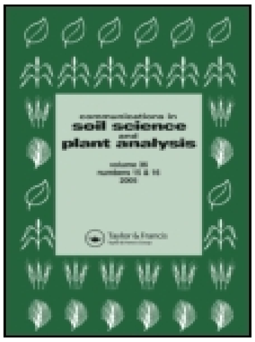

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Long-Term Effect of Lime, Mycorrhiza, and Inorganic and Organic Sources on Soil Fertility, Yield, and Proximate Composition of Sweet Potato in Alfisols of Eastern India

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A field experiment was conducted for five kharif *seasons (2006–2011) in an Alfisol to study the effect of integrated use of lime, mycorrhiza, and inorganic and organics on soil fertility, yield, and proximate composition of sweet potato. Application of graded doses of nitrogen, phosphorus, and potassium (NPK) significantly increased the mean tuber yield of sweet potato by 44, 106, and 130 percent over control. Green manuring along with* $\frac{1}{2}$ *NPK showed greater yield response over that of* $\frac{1}{2}$ *NPK. The greatest mean tuber yield was recorded due to integrated application of lime, farmyard manure (FYM), NPK, and* $MgSO_4$ *(13.69 t* ha^{-1}*) over the other treatments. Inoculation of mycorrhiza combined with lime, FYM, and NPK showed a significant yield response of 10 percent over FYM + NPK. Conjunctive use of lime, inorganics, and organics not only produces sustainable crop yields but also improve soil fertility, nutrient-use efficiency, and apparent nutrient recovery in comparison to NPK and organic manures.*

Keywords Apparent nutrient recovery, NPK, nutrient uptake, nutrient-use efficiency, organic manures, soil properties, tuber yield

Introduction

Sweet potato has a long history as a crop to stave off famine—especially as a cheap source of calories. China produces more than 72 percent of world's sweet potato with a productivity of 21.65 Mg ha^{-1}, and around 40 percent of the Chinese harvest is used as animal feed to support a growing domestic demand for animal protein. In contrast with China, 90 percent of production in South America (and in Africa) is for human consumption. However, Israel leads in the productivity of 32.60 Mg ha^{-1} in comparison to other countries. In India it grows in an area of 1.132 lakh ha with a production of 10.47 lakh tons, according to the estimates for 2010–2011 (FAOSTAT 2011). Odisha occupies 0.44 lakh ha in India with a production of 4.10 lakh tons and a productivity of 9.30 Mg ha^{-1} compared the world and all-India averages of 13.11 and 9.25 Mg ha^{-1}, respectively, and its cultivation was mostly

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confined to plains and hilly areas. Sweet potato is nutritionally rich and contains 28.2 g carbohydrates; 2–4 g sugars; 3.0 g dietary fiber; 46, 25, 50, 337, 0.3, 0.8, 24, 0.7, and 0.8 mg of Ca, Mg, P, K, Zn, Fe, vitamin C, niacin (vitamin B_3), and pantothenic acid (vitamin B_5), respectively; and 11 μg folate (vitamin B_9) per 100 g fresh tuber.

Low fertilizer consumption coupled with poor efficiency of applied fertilizers and minimal adoption of improved technologies have led to poor crop productivity. Soil acidity is a major problem in most agricultural soils of the tropics and liming with materials contain calcium and/or magnesium oxides or carbonates is commonly practiced to ameliorate the acidic soils (Brady and Weil 2006). The high cost of fertilizers and unsustainable crop production call for use of locally available low-cost organic sources such as manures, green manures, and biofertilizers along with inorganics in a synergistic manner for sustainable production and maintenance of soil quality (Acharya 2002). However, because of the paucity of organic sources and their inability to meet total nutrient requirements to sustain large-scale productivity and to safeguard soil health, their integrated use with chemical fertilizers is inevitable. The use of inorganic chemical fertilizers has not been helpful under intensive agriculture because it is often associated with reduced crop yield, soil acidity, and nutrient imbalance (Ojeniyi 2000). The crop response to applied fertilizers depends on soil organic matter, which could be enriched either by natural returns through roots, stubbles, and crop wastes as well as application of various organic resources (Ayoola and Adeniyan 2006). The supplementary and complementary use of organic manures and inorganic chemical fertilizers augment the efficiency of both the substances to maintain a high level of soil productivity (Thakuria, Borgohain, and Sarma 1991). Keeping this in view, the present investigation was planned to monitor the long-term effect of integrated application of lime, mycorrhiza, inorganic materials, and organic manures on yield, proximate composition, and nutrient uptake of sweet potato and their residual effect on soil fertility in acidic Alfisols.

Materials and Methods

A long-term field experiment was conducted in a Typic Haplustalf at the farm of the Regional Centre of Central Tuber Crops Research Institute, Bhubaneswar, Odisha, India, for five consecutive *kharif* (rainy) seasons during 2006–2011 to study the effects of lime, mycorrhiza, and inorganic and organic sources on soil fertility, yield, proximate composition, and nutrient uptake of sweet potato. The experimental soil is sandy loam, acidic (pH 5.51), and nonsaline (0.58 dS m^{-1}) and has 0.33 percent organic carbon, 0.075 percent total N, and 141.8, 12.32, and 217.8 kg ha^{-1} of available N, P, and K, respectively. The experiment was laid out with 20 treatments replicated three times in a randomized block design. The treatments include control, ½ NPK, full NPK (75–22–63 kg N, P, and K ha^{-1}), 1½ NPK (113–33–94 kg N, P, and K ha^{-1}), lime + NPK, FYM + ½ NPK, FYM + NPK, lime + FYM + ½ NPK, neem cake + ½ NPK, lime + neem cake + ½ NPK, green manure + ½ NPK, lime + green manure + ½ NPK, FYM + NPK + $ZnSO_4$ @ 10 kg ha^{-1}, lime + FYM + NPK + $ZnSO_4$, FYM + NPK + Borax @ 2.5 kg ha^{-1}, lime + FYM + NPK + Borax, FYM + NPK + $MgSO_4$ @ 25 kg ha^{-1}, lime + FYM + NPK + $MgSO_4$, FYM + NPK + VAM, and lime + FYM + NPK + VAM. Well-decomposed farmyard manure @ 4 Mg ha^{-1} on dry wt. basis), neem cake @ 0.5 Mg ha$^{-1,}$ and lime @ 0.5 Mg ha^{-1} were applied 1 month in advance of planting of the cuttings. Cowpea (cv. SB-2) was grown up to 45 days, uprooted, and chopped, and fresh biomass (1.5 Mg ha^{-1} on dry wt. basis) was incorporated in the respective treatments 10 days before planting. However, the mycorrhizal fungal (*Glomus microcarpum* var. microcarpum) culture was mixed with fine sand, broadcasted on the raised bed, and thoroughly mixed with the soil, and the vine cuttings were planted as per treatments. Neem cake, FYM, and green manure contain 2.15, 1.16, 1.32; 0.46, 0.28, 0.54; and 1.72, 0.46, 1.28 percent N, P, and K, respectively.

One-third of N, all of P, and half of the K in the forms of urea, single superphosphate, and muriate of potash, respectively, were applied before planting, 1/3 of N at 30 days after planting (DAP), and the balance 1/3 of N and ½ of K at 50 DAP. Sweet potato (cv. Kalinga) cuttings were planted at a spacing of 60 × 20 cm. All the cultural practices were followed as per the schedule. The crop was harvested at physiological maturity and the tuber yield, vine yield, number of tubers/plant, and average weight of tubers were recorded. Soil samples were collected from individual treatments after harvest of the tubers and then processed and analyzed for physicochemical properties using standard procedures as outlined by Jackson (1973). The tuber and vine samples were collected at harvest, washed thoroughly with distilled water, and oven dried at 60°C, and dry weights were recorded. Total sugars were estimated in the alcohol filtrate and the starch was determined in the residue as per the procedure outlined by Moorthy and Padmaja (2002). The oven-dried tuber and vine samples were ground, digested in concentrated H_2SO_4, and analyzed for N content by steam distillation (Humphries 1956), and the N uptake was computed. Plant samples were digested in diacid mixture (HNO_3 and $HClO_4$, 7:3), and total P and K were estimated by using a spectrophotometer and a flame photometer, respectively (Jackson 1973). Uptake amounts of P and K were computed. Percent yield / uptake response, nutrient-use efficiency, apparent nutrient recovery, and contribution of organic sources to nutrient recovery were derived as

$$\text{Percent yield / uptake response: } \{(\text{Treatment yield / uptake} - \text{Control yield / uptake}) \div (\text{Control yield / uptake})\} \times 100$$

$$\text{Nutrient-use efficiency (kg tubers per kg nutrient applied): } (\text{Treatment yield} - \text{Control yield}) \div \text{Amount of nutrient applied}$$

$$\text{Apparent nutrient recovery (\%): } \{(\text{Uptake in treated plot} - \text{Uptake in control plot}) \div (\text{Amount of nutrient applied})\} \times 100$$

$$\text{Contribution of organics to nutrient recovery (\%): } \{(\text{Uptake in organic manure treated plot} - \text{Uptake in 50 percent or 100 percent NPK plot}) \div \text{Nutrient applied through organic manure}\} \times 100$$

Results and Discussion

Effects of Graded Doses of NPK

The results in Table 1 revealed that the tuber yield was significantly increased with the increased doses of NPK and the increases in tuber yield were pronounced to be 44, 106,

Table 1

Effects of lime and inorganic and organic manures on yield performance of sweet potato

Treatment	Tuber yield (Mg ha^{-1})						Mean yield response (%)	Vine yield (Mg ha^{-1})					
	2006	2007	2008	2009	2010	Mean		2006	2007	2008	2009	2010	Mean
1. Control	5.83	3.39	3.53	5.36	5.70	4.76	—	4.20	5.35	4.26	6.86	5.47	5.23
2. ½ NPK	7.24	6.75	5.75	7.06	7.50	6.86	44.1	5.72	6.86	6.41	8.65	7.93	7.11
3. NPK	10.64	9.29	8.40	9.87	10.23	9.81	106.1	6.37	8.65	8.92	9.98	10.88	8.96
4. 1½ NPK	11.55	11.39	8.31	12.23	11.20	10.94	129.8	8.35	10.83	9.82	14.03	13.20	11.24
5. Lime + NPK	10.97	9.91	8.61	10.07	10.74	9.94	108.8	6.64	9.17	9.44	11.52	10.97	9.55
6. FYM + ½ NPK	9.21	8.10	6.47	8.36	10.76	8.58	80.3	6.92	8.40	7.66	9.47	11.10	8.74
7. FYM + NPK	11.75	11.27	9.36	12.00	13.29	11.53	142.2	6.93	10.55	9.81	13.21	13.79	10.93
8. Lime + FYM + ½ NPK	9.80	8.63	6.72	8.96	11.25	9.07	90.5	5.32	9.27	7.90	9.62	12.20	8.90
9. Neem + ½ NPK	8.13	7.27	6.01	7.98	9.10	7.70	61.8	5.71	7.98	6.71	9.31	9.55	7.85
10. Lime + neem + ½ NPK	9.02	8.82	6.15	8.39	11.22	8.72	83.2	9.24	8.66	6.80	10.18	10.05	8.99
11. Green manure + ½ NPK	8.64	9.39	7.15	8.87	11.37	9.08	90.8	6.57	9.76	7.45	11.19	12.87	9.57
12. Lime + GM + ½ NPK	11.65	11.95	7.49	9.85	13.15	10.82	127.3	7.38	10.36	7.76	11.99	14.05	10.38
13. FYM + NPK + $ZnSO_4$	11.88	12.42	10.49	12.53	14.24	12.31	158.6	7.73	10.97	10.48	14.82	14.69	11.75
14. Lime + FYM + NPK + $ZnSO_4$	14.43	14.36	10.72	12.97	15.07	13.51	183.8	10.42	13.45	10.80	15.85	15.02	13.14
15. FYM + NPK + B	11.84	11.28	9.87	11.71	13.47	11.63	144.3	7.08	9.93	9.85	14.30	14.27	11.09
16. Lime + FYM + NPK + B	12.21	12.63	10.01	12.09	14.04	12.20	156.3	8.06	11.95	9.99	15.38	14.75	12.09
17. FYM + NPK + $MgSO_4$	12.92	11.31	10.31	12.65	14.76	12.39	160.3	8.60	9.27	10.41	14.17	15.26	11.54
18. Lime + FYM + NPK + $MgSO_4$	15.24	14.04	10.65	13.33	15.21	13.69	187.6	10.28	13.60	10.63	15.70	16.49	13.41
19. FYM + NPK + VAM	12.98	9.86	9.93	12.06	13.54	11.67	145.2	9.55	9.63	9.93	14.25	14.09	11.55
20. Lime + FYM + NPK + VAM	14.57	12.05	10.12	12.65	14.19	12.72	167.2	9.03	12.72	10.20	15.37	15.37	12.61
CD ($P = 0.05$)	0.77	0.50	0.18	0.26	0.57	0.53	—	0.77	0.49	0.18	0.25	0.48	0.59

and 130 percent with respect to 50, 100, and 150 percent of the recommended doses of NPK over control. Addition of lime @ 0.5 Mg ha^{-1} along with 100 percent NPK showed an increase of 109 percent tuber yield over the control, and lime in combination with NPK showed a marginal yield response by enhancing the tuber yield by 1.3 percent over that of 100 percent NPK. The vine yield was also significantly increased with the graded doses of NPK, and lime addition further enhanced the vine yield. Sweet potato is a heavy feeder of nutrients and the tuber and vine yields were increased considerably due to application of excess doses of NPK fertilizers in poor and marginal soils, where it is being cultivated extensively (Halavatau et al. 1998).

Effects of Organic Manures

Among the organic sources, the significantly greatest mean tuber yield was recorded for application of FYM in combination with optimum doses of NPK (11.53 Mg ha^{-1}) with yield responses of 142.2, 17.5, and 5.4 percent over control, ½ NPK, and 1½ NPK, respectively. Half of the recommended doses of NPK in combination with organic manures showed yield responses of 25, 12, and 32 percent over that of ½ NPK in respect of FYM, neem cake, and green manure; however, addition of lime along with organic manures and suboptimal doses of NPK showed increases of 6, 13, and 19 percent tuber yield in comparison to organics + ½ NPK without lime. In situ incorporation of green manure along with ½ NPK produced the significantly greatest tuber yield (9.08 Mg ha^{-1}) with a yield response of 91 percent over control followed by FYM + ½ NPK (8.58 Mg ha^{-1}) and neem cake + ½ NPK (7.70 Mg ha^{-1}). Green manuring along with lime and ½ NPK showed an almost equivalent yield response in comparison to superoptimal doses of NPK, which might be due to greater retention and availability of all the essential nutrients as well as improvement in soil physical and biological properties, similar to the findings of Kamara and Lahai (1997). The varying yield response to the organic sources might be attributed to the nature and amount of nutrients present in the manures and their decomposition and nutrient-release pattern in the soils.

However, lime addition has further showed increases of 19, 6, and 13 percent tuber yield due to green manure + ½ NPK, FYM + ½ NPK, and neem cake + ½ NPK, respectively, over that of unlimed plots. The results emphasized that lime had profound influence when applied in combination with organic sources in comparison to inorganic chemical fertilizers, which might be ascribed to enhanced nutrient transformations and improvement in soil physical properties (Ossom and Rhykerd 2008). Significantly greatest vine yield was recorded with the application of lime + green manure + ½ NPK (10.38 Mg ha^{-1}) followed by lime + neem cake + ½ NPK (8.99 Mg ha^{-1}) at par with lime + FYM + ½ NPK (8.90 Mg ha^{-1}). Application of lime in combination with inorganic and organic sources had a favorable effect on vine yield as well as total biomass and the effect of organic sources is more pronounced when applied in combination with lime rather than alone.

Effects of VAM

Inoculation of VAM combined with optimum doses of NPK and FYM recorded a mean tuber yield of 11.67 Mg ha^{-1}, an increase of 19.0 and 1.2 percent over those of NPK and NPK + FYM, respectively. Integrated use of FYM + NPK + VAM has shown an increase of 6.7 percent mean tuber yields in comparison to superoptimal doses of NPK; however, liming further enhanced the tuber yields by 9.0 percent over that of FYM + NPK + VAM. Fungal inoculation along with lime had a greater impact on tuberization, resulting in greater tuber yields than FYM + NPK. Fungal inoculation with *Glomus microcarpum* enhanced the root length density, volume with root hairs, and VAM colonization and released organic acids, which facilitates mineralization of organic P and solubilization of insoluble inorganic P fractions and ultimately contributed to greater absorption of P, including Fe, Cu, Mn, and Zn. These results are in agreement with the findings of O′Keefe and Sylvia (1993).

Effects of Zn, B, and Mg

Significantly greatest mean tuber yield (13.69 Mg ha^{-1}) was recorded with the application of lime + FYM + NPK + $MgSO_4$ with a yield response of 40 and 19 percent over that of NPK and FYM + NPK, respectively, followed by lime + FYM + NPK + $ZnSO_4$ (13.51 Mg ha^{-1}). Incorporation of organic manure (FYM) provides a better physical environment, which helps root growth and absorption of nutrients from the native and applied sources, which favors nutrient absorption and results in greater tuber and vine yields of sweet potato. These results are in conformity with the findings of Singh et al. (2002). The mean yield response was best with Mg (7.5 percent), followed by Zn (6.8 percent) and B (2.9 percent). Addition of lime along with FYM, 100 percent NPK, and micronutrients showed a significant rise in tuber yields over that of unlimed plots, and the difference between limed and unlimed treatments was greatest with Mg (10.5 percent), followed by Zn (9.7 percent) and B (4.9 percent). Significantly greatest mean vine yield (13.41 Mg ha^{-1}) was observed due to integrated application of lime + FYM + NPK + $MgSO_4$, which was at par with lime + FYM + NPK + $ZnSO_4$ (13.14 Mg ha^{-1}). The greatest yield response due to liming and addition of $MgSO_4$ in these acidic soils was attributed to neutralization of soil acidity, which contributed to greater absorption of all the essential nutrients both from native and applied sources.

Proximate Composition

Significantly greatest dry matter (34.6 percent) was recorded due to integrated application of lime + FYM + NPK + B (Table 2) followed by lime + FYM + NPK + $MgSO_4$ (34.0 percent) and lime + FYM + NPK + VAM (33.7 percent). Application of graded doses of NPK significantly increased the dry-matter content by 3.4 percent with ½ NPK over the control and by 6.0 percent with 100 percent NPK over 50 percent NPK. Of all the treatment combinations, the significantly greatest starch content (26.64 percent) was recorded due to integrated use of lime + FYM + NPK + $MgSO_4$ at par with lime + FYM + NPK + $ZnSO_4$ (25.79 percent) and lime + FYM + NPK + VAM (25.75 percent). Among the organic sources, in situ incorporation of green manure integrated with lime + FYM + ½ NPK showed the greatest starch (25.72 percent) and dry matter (32.6 percent) rather than neem cake and FYM. Addition of superoptimal doses of NPK showed significant response in respect of starch content, indicating that the sweet potato even can produce greater crop yields as well as biochemical constituents with the increased doses of inorganic fertilizers under acidic soils of this region. These results are in agreement with the findings of Hill (1984). Integrated application of lime, ½ NPK, and organics showed increases of 4.6, 3.7, and 10.7 percent starch content in comparison to FYM, neem cake, and green manure over that of ½ NPK, and lime addition along with the organic sources further increased the starch content, which might be attributed to the increased rate of mineralization of the organic manure with the addition of soil amendment (lime), resulting in nutrient transformations and mobility in the plant system. Total sugars ranged from 2.87 to 3.38 percent, with greatest due to application of

Table 2

Effects of lime and inorganic and organic manures on proximate composition and nutrient uptake of sweet potato (mean of 5 years)

	Proximate composition (%)			Nutrient uptake (kg ha^{-1})											
				Tubers			Vines			Total uptake			Uptake response (%)		
Treatment	Starch	Total sugars	Dry matter	N	P	K	N	P	K	N	P	K	N	P	K
Control	21.84	2.87	29.04	10.21	7.50	16.23	17.74	5.61	14.78	27.96	13.10	31.02	—	—	—
½ NPK	23.23	3.15	30.04	12.75	9.88	21.13	24.62	7.97	20.62	37.38	17.85	41.74	33.7	36.3	34.6
NPK	23.92	3.29	31.84	18.75	13.64	30.62	32.22	10.68	31.24	50.97	24.32	61.86	82.3	85.6	99.4
1½ NPK	24.51	3.31	33.23	22.17	16.12	36.38	43.52	14.18	41.15	65.69	30.31	77.53	134.9	131.4	149.9
Lime + NPK	24.44	3.17	32.46	19.93	14.27	32.17	36.54	11.23	34.62	56.47	25.50	66.79	102.0	94.7	115.3
FYM + ½ NPK	24.51	3.19	31.26	16.64	12.31	27.69	31.73	9.75	26.37	48.36	22.06	53.72	73.0	68.4	73.2
FYM + NPK	24.96	3.36	33.53	22.43	16.31	36.63	41.18	13.37	42.62	63.61	29.68	79.26	127.5	126.6	155.5
Lime + FYM + ½ NPK	24.29	3.17	32.32	18.83	13.63	28.93	33.08	10.38	30.90	51.91	24.01	59.82	85.7	83.3	92.8
Neem + ½ NPK	23.75	3.21	30.78	15.04	11.09	24.65	28.19	8.60	27.12	43.23	19.69	51.77	54.6	50.3	66.9
Lime + neem + ½ NPK	24.09	3.29	31.67	16.99	13.03	28.06	32.14	9.83	33.48	49.12	22.86	61.53	75.7	74.5	98.4
Green manure + ½ NPK	24.17	3.13	31.51	18.49	13.92	29.26	37.18	10.36	34.27	55.67	24.27	63.52	99.1	85.3	104.8
Lime + GM + ½ NPK	25.72	3.22	32.59	22.32	16.59	33.94	41.85	11.85	38.52	64.17	28.44	72.46	129.5	117.1	133.6
FYM + NPK + $ZnSO_4$	24.48	3.22	33.02	23.19	16.81	40.05	44.17	10.87	44.02	67.36	27.68	84.06	140.9	111.3	171.1
Lime + FYM + NPK + $ZnSO_4$	25.79	3.35	33.48	25.72	19.11	44.06	48.07	12.37	49.95	73.79	31.48	94.01	163.9	140.3	203.1
FYM + NPK + B	24.63	3.30	33.14	22.01	16.67	38.24	41.55	12.59	43.40	63.56	29.25	81.64	127.3	123.3	163.2
Lime + FYM + NPK + B	25.38	3.37	34.61	23.57	19.03	41.84	43.41	13.83	45.00	66.97	32.85	86.84	139.5	150.8	179.9
FYM + NPK + $MgSO_4$	24.41	3.25	33.50	24.38	17.46	41.56	42.98	13.55	46.43	67.36	31.01	87.98	140.9	136.7	183.6
Lime + FYM + NPK + $MgSO_4$	26.64	3.38	33.99	28.13	20.48	45.96	49.56	15.02	47.52	77.69	35.51	93.48	177.9	171.1	201.4
FYM + NPK + VAM	24.96	3.29	32.97	23.31	17.70	39.07	43.43	14.32	43.86	66.74	32.02	82.93	138.7	144.4	167.3
Lime + FYM + NPK + VAM	25.75	3.37	33.68	25.68	19.88	43.20	46.17	16.15	48.12	71.85	36.04	91.33	157.0	175.1	194.4
CD ($P = 0.05$)	1.46	0.11	0.60	1.17	0.89	2.11	2.07	0.72	2.55	2.64	1.21	3.67	—	—	—

lime + FYM + NPK + $MgSO_4$. Total sugars also significantly increased with the addition of lime and organic manures over the inorganic sources.

Nutrient Uptake

Total uptake of N, P, and K significantly increased due to application of graded doses of NPK. Of all the treatment combinations, the significantly greatest total uptake of N (77.69 kg ha^{-1}) was recorded due to integrated application of lime + FYM + NPK + $MgSO_4$ with uptake responses of 178, 52, and 18 percent over control, optimum, and superoptimal doses of NPK, respectively (Table 2), followed by lime + FYM + NPK + $ZnSO_4$ (73.79 kg ha^{-1}). The total uptake of P was greatest due to combined application of lime + FYM + NPK + VAM (36.04 kg ha^{-1}) with uptake responses of 48 and 19 percent over those of optimum and superoptimal doses of NPK, respectively. However, total uptake of K was due to combined application of lime + FYM + NPK + $ZnSO_4$ (94.0 kg ha^{-1}), at par with lime + FYM + NPK + $MgSO_4$ (93.5 kg ha^{-1}). Among the organic sources, in situ incorporation of green manure showed greater NPK uptake response both in tubers and vines followed by FYM and neem cake. Vines contain greater concentrations of N and K than tubers do, whereas tubers had greater P in comparison to vines. The uptake of N, P, and K in both tubers and vines significantly increased with the application of graded doses of NPK; however, lime addition along with half of the recommended doses of NPK and organic manures further aggravated the uptake of N, P, and K in sweet potato.

Nutrient-Use Efficiency

Application of optimum doses of NPK recorded the greatest efficiencies of N, P, and K (67, 101, and 67 kg tubers kg^{-1} of N, P, and K, respectively), whereas the nutrient-use efficiencies were considerably decreased by application of suboptimal and superoptimal doses of NPK over optimum doses of NPK (Table 3). Thus, the results emphasized the need for balanced and optimum fertilization to obtain greater productivity as well as nutrient-use efficiency. Liming in combination with optimum doses of NPK showed greater use efficiencies of N, P, and K over that of NPK. Among the organics, incorporation of green manure along with lime and ½ NPK recorded the greatest nutrient-use efficiency in terms of kg tubers kg^{-1} fertilizer N (96), kg tubers kg^{-1} P (190), and kg tubers kg^{-1} K (107) with contributions of 154, 574, and 206 percent, respectively. The results emphasized that neem cake has contributed the maximum toward N-, P-, and K-use efficiencies in comparison to FYM, which might be due to greater concentrations of N, P, and K in neem cake than in FYM. It can be inferred from the results that integrated use of lime and inorganic and organic manures not only enhances sweet potato productivity but also increases nutrient-use efficiency (Hartemink 2003). Liming had significant effect on productivity of sweet potato and efficiency of applied chemical fertilizers by countering the acidity and exchangeable aluminium content in the soils (Vele, Pax, and Colin 2000).

Apparent Nutrient Recovery

A perusal of the data (Table 3) showed that application of superoptimal doses of NPK recorded the greatest N recovery (33.5 percent) in comparison to optimum doses of N (30.7 percent), whereas the application of lime + NPK enhanced the recovery of applied N over that of NPK, which may be ascribed to greater biomass production and nutrient

Table 3

Effects of integrated use of lime and inorganic, biological, and organic sources on nutrient-use efficiency and apparent nutrient recovery

	Nutrient-use efficiency (kg kg^{-1})			Apparent nutrient recovery (%)		
Treatment	N	P	K	N	P	K
½ NPK	56.0	84.0	56.0	25.1	19.0	28.6
NPK	67.3	101.0	67.3	30.7	22.4	41.1
1½ NPK	54.9	82.4	54.9	33.5	22.9	41.3
Lime + NPK	69.1	103.6	69.1	38.0	24.8	37.0
FYM + NPK	72.5 (93.5)	110.6 (153.6)	70.1 (79.6)	47.5 (68.7)	27.1 (47.9)	49.9 (80.5)
Lime + FYM + ½ NPK	77.1 (120.1)	119.1 (197.3)	72.9 (102.3)	42.8 (79.0)	30.1 (55.0)	48.7 (83.7)
Lime + neem cake + ½ NPK	82.1 (173.0)	128.6 (320.7)	89.8 (281.8)	43.9 (109.2)	31.7 (86.4)	69.2 (299.8)
Lime + green manure + ½ NPK	95.7 (153.5)	190.0 (573.9)	106.9 (206.3)	57.2 (103.8)	48.1 (153.5)	73.1 (160.0)
Lime + FYM + NPK + $ZnSO_4$	93.7 (201.1)	143.0 (330.4)	90.6 (171.3)	49.1 (124.0)	30.0 (63.9)	65.2 (148.8)
Lime + FYM + NPK + B	79.7 (129.9)	121.6 (213.4)	77.0 (110.6)	41.8 (87.0)	32.3 (76.2)	57.8 (115.6)
Lime + FYM + NPK + $MgSO_4$	95.6 (210.9)	145.9 (346.4)	92.4 (179.6)	53.2 (145.2)	36.6 (99.9)	64.7 (146.4)
Lime + FYM + NPK + VAM	85.2 (158.2)	130.1 (259.8)	82.4 (134.7)	47.0 (113.5)	37.5 (104.6)	62.4 (136.4)

Note. Parentheses indicate the contribution of the organic sources over 50 percent or 100 percent NPK.

uptake due to balanced fertilization. These results are in agrement with the findings of Martí and Mills (2002). Among the organic sources, integrated application of lime + green manure + ½ NPK recorded the greatest N recovery (57.2 percent) followed by lime + neem cake + ½ NPK (43.9 percent) and lime + FYM + ½ NPK (42.8 percent). It was noticed that the contributions of organics toward apparent N recovery were 104, 109, and 79 percent with respect to green manure, neem cake, and FYM over that of ½ NPK, indicating that the contribution of organics towards N recovery was greater at lower doses of N application. However, the contribution of organic manures toward nutrient recovery may also be the result of native as well as applied sources of the nutrient concerned. The difference in N release from the organics is also related to the amount and composition of manure, C/N ratio, lignin content of plants, and management practices (Ali 1999).

It was observed that the efficiencies of applied P under optimum and superoptimal doses of NPK were 22.4 and 22.9 percent, respectively, whereas the P recovery was 27.1 percent due to incorporation of lime + NPK with a contribution of 47.9 percent attributed by FYM toward the N recovery (Table 3). The results emphasized that lime has profound influence in these acidic Alfisols when applied along with organic sources and limited doses of NPK. Green manuring along with lime and ½ NPK showed the greatest P recovery (48.1 percent) with a contribution of 153.5 percent from green manure followed by lime + neem cake + ½ NPK (31.7 percent with a contribution of 86.4 percent from neem cake). Similar increase of nutrient-use efficiency with the integrated application of NPK fertilizers and organic manures was reported by Janssen (1993). Inoculation of sweet potato with VAM in combination with lime + FYM + NPK recorded the greatest P recovery (37.5 percent) with a contribution of 104.6 percent from VAM towards P recovery.

Application of optimum and superoptimal doses of NPK recorded the greatest K recovery (41.1 and 41.3 percent, respectively) and liming with optimal doses of NPK showed greater K recovery (49.9 percent) with a contribution of 80.5 percent from FYM toward the K recovery. Among the organics, the greatest apparent K recovery (73.1 percent) was observed due to green manuring along with lime + FYM + ½ NPK with a contribution of 160 percent from green manure toward K recovery when considering the nutrient supply from both sources. The efficiency of $ZnSO_4$ in combination with lime + FYM + NPK toward K recovery was 65.2 percent, closely followed by lime + FYM + NPK + $MgSO_4$ (64.7 percent). These results are in agreement with the findings of Martí and Mills (2002).

Soil Fertility

The pH of the soil increased to 5.92 due to long-term application of lime + FYM + NPK + $MgSO_4$ from the initial level of 5.51 (Table 4). Application of lime and greater amounts of organic sources, which can buffer pH, countered the soil acidity. Addition of inorganic chemical fertilizers over a period of 5 years resulted in further increase in soil acidity, but relatively greater status of soil pH resulted under 100 percent NPK when applied in combination with lime or organic manure as compared to sole application of 100 percent NPK. Combined application of lime + ½ NPK + FYM showed relatively greater pH of the soil than other organic sources, because organic matter has high cation exchange capacity (CEC) and facilitated retention of exchangeable bases (Svotwa, Baipai, and Jiyane 2007; Ossom and Rhykerd 2008). Apart from yield gains, green manuring adds organic matter, improves soil physical properties, and neutralizes soil pH (Hartemink and O'Sullivan 2001). Continuous cropping without fertilization or

Table 4

Effects of integrated use of lime and inorganic, biological and organic sources on soil physicochemical properties (after the fifth year)

Treatment	pH (1:2)	EC (dS m^{-1})	Org. C (%)	Total N (%)	Available nutrient (kg ha^{-1})		
					N	P	K
Initial	5.51	0.58	0.328	0.0746	141.8	22.3	217.8
Control	4.85	0.39	0.274	0.0683	195.7	56.2	175.5
½ NPK	4.84	0.56	0.382	0.0709	200.0	80.6	192.8
NPK	4.79	0.61	0.403	0.0763	228.0	92.3	212.4
1½ NPK	4.78	0.69	0.585	0.0892	255.9	107.5	248.2
Lime + NPK	5.22	0.65	0.415	0.0812	238.7	96.8	225.9
FYM + ½ NPK	5.02	0.57	0.388	0.0779	217.1	94.6	211.9
FYM + NPK	5.23	0.66	0.446	0.0825	240.4	101.0	239.8
Lime + FYM + ½ NPK	5.44	0.59	0.422	0.0804	233.4	97.8	222.6
Neem + ½ NPK	5.20	0.62	0.390	0.0762	215.7	86.6	208.0
Lime + neem + ½ NPK	5.36	0.65	0.429	0.0776	225.9	91.4	220.8
Green manure + ½ NPK	5.20	0.59	0.474	0.0808	232.5	92.3	218.9
Lime + green manure + ½ NPK	5.37	0.61	0.541	0.0826	242.1	105.3	229.9
FYM + NPK + $ZnSO_4$	5.31	0.68	0.532	0.0831	251.9	92.1	256.6
Lime + FYM + NPK + $ZnSO_4$	5.45	0.71	0.655	0.0856	265.9	101.6	272.9
FYM + NPK + B	5.25	0.65	0.462	0.0837	243.4	102.7	246.1
Lime + FYM + NPK + B	5.42	0.66	0.518	0.0842	254.1	105.2	255.8
FYM + NPK + $MgSO_4$	5.54	0.72	0.610	0.0854	260.5	103.8	263.2
Lime + FYM + NPK + $MgSO_4$	5.92	0.74	0.730	0.0866	274.9	112.0	286.9
FYM + NPK + VAM	5.35	0.67	0.582	0.0840	249.8	108.5	254.2
Lime + FYM + NPK + VAM	5.50	0.68	0.651	0.0852	260.3	127.6	264.4
CD ($P = 0.05$)	0.17	0.029	0.023	0.004	3.67	7.53	4.75

manuring of the soil led to reduction in organic C content from 0.328 to 0.274 percent (in control). The greatest organic C content was observed with the incorporation of lime + FYM + NPK + $MgSO_4$ (0.73 percent) with an increase of 123 percent of organic C over the control. Incorporation of green manure significantly enhanced organic matter over that of other organic manures. The total N content of the soil was significantly increased with the integrated application of NPK and organic manures over NPK alone; however, suboptimal doses of NPK and control treatments showed lower status of total N over that of the initial level. This could be attributed to N-mineralization pattern of these organics and indirect influence on physicochemical characteristics of the soil (Singh et al. 2002). Addition of nitrogenous fertilizers tended to increase the available N status of the soil by 2.2, 16.5, and 30.8 percent for 50, 100, and 150 percent NPK over the control. Significantly greatest available N (275 kg ha^{-1}) was recorded due to combined application of lime + FYM + NPK + $MgSO_4$ followed by lime + FYM + NPK + $ZnSO_4$ (266 kg ha^{-1}). Incorporation of organics along with ½ NPK increases the available N status by 8.6, 7.9, and 16.3 percent due to FYM, neem cake, and green manure, respectively, over ½ NPK, whereas lime addition along with ½ NPK and organics further increases the available N content by 7.5, 4.7, and 4.1 percent over that of unlimed plots. The humus produced from the organic manures on their decomposition can supply almost all the essential nutrients slowly but steadily to the growing crops, and direct supply from the inorganic fertilizers contributed to improvement of available nutrient status of the soil. The magnitudes of increases in available P under 50, 100, and 150 percent NPK were 43, 64, and 91 percent over the control; however, the integrated use of recommended doses of fertilizers with FYM recorded the significantly greatest available P (101 kg ha^{-1}) with an increase of 25 and 9 percent over suboptimal and optimal doses of NPK. Fungal inoculation with VAM in combination with lime, FYM, and optimum doses of NPK registered the significantly greatest available P status (127.6 kg ha^{-1}) with an increase of 19 percent over that of superoptimal doses of NPK. Increase in available P content of the soil attributed to decomposition of organic manures could have enhanced the labile P in the soil by complexing Ca, Mg, and Al (Subramanian and Kumaraswamy 1989) and solubilizing phosphate-rich organic compounds through release of organic acids upon decomposition of organic matter and chelation of organic anions with Fe and Al, resulting in effective solubilization of inorganic phosphates into soil (Subba Rao 1999).

The greatest available K content in the soil was observed due to integrated application of lime + FYM + NPK + $MgSO_4$ (287 kg ha^{-1}) followed by lime + FYM + NPK + $ZnSO_4$ (273 kg ha^{-1}) and lime + FYM + NPK + VAM (264 kg ha^{-1}). The available K status of the soil sharply declined from the initial level due to addition of suboptimal and optimal doses of NPK, and integrated use of organic manures along with optimum doses of NPK enhanced the available K status. It seems that the crop requirements for K were partly met from the added inorganic sources and also from the native soil, resulting in depletion of available K in the soil, whereas supplementing the crop with inorganic fertilizers along with organic sources released K on their decomposition, and both the applied K and released K built up the available K in the soil. Addition of lime in combination with limited doses of NPK and organic manures showed a marginal increase in available K over that of inorganic and organic sources. The differential release pattern of nonexchangeable K from the soil reserve besides variation in K uptake by the crop will be held responsible for such differences in the available K status of the soil (Svotwa, Baipai, and Jiyane 2007).

In conclusion, conmbined use of organic manures and balanced doses of inorganic chemical fertilizers not only enhanced the crop productivity but also improved the biochemical constituents and sustained the soil fertility. Application of Mg, Zn, and B had profound influence on sustainable crop production with quality tubers in the acidic soils. Fungal inoculation with mycorrhiza had great impact on not only tuberization but also on the soil fertility. Incorporation of organics in combination with limited doses of lime and inorganic chemical fertilizers could be effective in producing sustainable crop yields and maintaining soil health under acidic soils of eastern India.

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