₀₀K₇₅ with KSB treatment (2.7 and 0.7%, respectively) and N₁₀₀P₁₀₀K₁₀₀ with KSB and Vermicompost treated (2.2 and 0.6%, respectively) plots whereas, the N content was recorded higher in N₁₀₀P₁₀₀K₁₀₀ with KSB and Vermicompost, followed by N₁₀₀P₁₀₀K₁₀₀ with KSB alone (6.2 and 6.0%) treated plots. The contents

of protein, catechin, and polyphenol (11.4, 28.2 and 19.5%, respectively) contents were registered in the plants treated with N₁₀₀P₁₀₀K₇₅ with KSB when compared to other treatments. High amino-acid content was observed in the plots wherever KSB was incorporated and this was substantiated with the findings of Ruan et al. (1998). The significant increase in sugar content was observed in the treatment with N₁₀₀P₁₀₀K₇₅ (7.4%) followed by N₁₀₀P₁₀₀K₁₀₀ with KSB and Vermicompost (7.1%). Less sugar content was registered in control plots (5.5%).

An integrated application of inorganic manures with KSB that solubilize them might provide faster and continuous supply of K for higher plant growth. Similarly, the use of plant growth promoting rhizobacteria (PGPR) including phosphate solubilizing bacteria (PSB) and KSB as bio-fertilizers was suggested as a sustainable solution to improve plant nutrient and production. The importance of potassium in the yield potential in tea has been reported earlier by Venkatesan et al.

Table 4. Evaluation of KSB on growth parameters of tea plants.

Treatment details	Green leaf yield (kg made tea ha ⁻¹)	Productivity index (PI)	Banji content (%) #
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB	2624.3 ± 65.2 ^e	1.2 ± 0.1 ^e	40.0 ± 1.0 ^b
N ₁₀₀ P ₁₀₀ K ₇₅ + KSB	2957.0 ± 75.7 ^g	1.6 ± 0.1 ^g	36.0 ± 2.0 ^a
N ₁₀₀ P ₁₀₀ K ₅₀ + KSB	2524.7 ± 52.8 ^d	1.3 ± 0.1 ^f	41.7 ± 0.6 ^b
N ₁₀₀ P ₁₀₀ K ₂₅ + KSB	2358.0 ± 43.1 ^b	0.9 ± 0.1 ^b	48.3 ± 1.5 ^c
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB+VC	2562.7±38.9 ^d	1.2 ± 0.2 ^c	50.0 ± 1.0 ^d
N ₅₀ P ₅₀ K ₅₀ + KSB+VC	2451.3 ± 41.1 ^c	1.2 ± 0.1 ^c	55.3 ± 4.1 ^e
N ₁₀₀ P ₁₀₀ K ₁₀₀ alone	2739.3 ± 59.7 ^f	1.5 ± 0.1 ^d	53.7 ± 5.5 ^f
Control (N ₀ P ₀ K ₀)	1904.3 ± 83.1 ^a	0.7±0.2 ^a	63.0 ± 2.0 ^g
SE ±	41.39	0.05	2.22
CD at P=0.05	119.14	0.16	6.41
CV %	2.06	5.72	5.45

Values are mean of three replications. Standard deviations followed by the same letter are not significantly different ($P < 0.05$) as determined by Duncan's multiple range test. VC = Vermicompost. KSB = Potassium solubilizing bacteria. A higher alphabet indicates the improvements obtained due to treatment. # A lower alphabet indicates the improvement obtained due to treatment.

(2005). Significant positive effect was observed by (Singh et al., 2010) for quality-related parameters like sugars, amino acids, proteins, polyphenols and caffeine by the inoculation of plant growth promoting fungus. Amino acids are responsible for flavor profile of made tea, it was noticed in Chinese tea gardens (Thomas et al., 2009). Lowest content of amino acids in control plot could be due to the reduction of inorganic K fertilizer or lack of indigenous K solubilizers (Venkatesan and Ganapathy, 2004).

Evaluation of potassium solubilizing bacteria on growth parameters and enumeration of KSB and dehydrogenase activity in tea soil

Green leaf yield was recorded at every harvesting period and presented as made tea yield/ha (Table 4). Application of indigenous KSB formulation with various doses of potash fertilizers with N and P had enhanced green leaf yield and productivity index (PI) significantly. The higher yield (2957 kg made tea/ha) was observed in N₁₀₀P₁₀₀K₇₅ with KSB treatment followed by N₁₀₀P₁₀₀K₁₀₀ (2739 kg made tea/ha) treatment. A drastic reduction in yield potential was noticed in N₁₀₀P₁₀₀K₂₅ with KSB formulation and control blocks (2358 and 1904 kg made tea/ha, respectively). Significant improvement of green leaf yield was observed in the experimental plots which may be due to proper fixation of nutrients in the soil through solubilization by producing organic acids by KSB strains. Likewise Sheng et al. (2002) reported that KSB namely *Bacillus mucilaginosus* is able to solubilize inorganic source of K like muriate of potash and sulphate of potash by means of production of organic acids in order to improve the yield. The plants which receive the highest level of K gave the highest yield in all the years (Natesan et al. 1984). PI in our experiment was positively correlated with the yield of tea plants applied with highest

level of K along with KSB. As the yield increases, there was a decrease in percentage of banji content in the plucking surface during harvest.

The highest enzyme activity (41.23 mg of CO₂ evolutions) and population (3.2×10^6 cfu/g of soil) was observed in N₁₀₀P₁₀₀K₇₅ with KSB followed by N₁₀₀P₁₀₀K₁₀₀ with KSB combinations and least microbial activity was noticed in control plot (Figures 1 and 2). Significant improvement of dehydrogenase activity and KSB population was observed in KSB incorporated plots due to their native origin of environment and better establishment.

Higher green leaf yield and bush health in terms of number of plucking points, internodal length, and physiological and biochemical constituents might be due to the action of KSB by solubilizing K content in the soils. These parameters were further coincided with higher population of KSB and dehydrogenase activity (Figures 1 and 2). Least KSB population was recorded in control and other treatments due to either lesser/native state of KSB or lack of reduced level of inorganic fertilizers. The population density of KSB was significantly coincided with soil nutrients like total organic carbon, total N and available P contents. Similar observations were reported in tea soils (Bagyalakshmi et al., 2009).

Quality parameters of black tea

Influence of KSB on TF, TR, highly polymerized substances (HPS), total liquor colour (TLC) and caffeine contents were presented in Table 5. Significant increase in the level of TF and TR contents was observed in N₁₀₀P₁₀₀K₇₅ along with KSB treatment (1.3 and 9.9%) and N₁₀₀P₁₀₀K₁₀₀ with KSB and Vermicompost treated blocks (1.2 and 9.5%, respectively). Least contents were observed in the control (0.8% TF and 7.6% TR) plots, where no KSB was incorporated. TF and TR contents

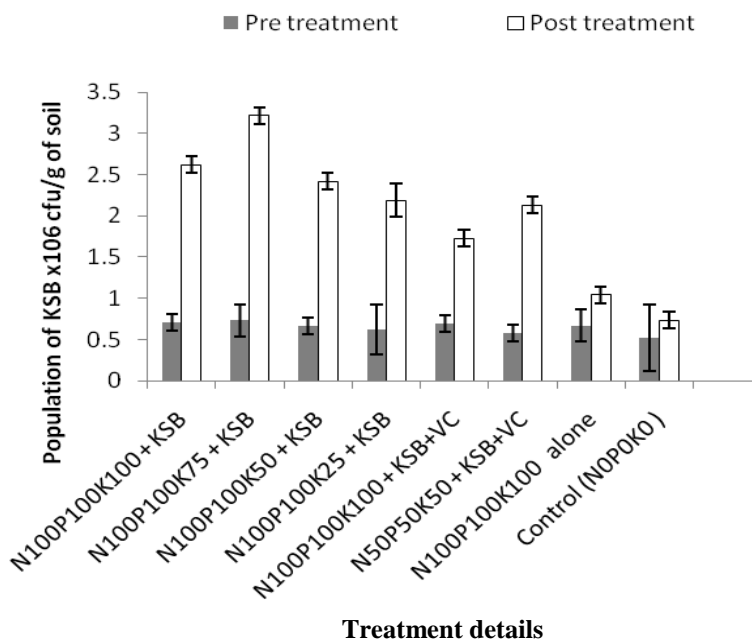


Figure 1. Enumeration of KSB Population in tea soil. VC, Vermicompost; KSB, Potassium solubilizing bacteria.

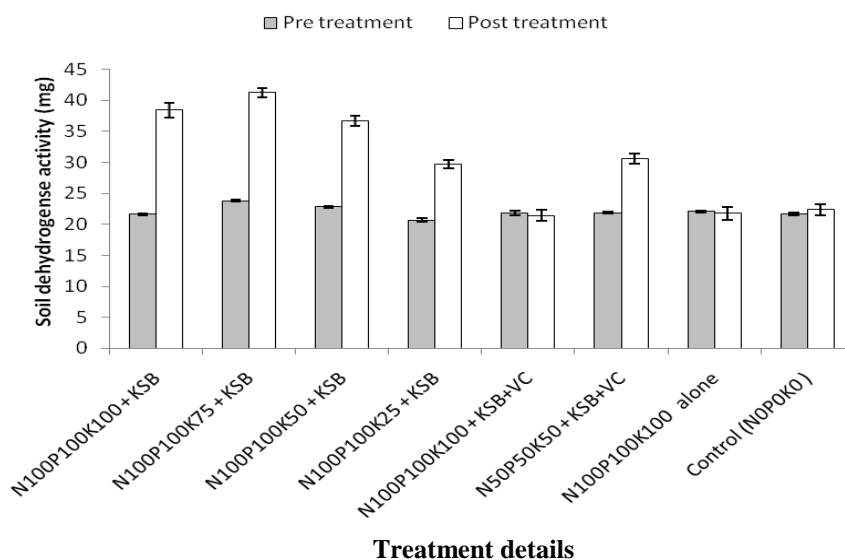


Figure 2. Evaluation of dehydrogenase activity in tea soil. VC, Vermicompost; KSB, Potassium solubilizing bacteria.

were found to be lower in control blocks. In the case of HPS status, significant variation was observed among the treatments studied. There was a drastic improvement in caffeine content in KSB amended plots. Similarly, higher caffeine content (3.9, 2.9 and 2.9%) was observed in the treatment of N₁₀₀P₁₀₀K₇₅ with KSB, N₁₀₀P₁₀₀K₁₀₀ + KSB +Vermicompost and N₁₀₀P₁₀₀K₁₀₀ alone, respectively.

Colour, flavour and briskness indexes were significantly higher in the same order of treatments.

The chemical basis of the quality of black tea indicated that TF and TR are the two important factors determining the liquoring characteristics of tea. When observing made tea parameters in order to evaluate the quality attributes, TF and TR ratio was higher with KSB applied plants

Table 5. Analysis of quality parameters of black tea of KSB treated tea leaves.

Treatment details	Made tea characteristics (%)							
	Theaflavin	Thearubigin	Highly polymerized Substances	Total liquor colour	Caffeine	Briskness Index	Colour Index	Flavour Index
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB	1.2 ± 0.2 ^d	9.1 ± 0.4 ^d	9.8 ± 0.2 ^e	3.6 ± 0.1 ^d	2.9 ± 0.1 ^e	10.0 ± 0.1 ^d	35.5 ± 1.2 ^e	23.1 ± 0.1 ^c
N ₁₀₀ P ₁₀₀ K ₇₅ + KSB	1.3 ± 0.1 ^d	9.9 ± 0.8 ^h	10.5 ± 0.6 ^f	3.8 ± 0.1 ^e	3.9 ± 0.1 ^f	14.0 ± 0.1 ^e	36.6 ± 0.6 ^f	24.1 ± 0.1 ^h
N ₁₀₀ P ₁₀₀ K ₅₀ + KSB	1.1 ± 0.1 ^c	9.1 ± 0.5 ^f	10.2 ± 0.8 ^f	3.3 ± 0.1 ^c	2.6 ± 0.2 ^d	11.2 ± 0.1 ^c	33.2 ± 1.2 ^b	23.8 ± 0.2 ^g
N ₁₀₀ P ₁₀₀ K ₂₅ + KSB	1.0 ± 0.2 ^b	9.1 ± 0.0 ^e	8.8 ± 0.1 ^c	3.2 ± 0.1 ^b	2.4 ± 0.2 ^b	11.9 ± 0.1 ^b	33.8 ± 0.3 ^c	22.3 ± 0.2 ^d
N ₁₀₀ P ₁₀₀ K ₁₀₀ + KSB + VC	1.2 ± 0.1 ^c	9.5 ± 0.5 ^g	9.8 ± 0.1 ^e	3.6 ± 0.2 ^d	2.8 ± 0.1 ^c	10.1 ± 0.2 ^d	34.1 ± 0.8 ^d	23.4 ± 0.5 ^e
N ₅₀ P ₅₀ K ₅₀ + KSB+VC	1.1 ± 0.1 ^b	8.9 ± 0.9 ^c	9.2 ± 0.2 ^d	3.1 ± 0.2 ^b	2.5 ± 0.1 ^b	11.2 ± 0.1 ^c	33.8 ± 0.2 ^c	21.9 ± 0.9 ^b
N ₁₀₀ P ₁₀₀ K ₁₀₀ alone	0.9 ± 0.1 ^a	8.4 ± 0.6 ^b	8.5 ± 0.1 ^b	3.2 ± 0.1 ^c	2.9 ± 0.1 ^e	10.4 ± 0.1 ^d	34.7 ± 0.3 ^d	23.6 ± 0.5 ^f
Control (N ₀ P ₀ K ₀)	0.8 ± 0.2 ^a	7.6 ± 0.3 ^a	7.2 ± 0.1 ^a	2.3 ± 0.2 ^a	2.1 ± 0.1 ^a	12.9 ± 0.1 ^a	30.7 ± 0.7 ^a	20.9 ± 0.3 ^a
SE ±	0.06	0.48	0.24	0.12	0.08	0.15	0.43	0.26
CD at P=0.05	0.20	1.39	0.71	0.35	0.25	0.45	1.27	0.77

Values are mean of three replications. Standard deviations followed by the same letter are not significantly different ($P < 0.05$) as determined by Duncan’s multiple range test. VC = Vermicompost. KSB = Potassium solubilizing bacteria. A higher alphabet indicates the improvements obtained due to treatment.

(Table 5). This may be due to the K source, and is the most important nutrient to increase the TF value (Venkatesan et al., 2006). The optimum TF/TR ratio has been reported to be around 1:10 (ideal ratio) and any wide deviation in the ratio would lead to quality deterioration. The higher the water extracts content, the higher the quality. All the treatments had above 32%; the limiting factors which influence the cuppage of black tea. The increase in TF could be due to the increase in polyphenols at the optimum ratio, which is the precursor of TF and TR. In case of other parameters, HPS, TLC, polyphenols (PP), catechins (Cat), amino acids (AA) and reducing sugars (RS) contributed to the overall performance of the plants treated with N₁₀₀P₁₀₀K₇₅ + KSB. More polyphenols is found in the tea shoots undoubtedly; the quality of the manufactured tea will be greater (Venkatesan et al., 2005) because polyphenols are so important and responsible for all the biochemical reactions which contribute to make a good cup of tea.

In made tea, flavor index (FI) was estimated and observed was the significant increase due to the application of KSB in tea soil, and tea aroma consists of groups of flavor compounds. Higher amount of crude fiber in control and vermicompost treated plots was due to the decreased availability of K in soil. This leads to the accumulation of carbohydrates and cellulose. Our results are on par with the findings of Venkatesan and Ebert (2005).

Conclusion

Hence, with the existing economics crisis for tea growers, it is necessary to look for KSB bio-fertilizers integrated with reduced level of K fertilizers which in turn provide high crop yield with low cost. The present research findings provide the information that balanced nutrient application to tea plants and sustain yield were achieved with 75% of K fertilizers along with indigenous KSB.

Moreover, quality of black tea may be improved

by the application of 75% K along with KSB. Thus, the application of KSB can be recommended as a sustainable way to increase yield potential and maintain the soil health in the tea ecosystem.

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