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Integrated use of potassium-enriched composts to enhance tomato yield and fertilizer efficiency in kitchen gardens

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Abstract

Potassium (K) value addition in composts is often overlooked, despite its critical role in enhancing tomato yield and quality for kitchen gardening. Over two years of pot experiments, Biochar Enriched Compost (BEC) and Value-Added Compost (VAC) were assessed as potential substitutes (25 to 75%) for inorganic K. Treatments comprised different combinations of BEC+SOP or VAC+SOP to evaluate their potential for improving crop performance. Results demonstrated that substituting 25 to 75% of inorganic K with BEC or VAC significantly improved fruits per plant (4-40%), plant biomass (4-12%), photosynthetic rate (2-33%), chlorophyll content (2-25%), water use efficiency (6-17%), biological yield (4-14%), and fruit yield (3-17%) compared with sole inorganic K application. Integrated use of BEC and SOP or VAC and SOP enhanced K recovery efficiency (24-81%), and K agronomic use efficiency (4-25%) over SOP alone. Fruit quality was also enhanced, with higher total soluble solids (46-64%), ascorbic acid (2-15%), lycopene content (2-97%), and fruit pulp (15-32%). VAC consistently outperformed BEC, suggesting that replacing 25% inorganic K with VAC or BEC optimize K utilization, yield, and quality. This study established a baseline for K value addition during composting of organic wastes to produce nutrient-rich compost for sustainable kitchen gardening of high-quality tomatoes.

Keywords: Biochar enriched compost, Potassium-rich compost, K use efficiency, Kitchen gardening, tomato yield and quality

Introduction

Tomato (*Lycopersicon esculentum* Mill.) is a popular and important vegetable from the Solanaceae family (Kumar Tiwari *et al.*, 2022). It is a rich source of nutrients like vitamins A and C, K, and lycopene, which is an antioxidant linked to a reduced risk of certain cancers (Waheed *et al.*, 2020). Tomatoes can be eaten raw or used in various dishes such as salads, sauces, soups, and stews. They are widely cultivated globally due to their popularity and nutritional benefits (Derbe *et al.*, 2024; Ouattara and Konate, 2024). Pakistan is the 35th largest tomato producer globally and ranks 11th in production area (FAOSTAT, 2022). Despite similar climatic conditions and the adoption of hybrid cultivars and tunnel farming technology, Pakistan's tomato production lags behind India. Pakistan's tomato production per person, overall yield per acre, and average acreage are 79%, 97%, and 92% lower than India's, respectively (FAOSTAT, 2022). Kitchen gardening has the potential to increase the per-person yield of tomatoes in Pakistan (Kanosvamhira, 2024) if researchers develop a cost-effective integrated nutrition management plan (Bashir *et al.*, 2024).

In Pakistan, the yield of vegetables per acre is still below the potential yields of cultivars, even with the best agronomic and nutrition management practices (Bashir *et al.*, 2024). This is mainly due to the continuous decline in soil health and sudden changes in climate, which have greatly impacted the fertility and productivity of the soil (Rahman *et al.*, 2024). The rapid deterioration of soil health is a global issue (Cárceles Rodríguez *et al.*, 2022). The unbalanced use of chemical fertilizers, lack of organic manures, green manuring, and crop residue incorporation have turned once productive soils in Pakistan into unproductive and barren ones, resulting in lower crop yields and poor fruit quality (Lal, 2018). This decline in soil health and abrupt climate changes have led to a poverty trap in Pakistan. The use of organic sources is seen as an effective way to sustain soil health and mitigate the impact of climate changes on crops and vegetable production (Singh *et al.*, 2024). However, the use of organic sources in plant nutrition management currently is

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low as organic manures are only used on a small scale and cannot meet the nutritional demands of vegetables (Derbe *et al.*, 2024). There is a critical need to enhance the value of organic manures and use them in conjunction with synthetic fertilizers in the right proportions (Saha *et al.*, 2019). By selecting the right organic sources and application rates, the reliance on synthetic fertilizers can be reduced, leading to increased vegetable production per capita (Xiang *et al.*, 2022). This approach can also help reduce greenhouse gas emissions and promote sustainable agricultural practices (Xiang *et al.*, 2022).

Treatments Table:

Organic K : Synthetic K (kg per acre)	**Detailed treatment**
Control-I*	Blank (Without N, P and K fertilizers and manures)
Control-II**	NP control
0% organic K+100% K-SOP	100% of the K supply from SOP to meet the tomato's K requirement [Conventional approach]
25% K-BEC+75% K-SOP	25% of the K supply from BEC and the remaining 75% from SOP to meet the tomato's K requirement
50% K-BEC+50% K-SOP	50% of the K supply from BEC and the remaining 50% from SOP to meet the tomato's K requirement
75% K-BEC+25% K-SOP	75% of the K supply from BEC and the remaining 25% from SOP to meet the tomato's K requirement
25% K-VAC+75% K-SOP	25% of the K supply from VAC and the remaining 75% from SOP to meet the tomato's K requirement
50% K- VAC+50% K-SOP	50% of the K supply from VAC and the remaining 50% from SOP to meet the tomato's K requirement
75% K- VAC+25% K-SOP	75% of the K supply from VAC and the remaining 25% from SOP to meet the tomato's K requirement

*In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively, to eliminate their effect on tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K.*

Table 1: Characteristics of the organic manures utilized in the study

Organic manure	**Manure Characteristic**							
	pH	OM (%)	Carbon (%)	Total N (%)	Available P (%)	Available K (%)	C:N	C:P
FYM	7.3	27.5	16.0	0.97	0.06	0.42	16.5	266
BEC	7.2	76.0	44.2	0.61	0.24	0.70	72.4	184
VAC	6.3	60.6	35.2	1.58	2.56	1.23	22.3	13.8

Table 2: Physiochemical characteristics of the experimental soil

Soil Characteristic	**Value**	**Reference**
Soil Texture	Silt Loam	Black *et al.* (1965)
Sand (%)	30.0	
Silt (%)	52.0	
Clay (%)	18.0	
Soil organic matter (%)	0.76	Walkley (1947)
CEC Cmol (-) kg^{-1}	11.6	Chapman and Pratt(1962)
EC (dS m^{-1})	2.1	
pH	8.2	Jackson *et al.* (1973)
Total N (%)	0.039	Bremner and Mulvaney (1982)
Total P (mg kg^{-1})	8.6	Olsen *et al.* (1954)
Total K (mg kg^{-1})	172.2	Knudsen *et al.* (1983)

Potassium (K) plays a crucial role in vegetable production by enhancing the size and quality of fruits and vegetables, improving water use efficiency, and boosting plant resistance to stress particularly an abiotic stress (Havlin *et al.*, 2014). It is especially important for crops like tomatoes, potatoes, peppers, and eggplants, which have high K requirements and need regular soil testing to determine the amount of K fertilizer to apply (Cui *et al.*, 2024; Praveen and Singh, 2024). Additionally, K also helps to prolong the shelf life of vegetables by reducing susceptibility to diseases and decay. It also aids in regulating the plant's water balance, reducing wilting and enhancing overall crop quality(Praveen and Singh, 2024). Therefore, ensuring adequate K levels in vegetable crops is essential for maximizing yields and quality. Proper soil testing and fertilization practices are crucial for maintaining optimal K levels in vegetable production (Havlin *et al.*, 2014).

Organic manure is essential for the nutrition of vegetable crops as it provides essential nutrients in a slow-release form (Shao *et al.*, 2024). The application of organic manure improves soil health and quality by enhancing various soil physical and chemical properties such as structure, porosity, aeration, bulk density, color, water retention, cation exchange capacity (CEC), nutrient retention and water holding capacity (Agegnehu *et al.*, 2016; Hossain *et al.*, 2020). The slow-release of nutrients from organic manures ensures a steady nutrient supply to vegetable crops, preventing nutrient losses and offering a long-lasting nutrient source. Organic manures also enhance soil fertility, improve nutrient uptake by plants, and reduce impacts of stress (Ierna and Distefano, 2024; Singh *et al.*, 2024). Additionally, applying organic manures can lower soil pH, enhance microbial activity, improve nutrient uptake efficiency, reduce reliance on synthetic fertilizers and decrease the risk of nutrient pollution (Lu *et al.*, 2021).

Despite the recognized importance of K for crop productivity, compost value addition with K is rarely practiced, leading to imbalanced nutrient supply from organic amendments. Kitchen gardening, particularly for tomato production, requires nutrient sources that not only sustain yield but also enhance fruit quality. Biochar-enriched Compost (BEC) and Value-Added Compost (VAC) offer promising options to improve nutrient release dynamics and reduce reliance on inorganic fertilizers. Moreover, substituting inorganic K source with organic sources is crucial in modern agriculture to achieve a balanced nutrient profile in soils (Abrol *et al.*, 2024). We hypothesized that partial substitution of inorganic K with BEC or VAC would enhance K recovery, agronomic efficiency, and fruit quality compared with sole inorganic fertilization. Therefore, the objectives of the study were: (i) to enhance the effects of K -enriched composts on nutrient mineralization and tomato growth, (ii) to assess their contribution to K use efficiency and yield, and (iii) to determine their role in improving fruit quality for sustainable kitchen gardening.

Materials and Methods

Study conditions and treatment plan

Pot studies were conducted for two years to evaluate the alone and combined effects of organic and synthetic sources of nutrition for improving morphological and physiological characteristics of tomatoes. The studies were conducted for two consecutive years, 2020 and 2021 in the Greenhouse of Muhammad Nawaz Shareef University of Agriculture Multan (MNS-UAM). These studies were laid out in compliance with completely randomized design (CRD) with four replications. The treatment plan included two organic sources, i.e. VAC, and VAC and one inorganic K source i.e., sulfate of potash (SOP). The detailed treatment plan is given in treatment table.

Preparation of compost

The university's lawn development waste and farmyard manure (FYM) were collected and for composting, both the materials were buried in an earthen pit lined with a polyethylene sheet for 90 days in the Research block of the university. Biochar prepared from the cutting of pruned trees and shrubs was collected from the Solid Waste Management site of the university (Ali *et al.*, 2025) and added to the pit of manure to produce BEC. Proper moisture was maintained to keep all the materials wet while avoiding waterlogging. The materials were turned over two to three times a week. After 90 days, the materials from each pit were collected, shade-dried, ground, and placed at 4°C until use. For VAC, several grades were prepared at Ambala Agri Tech Industry Multan and tested, and the optimal composition was determined to be 40% PM, 10% FYM, 10% kitchen organic waste, 5% press mud (PM), 15% biochar, 10% peat moss, and 10% rock phosphate. The characteristics of BEC and VC are given in Table 1.

Conducting the experiment

A composite sample from depth of 15-30 cm was taken from the experimental area of MNS-UAM and analyzed physiochemical properties (Table 2). After analysis, the collected soil was dried, ground, and sieved through a 2 mm sieve and then used to fill earthen pots @ 10 kg pot^{-1}. The N and P were 150 and 100 kg ha^{-1} using urea and DAP as source applied, respectively, in all treatments except control. However, K @ 100 kg ha^{-1} was applied using organic source (BEC and VAC) and SOP according to treatment plan. N, and P sources were applied as basal dose while N was applied in three splits. The measured amounts of BEC and VAC were applied and thoroughly mixed into the soil before transplanting the nursery. The nursery for Syngenta T-1359 F-1 tomatoes was established under control conditions in a greenhouse at the Department of Horticultural Sciences, MNS-UAM. Peat moss was used as the growth medium in trays, and two seedlings were transplanted in each pot and irrigated. At field capacity, each pot was weighed, and moisture was maintained on weight basis.

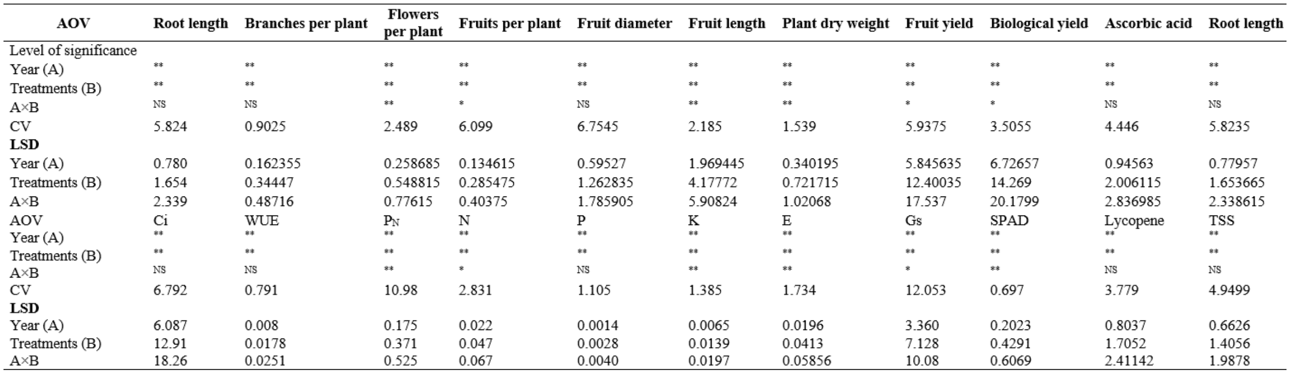
Data collection for agronomic parameters

Plant growth and physiological parameters were recorded at different plant growth stages while yield and yield-contributing parameters were recorded at maturity (Ahmed *et al.*, 2020). Chlorophyll contents were measured before anthesis by using a portable Chlorophyll meter (SPAD-502) whereas CIRAS-3 was used to measure gaseous exchange, photosynthetic rate, and water use efficiency (WUE) from the fully expanded leaves at anthesis stage.

Soil analysis, nutrient uptake and Nutrient use efficiency

Soil samples were analyzed using standardized methods (Estefan *et al.*, 2013). The physicochemical properties of the soil are presented in Table 2. Following the procedures outlined by Wolf (Wolf, 1996), Jackson (Jackson, 1985), and Chapman and Pratt (Chapman and Pratt, 1962), the concentrations of N, P, and K in tomato plants were determined. K Apparent recovery efficiency (KARE), K physiological use efficiency (KPUE) and K agronomic use

Table 3: ANOVA table for various parameters of tomato



AOV	Root length	Branches per plant	Flowers per plant	Fruits per plant	Fruit diameter	Fruit length	Plant dry weight	Fruit yield	Biological yield	Ascorbic acid	Root length
Level of significance											
Year (A)	**	**	**	**	**	**	**	**	**	**	**
Treatments (B)	**	**	**	**	**	**	**	**	**	**	**
A×B	NS	NS	**	*	NS	**	**	*	*	NS	NS
CV	5.824	0.9025	2.489	6.099	6.7545	2.185	1.539	5.9375	3.5055	4.446	5.8235
LSD											
Year (A)	0.780	0.162355	0.258685	0.134615	0.59527	1.969445	0.340195	5.845635	6.72657	0.94563	0.77957
Treatments (B)	1.654	0.34447	0.548815	0.285475	1.262835	4.17772	0.721715	12.40035	14.269	2.006115	1.653665
A×B	2.339	0.48716	0.77615	0.40375	1.785905	5.90824	1.02068	17.537	20.1799	2.836985	2.338615
AOV	Ci	WUE	P_N	N	P	K	E	Gs	SPAD	Lycopene	TSS
Year (A)	**	**	**	**	**	**	**	**	**	**	**
Treatments (B)	**	**	**	**	**	**	**	**	**	**	**
A×B	NS	NS	**	*	NS	**	**	*	**	NS	NS
CV	6.792	0.791	10.98	2.831	1.105	1.385	1.734	12.053	0.697	3.779	4.9499
LSD											
Year (A)	6.087	0.008	0.175	0.022	0.0014	0.0065	0.0196	3.360	0.2023	0.8037	0.6626
Treatments (B)	12.91	0.0178	0.371	0.047	0.0028	0.0139	0.0413	7.128	0.4291	1.7052	1.4056
A×B	18.26	0.0251	0.525	0.067	0.0040	0.0197	0.05856	10.08	0.6069	2.41142	1.9878

Note: Internal CO_2 concentration (Ci), Water use efficiency (WUE), Net photosynthesis rate (P_N), Fruit N concentration (N), Fruit P concentration (P), Fruit K concentration (K), Transpiration rate (E), Stomatal conductance (Gs), Chlorophyll content (SPAD), Harvest index (HI) and Root length (RL).

Table 4: Integrated effect of K enriched organic and inorganic sources of potassium on agronomic attributes of yield (mean data of 2020 and 2021 trials)

Treatment (K organic-inorganic source)	Plant dry weight (g plant^{-1})	Root length (cm)	Flowers Plant^{-1}	Fruits plant^{-1}	Fruit yield (g plant^{-1})
Control-I*	23±0.3f	14±0.3d	12±0f	1.5±0.2f	72±3.2f
Control-II**	46±0.4e	27±0.6c	15.8±0.4e	2.8±0.1e	105±0.9e
100% K (SOP)	51±0.7d	31±0.1bc	23.5±0.2d	5±0.1d	229±3.6d
25% BEC +75% SOP	50±0.4cd	30±0.3bc	24±0.7cd	5.2±0.2cd	229±2.3d
50% BEC +50% SOP	53±0.1c	32±0b	25.1±0.2c	5.3±0.2c	235±3.2c
75% BEC +25% SOP	54±0.9b	32±2.1b	27.4±0.2b	6.6±0.1b	258±5.7b
25% VAC+75% SOP	54±0.4b	33±0.3b	25.9±0.7b	5.6±0.2b	255±3.4c
50% VAC +50% SOP	54±0.1bc	32±0b	25.3±0.2bc	5.4±0.2bc	258±7.4c
75% VAC +25% SOP	57±1a	34±2.2a	28.9±0.2a	7±0.2a	268±0.7a

Values followed by different letter(s) within a column are significantly different at $p \leq 5\%$ (± indicates SE). In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K.

efficiency (KAUE) were calculated using formulae given by Fixen (Fixen *et al.*, 2015) and Ahmed (Ahmed *et al.*, 2020).

$$K\ uptake = K\ concentration\ (\%) \times dry\ weight,$$

$$\text{KAUE}\ (\text{kg kg}^{-1}) = \frac{\text{FY}_\text{T} - \text{FY}_\text{C}}{\text{KA}},\quad \text{KARE}(\%) = \frac{\text{KU}_\text{T} - \text{KU}_\text{C}}{\text{KA}} \times 100\ ,$$

$$\text{KPUE}\ (\text{kg kg}^{-1})\ = \frac{\text{KY}_\text{T} - \text{KY}_\text{C}}{\text{KU}_\text{T} - \text{U}_\text{C}}$$

Whereas FT_T = Fruit yeild of K treated plant, FT_C = Fruit yeild of control treatment plant, KU_T = K uptake in K treated plants, KU_C = K uptake in control treatment plants,

KA = K applied

Fruit quality parameters

Fruit pulp was extracted and TSS of fruit juice was measured using digital refractometer. The method developed by Ranganna (1986) was used to determine lycopene content. Lycopene was extracted with acetone, resulting in colorless residues that were treated with 10-15 mL of petroleum ether in a separating funnel. Subsequently, a 5% Na_2SO_4 solution was added. The acetone and petroleum ether process were repeated until a colorless endpoint was achieved. The color intensity was measured at 503 nm atomic absorption spectrophotometer (AAS) using petroleum ether as a blank. Ascorbic acid in tomato juices was determined by reducing the dye 2,6-dichlorophenol indophenol with ascorbic acid.

Statistical analysis

The data were analyzed using CRD, and means were compared using the Tukey's Significant Difference (HSD) test (Steel *et al.*, 1997).

Results and Discussion

Agronomic parameters

Significant variations were observed in various agronomic parameters of tomatoes such as plant biomass, branches plant^{-1}, flowers plant^{-1}, fruits plant^{-1}, branches plant^{-1}, root length, biological yield, and fruit yield due to different combinations of organic K and synthetic K (Table 3). The variations in agronomic parameters due to VAC+SOP were more pronounced with VAC+SOP combinations compared to BEC+SOP. Supplying K from SOP+BEC combinations increased plant dry mass by 4 to 6%, root length by 3%, flowers plant^{-1} by 2 to 17%, flowers plant^{-1} by 4 to 32% and fruit yield plant^{-1} by 3 to 11% compared to conventional approach i.e., 100% K-SOP (Table 4). However, in SOP+VAC combinations, these improvements ranged 6-12% in plant dry mass, 3-10% in root length, 8 to 23% in flowers plant^{-1}, 8 to 40% in fruit plant^{-1}, and finally 11-17% in fruit yield plant^{-1} (Table 4). Figure 1 also shows similar trends for the number of branches plant^{-1}, fruit length and fruit diameter. Overall, plants supplied with SOP + BEC or SOP +VAC had

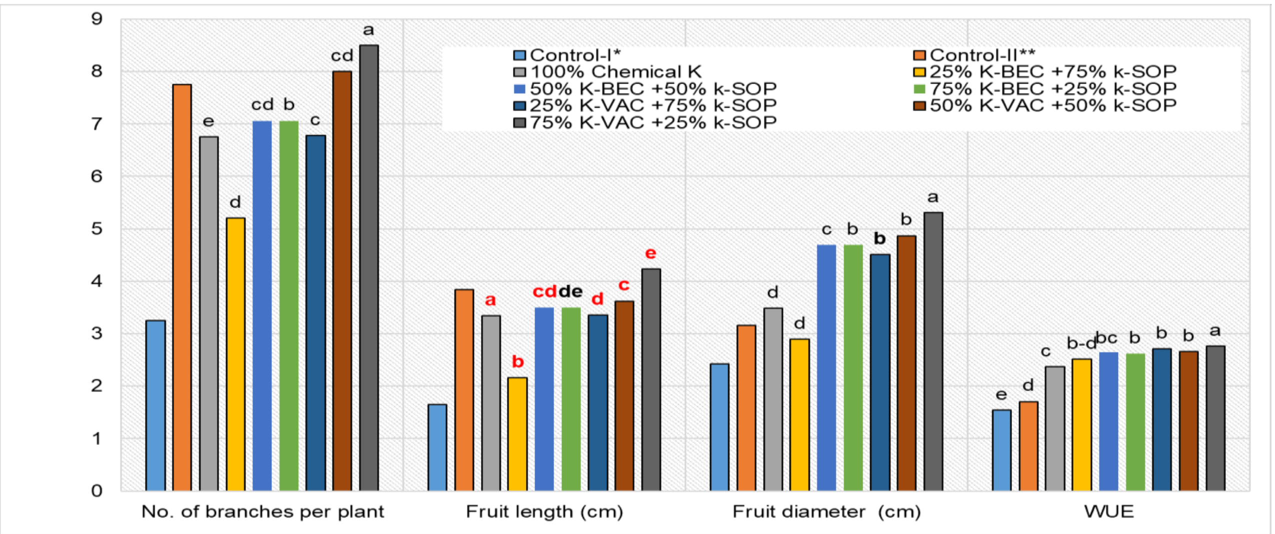


Figure 1: Integrated effects of organic and inorganic potassium sources on branches per plant, fruit length, fruit diameter, and Water use efficiency of tomato (two-year mean)

Bars with different letter(s) within a parameter indicate significant differences at $p \leq 5\%$. In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K. Whereas WUE = Water use efficiency

35 to 52% longer fruit diameter with 5 to 27% longer fruit length compared to conventional approach of K nutrition (100% K as SOP). Although significant variations were observed due to the varying K content from VAC or BEC, the combination of 75% K from VAC and 25% K from SOP (75% VAC + 25% SOP) showed the highest enhancement in agronomic parameters of tomatoes (Table 4, Figure 1). The results in Table 4 also indicate that VAC (75% K) + SOP (25% K) resulted in the highest plant weight per plant, followed by BEC (75% K) + SOP (25% K). Significant variations in root length, plant weight and other yield attributes were also observed due to the integrated use of VAC and chemical fertilizers or BEC and chemical fertilizers. The significant improvements in the number of fruits and flowers per plant, plant biomass, fruit and biological yield might be attributed to the K physiological role as an essential element.

The combined effects of K from BEC, VAC, and SOP on fruit yield (Table 4) had a significant impact on per plant fruit yield. The combined application of organic K and synthetic K sources had a statistically significant effect on fruiting and fruit yield, while plants application of SOP alone had lower fruiting and yield compared to treatments involving the K integrated use. The combination of VAC and SOP performed better in meeting the plant's K demand compared to the combination of BEC and SOP. These

Table 5: Integrated effects of K enriched organic and inorganic sources of potassium on net assimilation rate and water use efficiency of tomato plants (mean data of 2020 and 2021 trials)

Treatment (K organic-inorganic source)	Transpiration rate	Stomatal conductance	Net photosynthetic rate	Instantaneous WUE
Control-I*	1.62±0.21d	55±12.4c	2.29±0.38f	1.4±0.06e
Control-II**	2.9±0.08b	69±16b	2.90±0.50e	1.01±0.2f
100% K (SOP)	2.08±0.08bc	53±4.7c	3.41±0.62de	1.64±0.28c
25% BEC +75% SOP	3.35±0.1ab	46±11.1c	3.48±0.46d	1.05±0.16d
50% BEC +50% SOP	3.23±0.09b	49±2.3bc	3.68±0.37cb	1.15±0.14bc
75% BEC +25% SOP	3.86±0.11a	78±6.9ab	4.28±0.11ab	1.11±0.03bc
25% VAC+75% SOP	1.48±0.04de	50±12bc	3.76±0.5bc	2.56±0.4a
50% VAC +50% SOP	1.61±0.05d	50±2.3bc	3.7±0.37c	2.32±0.28b
75% VAC +25% SOP	1.48±0.04de	82±7.3a	4.52±0.12a	3.05±0.08a

Values followed by different letter(s) within a column are significantly different at p ≤ 5% (± indicates SE). In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K.

Table 6: Integrated effect of K enriched organic and inorganic sources of potassium on net assimilation rate and water use efficiency of tomatoes (mean data of 2020 and 2021 trials)

Treatment (K organic-inorganic source)	Plant N (%)	Plant P (%)	Plant K (%)	Chlorophyll Contents (SPAD)
Control-I*	1.1±0.03e	0.1±0d	0.46±0.01f	55±0.17f
Control-II**	1.53±0.05d	0.28±0.01c	0.94±0.03e	52±0.09e
100% K (SOP)	1.7±0.06c	0.29±0.01c	1.01±0.03d	60±0.14d
25% BEC +75% SOP	1.69±0.07c	0.3±0.01b	1.08±0.03c	61±0.01cd
50% BEC +50% SOP	1.85±0.09bc	0.31±0.01b	1.09±0.01c	71±0.09c
75% BEC +25% SOP	1.91±0.11a	0.32±0.01a	1.29±0.03a	71±0.59b
25% VAC+75% SOP	1.82±0.08b	0.3±0.01b	1.16±0.03b	65±0.01b
50% VAC +50% SOP	1.86±0.09bc	0.32±0.01a	1.1±0.01c	71±0.09bc
75% VAC +25% SOP	2.02±0.12a	0.33±0.01a	1.36±0.03a	75±0.63a

Values followed by different letter(s) within a column are significantly different at p ≤ 5% (± indicates SE). In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K.

improvements in fruit yield can be attributed to physiological role of K in plants, as it plays a crucial role in fruit yield by enhancing various physiological and biochemical processes (Havlin *et al.*, 2014). For example, K is essential for chlorophyll formation, leading to increased photosynthetic rates, higher carbohydrate production, and improved fruit yield (Pettigrew, 2008). Shao *et al.* (2024) also reported similar findings. Additionally, Khaskeli *et al.* (2023) also reported that K improved tomato yield by supporting photosynthesis, increasing energy levels, and aiding in nutrient translocation and water absorption in plants. However, its significance is often overlooked in Eritrean agriculture. The improvements in agronomic parameters of tomatoes might have happened because of physiological role of K in plants as it activates over 60 enzymes and is also considered a quality nutrient (Usherwood, 2015). Our findings support these facts, as all enhancements in yield attributes were attributed to the combination of VAC, BEC, and SOP. The integration of VAC or BEC with SOP provides various benefits that are not achievable using SOP alone (Abrol *et al.*, 2024).

Gaseous exchange and Net assimilation rate

The data in Table 5 show that plants receiving K from a combination of organic and synthetic sources (VAC + SOP or BEC + SOP) exhibited a 2 to 33% higher photosynthetic rate compared to plants with conventional K nutrition (SOP alone). The data also indicates that a higher share of K from organic sources led to a corresponding increase in photosynthetic rate. The highest photosynthesis rate was observed in plants that received 25% K from SOP and 75% from VAC. Stomatal conductance and transpiration rate data in Table 5 also showed significant variations due to the integrated use of K sources, with VAC and BEC at 75% K supply showing the most significant effects. Similar trends were observed in chlorophyll contents (Table 6) with an 8 to 25% increase in SPAD values due to the combined application of VAC and SOP or BEC and SOP. These improvements in photosynthetic rate and chlorophyll contents resulted in significant variations in water use efficiency (WUE). WUE values recorded from CIRUS (Figure 1) were 6 to 17% higher than values in plants without organic K (VAC, BEC). These improvements in WUE and photosynthetic rate might be attributed to the physiological role of K as it regulates the opening and closing of stomata and governs the xylem transport system (Havlin *et al.*, 2014; Usherwood, 2015). The effect of K-enriched organic manures on photosynthesis varied depending on the supply of K from organic and synthetic sources in different ratios (Table 2) as reported in literature (Saha *et al.*, 2019; Abrol *et al.*, 2024).

Studies have shown that K deficiency can decrease WUE due to increased stomatal conductance and transpiration rates (Grzebisz *et al.*, 2013; Sardans and Peñuelas, 2021; Yang *et al.*, 2023). Conversely, increased K supply can improve WUE by reducing water loss through transpiration while maintaining or increasing photosynthesis rates e.g. Pettigrew found in maize, wheat and soyabean plants that increasing K supply improved WUE by reducing transpiration rates while maintaining high photosynthesis rates (Pettigrew, 2008). These improvements might have occurred because of stress management in plants because of K nutrition because in addition to regulating stomatal behavior, K is also reported to improve plant water relations by maintaining turgor pressure and increasing drought tolerance (Praveen and Singh, 2024). K-deficient plants often have reduced turgor pressure, which can impair their ability to maintain water uptake during periods of drought stress (Cui *et al.*, 2024). The observed enhancements in K uptake and recovery efficiency during the study provide evidence that K plays a crucial role in regulating turgor pressure of plant cells and boosting stress tolerance mechanisms as also suggested by researchers (Grzebisz *et al.*, 2013; Karim *et al.*, 2017; Cui *et al.*, 2024). The improvements in yield attributes observed in the study might be attributed to the organic matter indirectly added by VAC and BEC into the soil as recently reported by Karim's team and Xia's coworkers (Karim *et al.*, 2017; Xia *et al.*, 2024). These improvements could be due to the additional supply of other nutrients from the minerals in compost, as organic manures release essential plant nutrients, including K, slowly into the soil compared to the fast release of nutrients from chemical fertilizers (Iqbal *et al.*, 2019; Xiang *et al.*, 2022; Bashir *et al.*, 2024).

Nutrient contents and chlorophyll contents

The combined use of VAC or BEC and SOP had a significant impact on plant N, P, and K concentrations (Table 6). However, there were variations in N, P, and K concentrations, likely due to the variable K supply from VAC, BEC, and SOP as indicated in Table 1. The data in Table 6 shows that the highest N, P, and K concentrations were 2.02%, 0.33% and 1.36%, respectively, observed in plants supplied with 75% of recommended K from VAC and the remaining 25%K from SOP, followed by N, P and K concentrations in plant treated with 75% K-BEC + 25% K-SOP. A comparison of organic manures revealed that VAC significantly increased the absorption of N, P, and K in plants compared to BEC (Table 6). Results also showed that VAC-based K combinations led to 7-19%, 3-14% and 9-35% higher plant N, P, and K concentrations compared to plants treated with 100% inorganic K (100% K-SOP), respectively.

BEC-based K combinations resulted in a 9-12%, 3-10%, and 7-28% increase in plant N, P and K concentrations, respectively (Table 6). The increase in N, P, and K concentrations might be attributed to improved soil health as organic manures are known to enhance soil organic matter, reduce soil pH, leading to increased N, P, and K uptake (Iqbal *et al.*, 2019). The enrichment of organic manures with K also enhanced N and P uptake due to synergistic effects. Additionally, organic manure facilitates P uptake by regulating the physiochemical properties of the rhizosphere.

K use efficiency vs integrated K nutrition management

The K concentration was used to calculate three types of K use efficiency (KUE) i.e. KAUE, KPUE, and KARE. Figure 2 illustrates the impacts of K supply from different combinations of BEC, VAC, and SOP on these forms of KUE. The data in Figure 2 shows that all forms of KUE are also affected by treatments as K content in plants was influenced. KARE and biological yield were significantly affected by the different combinations of VAC, BEC, and SOP for K nutrition in tomatoes. The combined application of organic K (VAC or BEC) and synthetic K (SOP) sources increased KAUE by 4 to 25%, KARE by 24 to 81% with a significant decrease in KPUE values (4-14%) compared to 100% K from SOP (100% K-SOP). A lower KPUE indicates efficient utilization of absorbed K in plant parts or yield. The significant decrease in KPUE suggests that organic manures enabled the plants to use the absorbed K from the root to fruit production, leading to higher fruit yield and profitability of the K applied. A higher biological yield (Figure 2) resulted in increased KARE and KAUE, contributing to a significant enhancement in the fruit yield of tomato plants.

The sufficient supply of K from various combinations of VAC or BEC and SOP likely played a significant role in chlorophyll synthesis, as potassium nutrition significantly improved the N and P contents (Table 6) and also WUE (Figure 1). The increase in fruit yield per plant may be attributed to improvements in yield attributes and effective K utilization due to integrated use of organic and inorganic sources. Variations in biological yield shown in Figure 2 were likely due to the variable K supply from BEC or VAC,

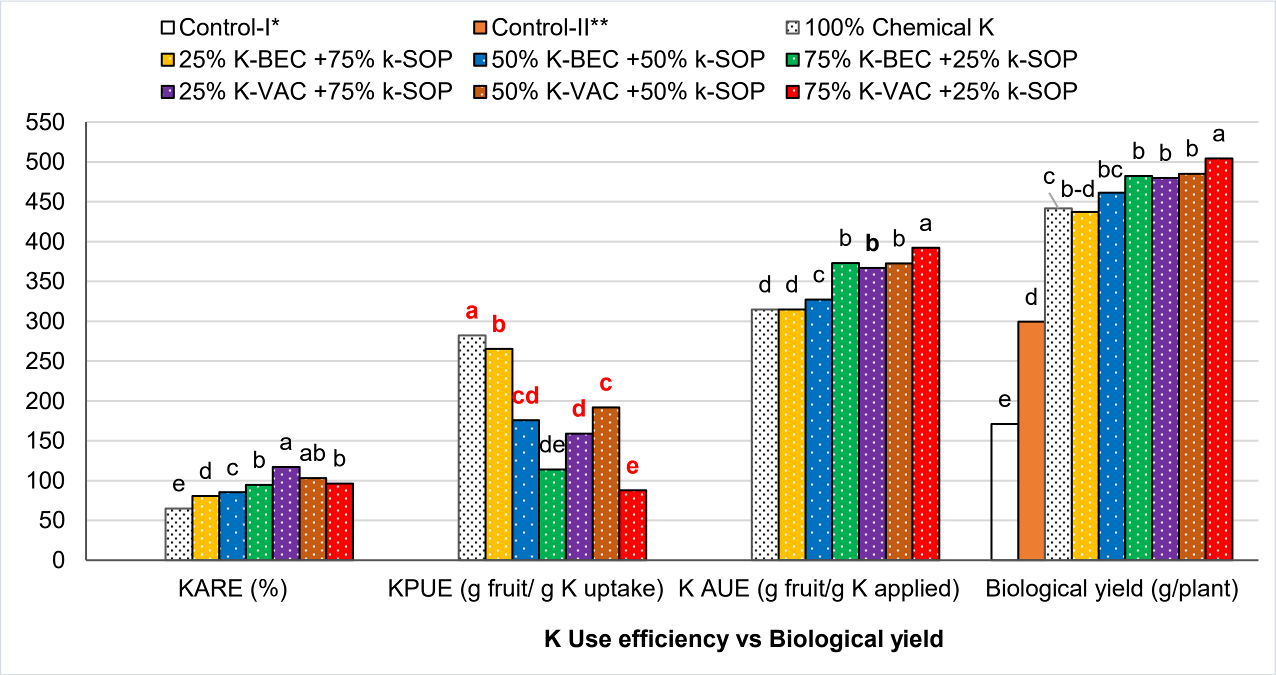


Figure 2: Integrated effects of organic and inorganic potassium sources on different forms of potassium use efficiency in tomato (two-year mean)

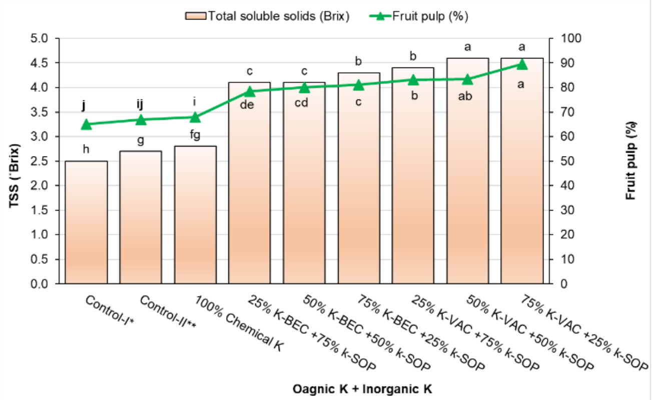
Bars with different letter(s) within a parameter indicate significant differences at $p \leq 5\%$. In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K. Whereas KARE = Potassium apparent recovery efficiency, KPUE = Potassium physiological use efficiency and KAUE = Potassium agronomic use efficiency.

as suggested by previous studies. Organic manure also improves soil structure, increases soil fertility, and enhances K uptake by plants (Xiang *et al.*, 2022). This, in turn, improves the soil's water-holding capacity (Yang *et al.*, 2023), reduces the risk of water stress (Grzebisz *et al.*, 2013), and enhances the plant's ability to take up K and other nutrients (Dai *et al.*, 2024; Shao *et al.*, 2024).

Fruit TSS, Fruit Pulp, Lycopene, and Ascorbic acid contents

Tomato is termed as a quality nutrient as it regulates ≥ 60 enzyme activations (Havlin *et al.*, 2014). The results presented in Figure 3 show that different combinations of organic and inorganic K sources significantly enhanced fruit quality parameters of tomatoes such as total soluble solids (TSS) and pulp characteristics of the fruit.

TSS is a measure of the sugar content in fruits and is an important indicator of fruit quality and flavor. The TSS of tomato fruits of the plants treated with 100% K-SOP was 2.8 Brix°, but it ranged from 4.4 to 4.6 Brix° (58 to 64% higher than Control-II) in fruits treated with different combinations of K-VAC and K-SOP. Similarly, TSS in BEC and SOP combinations ranged from 4.1 to 4.3 Brix° compared to 2.8 Brix° in K-SOP alone. Organic K sources with SOP induced 46 to 64% higher TSS than inorganic K source alone (Figure 3).



Bars or line marks with different letter(s) within a parameter indicate significant differences at p ≤ 5%. In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively, to eliminate their effect on tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K. Whereas TTS = total soluble solids of tomato fruit.

Figure 1: Integrated effects of organic and inorganic potassium sources on total soluble solids and fruit pulp content of tomato fruits (two-year mean)

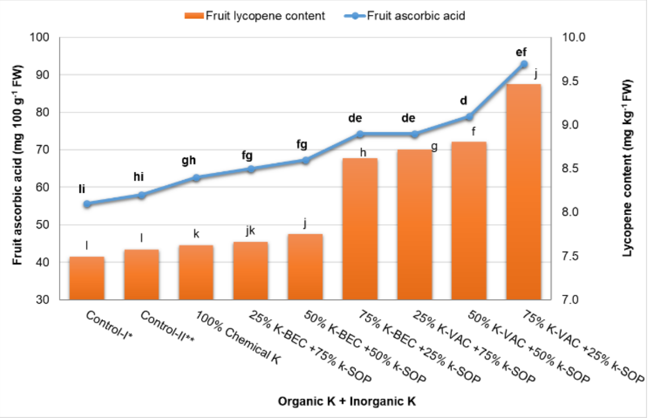


Figure 4: Integrated effects of organic and inorganic potassium sources on lycopene and ascorbic acid concentrations in tomato fruits (two-year mean)

Bars or line marks with different letter(s) within a parameter indicate significant differences at p ≤ 5%. In all treatments except Control-I, N and P were applied at 150 and 100 kg ha^{-1}, respectively to eliminate their effect tomato growth and yield. *Control-I: no chemical fertilizer, manure, or amendment; *Control-II: N and P applied without K. The quantities of BEC and VAC were calculated based on their K contents to substitute 25, 50 or 75% of inorganic K

Potassium plays a critical role in regulating sugar metabolism in plants, and adequate K supply improves TSS accumulation in fruits (Usherwood, 2015) e.g. Afzal *et al.* (2015) found that increasing K supply increased TSS levels in the fruit by enhancing sugar translocation from leaves to the fruit. The integrated use of K from VAC or BEC and SOP also significantly affected fruit pulp content. However, variations in fruit pulp were observed, which might be due to variable K supply from VAC, BEC, and SOP (Figure 3). It was noted that the highest fruit pulp occurred in plants treated with 25% K-SOP + 75% K- VAC. A comparison of VAC and BEC combinations with SOP showed that VAC induced significantly more fruit pulp compared to BEC (Figure 3). Overall, plants treated with BEC+SOP or VAC+SOP enhanced fruit pulp by 15 to 32% compared to SOP alone. Similar findings were also observed for lycopene contents and ascorbic acid contents, as shown in Figure 4. The fruits of plants treated with VAC+SOP had 57 to 92% higher lycopene contents compared to SOP alone while fruits of plants treated with BEC+SOP showed 2 to 52% more lycopene content than that of SOP alone (Figure 4). The treatments also enhanced ascorbic acid content compared to SOP alone, which was 2 to 15% higher than control-II (SOP alone). These improvements in lycopene and ascorbic acid contents might be due to the slow and steady release of nutrients from the manures, stimulating the enzymatic activity involved in lycopene synthesis. These improvements might be due to better soil health that might have led to an increased accumulation of lycopene, TSS and ascorbic acid in fruits (Çolpan *et al.*, 2013).

Results indicate that VAC based combinations performed better than BEC based combinations as VAC had more K content than that of BEC. Applying compost to soil is well reported to enhance fruit quality by improving size, firmness, sugar content, and antioxidant levels, while also increasing overall yield. Compost benefits soil structure, water retention, and aeration, creating a healthier environment for fruit trees or plants. It contains beneficial bacteria and fungi that aid in nutrient uptake and protect against soilborne diseases, resulting in larger fruit and higher yields. K is crucial for fruit quality, influencing size, firmness, color, and sugar content. It plays a vital role in cell division and expansion, directly impacting fruit size and firmness. It also helps in sugar synthesis and translocation, enhancing sweetness and flavor. Adequate K levels improve plant health and disease resistance, regulating water movement within the plant for proper fruit development and preventing disorders like cracking. While nitrogen and phosphorus are essential for plant growth, their effects on fruit quality are more indirect. Nitrogen is necessary for growth and yield, but excess nitrogen can negatively impact fruit quality. Phosphorus is vital for root development and energy transfer, with a less direct impact on fruit quality compared to K. In conclusion, compost is a valuable tool for improving fruit quality and promoting sustainable agriculture by enhancing soil health, providing essential nutrients, and fostering beneficial microorganisms for healthier, more flavorful, and more nutritious fruits.

Conclusion

Most composts are enriched with N and P, but there is often little focus on enriching these composts with K. K is termed as a quality nutrient and is well known for enhancing crop quality parameters. Composts enriched with K have the potential to mitigate abiotic stress on yield and fruit quality. It is important to calculate the application rate of compost or organic manure based on the nutrient contents present in compost or manure, especially for nutrients like K, to effectively manage integrated nutrient systems. This study demonstrated that using compost enriched with K, such as VAC or BEC along with SOP, significantly increased K recovery efficiency by 64 to 81% compared to SOP alone. This efficient utilization of applied K led to a 3 to 17% improvement in tomato yield compared to the conventional approach of using SOP alone. Additionally, fruit quality parameters such as total soluble solids (TSS), fruit pulp, ascorbic acid, and lycopene contents were also enhanced by integrated use of organic and inorganic K sources. The results suggest that incorporating at least 25% of the recommended K from organic manure can yield optimal results. Supplying up to 75% of the recommended K from organic sources, particularly K-enriched VAC, had the greatest impact on yield and fertilizer use efficiency. This will not only improve the farmer's yield with quality but also reduce fertilizer input cost due to significant improvement in KUE. Integrating VAC and BEC into nutrient management practices can reduce reliance on chemical fertilizers, but further research is needed to fully explore this approach. This study establishes a baseline for growing high quality tomatoes in a kitchen garden.

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