Hindawi
Advances in Agriculture
Volume 2023, Article ID 4717693, 14 pages
https://doi.org/10.1155/2023/4717693

Research Article

Tomato Production under Synergistic Application of Phosphate Solubilizing Bacteria and Phosphate Amendments

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Received 30 October 2022; Revised 27 January 2023; Accepted 14 February 2023; Published 1 March 2023

Academic Editor: Shakil Ahmed

Phosphate solubilizing bacteria have multi-dimensional benefits in broad host range interaction, accessing nutrients, phytohormone induction, stress alleviation, biocontrol activity, and eco-friend approach. This study aimed to evaluate the efficacy of PSB isolates coinoculated with compost, bone meal, and DAP fertilizer on tomato growth response. Tomato seeds were treated with 10 selected PSB isolates separately and grown for 20 days on seedbed, then transplanted to field that was treated with external P-sources and enriched by PSB inoculum. PSB isolates showed positive interaction and achieved significant plant assays including plant height, leaves, branches, flowers, and fruit development. Isolate K-10-41 significantly promoted tomato plant height, floral development, and fruit yield, Mk-20-7 enhanced height and fruit weight whereas K-10-27 induced tomato fruit numbers. Compost application promoted tomato-PSB interaction and induced tomato vegetative growth whereas bone meal was least promotor for most of tomato plant assays. Bone meal was however, one of the top fruit development inducers (harvested 20.94 fruits/plant weighing 881.97 gm). Mixing 50% of recommended compost and DAP fertilizer application enhanced tomato vegetative growth and fruit yield (21 fruits/plant harvested that weighed 872.46 gm). Based on the overwhelming performance, K-10-41 and Mk-20-7 application together with compost and fertilizer mixture were found effective. Therefore, the results of this study imply that application of competent PSB isolates together with nutrient supplements improved symbiotic effectiveness, sustainable production, and environmental health. Consequently, these promising isolates would be recommended for tomato production of higher yield and sustainability after verifying their efficacy at different agroecology and taxonomic identification. Screening potential strains and evaluating their competence under different conditions would be the future perspectives to develop efficient inoculants. Moreover, synergetic application of organic supplements (compost, farmyard, bone meal, or other biowastes), bioinoculants, and proper agrochemicals maximize production and environmental health and is feasible for the economic, social, and ecological sense of balance.

1. Introduction

Phosphorous (P) is one of the macro elements [1] essential to plant molecular, physiological, and structural activities [2–4]. The soil might be rich in phosphorous (400–1200 mg/kg soil) [5] although plant available phosphorus is very limited. Since soil P deficiency is often a limiting factor for crop production, application of organic matter and chemical fertilizers are common to overcome the nutrient deficiency [1, 6]. Due to the rapid fixation nature of phosphate ions, most of the applied fertilizer [2] converted to unavailable residues [7]. Different complications with the deficiency of plant available nutrients [8], the efficacy of applied chemical fertilizers and other constraints including production cost, environmental issue, and production demand calls organic matters and biological inputs for sustainable crop production [9–12]. As indicated in Rilling et al., 2019 [13] diverse microbial groups including beneficial microbes are rich in the root zone competing for root exudates. Plant growth-promoting rhizobacteria (PGPR) are considered as efficient biological inputs [14, 15] that enrich soil fertility, induce plant stress resistance, promote growth and development [16], reduce agrochemicals consumption, reduce production cost, improve crop yield, maintain environmental health [2], etc. Generally, Verma et al. 2019 [5] summarized that PGPR benefits plants in four major processes, namely, plant growth enhancement, biocontrol, stress management, and soil renovations by rhizoremediation. PSB are known PGPR [3, 12] with multidimensional benefits [17] including broad host range interaction, accessing nutrients, phytohormone induction, stress alleviation, biocontrol activity, resistance enhancement, and eco-friendly approach [8].

Application of efficient PSB strains [18] effectively colonize the root zone [5, 14] to solubilize phosphate composites and make them accessible for plants which perchance supplement or replace synthetic fertilizer [19–21]. Phosphatase enzymes and organic acids production are employed to facilitate the solubilization of insoluble phosphate groups [9]. Repeated inoculation of efficient phosphate solubilizing bacteria (PSB) strains eventually leads to successful colonization and richness of beneficial microbes [18]. As demonstrated by Kalayu, 2019 [19] and Sharma et al. 2013 [21] fortified that PSM applied as a supplement or alternative to synthetic fertilizer. The application of efficient strain together with proper agricultural inputs drives the attention of fruitful production. Currently, potential strains are amended with organic matter, cell protectants, and nanoparticles to increase their survival and efficacy [2].

Most arable lands of Ethiopia are poorly managed and have lost soil fertility [22]. Farmers have been traditional farming practices that might have contributed to strong soil fertility depletion and low productivity. As a result, smallholder farmers increased fertilizer application season-to-season [23]. Though, the production cost is heightened [12], soil fertility maintenance (nutrient amendment) and proper farm practice (ploughing, irrigation, conservation and weeding) are essential to increase production. Despite the increasing trends overtime, the proper chemical fertilizers application rate is relatively low [24]. For instance, Etissa et al. 2013 [6] reported that 51.5% of vegetable farms in the Central Rift Valley (which is one of the top vegetables producing area in the country) needs immediate amendments. Accordingly, farmers applied maximum fertilizer dose (200–800 kg/ha DAP) for tomato and onion production. The impacts of this overrated and unwise fertilizer application were narrated by Girshe et al., 2018 [25] in the way of economical loss, environmental pollution, soil fertility deterioration, and residue accumulation. The defective application might be attributable to a lack of proper fertilizers recommendation, climatic shocks, environmental risks, economical barriers, and limited awareness of smallholder farmers [24]. Moreover, most smallholder farmers practiced poor organic matter application trends due to competition for feed, cooking fuel, construction, and bedding purposes alongside substandard chemical fertilizer uses irrespective of the crops, soil nutrients composition, landscape, and rainfall gradients which led to poor crop response and production [23]. Tomato is one of the most agrochemicals consuming crops. Tomato production in Ethiopia is increased from time to time. The production and yield are low compared to other tomato-producing regions due to low fertility maintenance [25], inputs, poor infestation, and farm management [26]. Since tomato is vulnerable to various stresses [15], it showed minimal tolerance for different challenges. As a result, it requires continuous supervision/monitoring, proper infestation control [27], fertility maintenance (nutrient amendment), optimum growing conditions, and conducive environment, etc.

This study focused on cheap, affordable, and easily available tomato fertilization to replace or supplement traditional farm practices. Efficient phosphate solubilizing microbes (PSM) can supplement about 30–35 kg/ha of P_2O_5 [7]. As it indicated in Khan, 2015 [8] most soils have less organic matter, as a result complementing organic matters (compost, farmyard, or other organic wastes) and bioinoculants (biofertilizers and growth promoters) alongside recommended fertilizer rates can help to achieve the expected crop production in a sustainable manner. Previous reports on tomato inoculation with PSB [8, 15] indicated production increment, disease resistance, stress resistance, and lessened production cost. Similarly, Poonia and Dhaka, 2012 [28] have reported encouraging results after the application of PSB inoculum on tomato together with appropriate fertilizer rate. In Ethiopia, different studies have been conducted so far to screen PSB isolates from different crops and agroecology. However, the efficacy of a very limited number of isolates is attested at greenhouse and field level. Similarly, limited or no organic supplements like bone meal and compost application have been evaluated on tomato production. Therefore, this study aimed to evaluate the efficacy of PSB isolates coinoculated with compost, bone meal, and DAP fertilizer on tomato growth and yield. It is designed to reduce the agrochemicals consumption, to minimize farm production cost and to improve sustainable production by presenting competent bioinoculants along with nutrient supplements.

2. Material and Methods

2.1. Study Farm Preparation. The study was conducted from December 2021–February 2022 using irrigation (it was dry season) at Hawassa University main campus research site, Hawassa, Ethiopia. The land was twice ploughed, well prepared then blocks arranged in RCBD design with three replications. The blocks assigned for the group of external P-source treatments (i.e., each block was partitioned in to 5 plots for the respective P-treatment) and the plots assigned for the group of rows (i.e., each plot partitioned in to 11 rows for the 10 isolates and one control). Each experimental unit was arranged 1.5 m × 60 cm with 2 m space between blocks and 30 cm distance among each tomato plant. Each block was arranged with five plots (for external P-sources: (1) compost, (2) DAP fertilizer, (3) bone meal, and (4) a mixture of 50% compost and 50% of the recommended rate of fertilizer added separately as per the recommended rate and one plot set control (no external P-source)). Mixed P-sources (50% compost and 50% DAP fertilizer mixture) reflected as an integrated means to enrich the soil and improve the response [9]. Then the plots were randomly placed into 11 rows to inoculate the 10 prescreened PSB isolates (K-1-29, K-10-27, K-10-41, Mk-1-25, Mk-13-16, Mk-20-7, Mk-20-20, Z-1-16, Z-12-20, and Z-13-4) per row separately and one row set control (inoculum free).

2.2. Inoculum Preparation and Seed Inoculation. Prescreened from the tomato rhizosphere and partially characterized, 10 PSB isolates were taken from Hawassa University Soil Microbiology Lab and refreshed with PVK broth for 48 hrs in a shaker (121 rpm) incubator. These selected 10 PSB isolates were previously isolated from rhizospheres soils collected from 3 major tomato growing areas (Koka, Meki, and Ziway Zuria) and preserved by [29] and unpublished data by the same authors. To provide uniform coating the refreshed active culture used to soak tomato seeds [2]. Familiar tomato seeds called *Galilea* (GL) variety was soaked overnight in the respective PSB isolates separately. This tomato variety was chosen for the reason that it was strongly preferred by smallholder farmers and widely cultivated due to its good fruit quality, yield, and marketability. Materials and seeds surface sterilization was conducted following the method given by [30]. After overnight soaking [3] the extra inoculum was poured and seeds had left to dry for 30 minutes, then one seed per cell/hole was sown at 2 cm depth on a seedling tray containing compost and soil mixture. Before seeds were covered by soil, 1 ml inoculum was added [9] to enrich isolate colonization and cover the seeds. The conventional seed coating [31] and seed inoculation strategies help to improve colonization and interaction [32]. Each tray labelled as per the respected PSB inoculum and let to grow in a shade for 20 days. Trays were watered every day until transplantation was held. Transplantation is common practice for tomato [6] production than direct sowing because of germination issues, weeding, and infestation control.

2.3. Tomato Transplantation and Growth Performance Recording. Twenty days grown healthy tomato plants were selected from each tray and transplanted to the farm. In doing so, the selected healthy tomato seedlings were transplanted to the respective rows then 1 ml of the corresponding active culture was inoculated before covering the root zone with soil as described by [9]. This extra inoculation would maximize root and rhizosphere colonization as well as improve indigenous competition [32]. Five tomatoes were planted per row then one week after transplantation, missing tomatoes or seedlings that failed to regenerate were replaced. Afterward, regular watering, weeding, stacking, and monitoring were conducted until harvesting. Twenty days after transplanting, all treatments were reinoculated with 1 ml culture of the corresponding PSB isolates to increase the population and to maximize the root zone colonization (i.e., to overcome indigenous competition and improve dominance). Urea was added to all treatments including control at the first date and on the 45th day of transplantation as per recommended rate. Maize was planted at the corner of the farm to serve as biological control or bordering. Data were taken from three tomato plants per row at 30, 45, 60 days of transplantation and harvesting (90 days). Plant assays like tomato height, leaf development, branch number, flower parameters, and fruit yield (number and weight) were recorded. The final total fruits were harvested after three months of maintenance of transplantation.

2.4. Data Analysis. The collected quantitative data were organized and analysed by R.4.2.1 and SAS 9.4 version software. ANOVA was conducted using Fisher's and Tukey's tests (significance set at $P \leq 0.05$). Finally, the analysed data were explained and discussed in reference to other related works.

3. Result

PSB isolates showed positive interaction with tomatoes to achieve significant plant assays against the control. For instance, the mean-variance of tomato plant height indicates significant differences among isolates and the control at different growth periods (Table 1 and Figures 1(a)–1(c))). The highest plant height was recorded by Mk-20-7 at 30 and harvesting (90) days (15 cm and 67 cm, respectively), K-10-41 at 45 days (41 cm) and Mk-1-25 recorded 56 cm at 60 days whereas inoculum-free (control) tomatoes recorded the least average height at 30, 45 and 60 days of transplantation (Table 1). Similarly, supplemented P-sources showed significant differences among the treatments where the prominent tomato height was recorded from compost application at early growth stage whereas compost and fertilizer mixture improved at later growth periods (Table 1).

3.1. Tomatoes Leaves, Branches, and Floral Development. Application of PSB isolates together with external P-supplements showed positive results on tomato leaves and floral development. Analysing the leaf number mean-variance indicated that isolates significantly improved tomato leaf development over the control (Figures 2(a) and 2(b))). According to the three (30, 45, and 60) days of collected data (Table 2), the control (uninoculated tomatoes) recorded a minimum average number of leaves (5.4 and 11.05 at 30 and 60 days, respectively) whereas Z-12-20 inoculated tomatoes developed more leaves (7.43 and 11.37) at 30 and 45 days respectively and Mk-1-25 generated highest leaves (12.6) at 60 days after transplantation which were contemplated as the active growth periods. Likewise, the addition of compost promoted early-stage leaf development (7.24 at 30 days) although fertilizer induced at the middle growth stages (45 days) and mixed application of 50% the recommended fertilizer and compost induced more tomato leaves (12.32) development at 60 days (Table 2).

Tomato branch, flower bud development, and flower openings were significantly improved by joint application of PSB isolates and P-treatments. Inoculation of isolates stimulated tomato development at distinct levels at different growth periods, relatively the maximum number of tomato branches (4.9, 5.55 and 6.57) developed by inoculation of Mk-1-25, Z-13-4, and K-10-41 at 30, 45, and 60 days of

Table 1: Tomato plant height (cm) at different growth periods.

Isolate	30 days	45 days	60 days	Harvest
Control	12.3 ± 2.43^{c}	35.23 ± 6.77^{c}	47.45 ± 6.02^{c}	65.07 ± 9.45^{a}
K-1-29	14.32 ± 3.36^{ab}	39.74 ± 6.98^{ab}	54.89 ± 5.7^{ab}	65.27 ± 8.95^{a}
K-10-27	14.82 ± 2.86^{ab}	39.4 ± 8.76^{ab}	52.48 ± 6.04^{b}	63.73 ± 6.89^{a}
K-10-41	14.47 ± 3.21^{ab}	41.25 ± 6.22^{a}	53.12 ± 5.66^{ab}	61.73 ± 6.38^{a}
Mk-1-25	14.65 ± 2.52^{ab}	39.88 ± 6.84^{ab}	56.57 ± 6.35^{a}	65.53 ± 6.41^{a}
Mk-13-16	14.22 ± 3.84^{ab}	40.1 ± 8.2^{ab}	54.02 ± 6.83^{ab}	64.4 ± 8.06^{a}
Mk-20-20	14.23 ± 3.51^{ab}	38.57 ± 8.61^{ab}	53.55 ± 7.2^{ab}	65.2 ± 6.67^{a}
Mk-20-7	15.12 ± 3.71^{a}	39.45 ± 9.28^{ab}	54.2 ± 7.48^{ab}	67.2 ± 14.67^{a}
Z-1-16	14.48 ± 3.16^{ab}	39.04 ± 8.99^{ab}	53.5 ± 7.1^{ab}	64.4 ± 7.47^{a}
Z-12-20	15.15 ± 2.73^{a}	40.0 ± 6.96^{ab}	55.5 ± 5.05^{b}	63.67 ± 7.82^{a}
Z-13-4	13.62 ± 3.31^{bc}	37.79 ± 9.64^{bc}	52.64 ± 7.83^{b}	65.27 ± 6.57^{a}
CV	13.13	10.45	9.62	13.0
LSD	1.36	2.952	3.71	6.07
P-supplements				
BM	14.16 ± 2.83^{b}	38.67 ± 6.54^{ab}	52.56 ± 6.48^{a}	64.79 ± 10.52^{ab}
Compost	15.24 ± 3.94^{a}	40.27 ± 8.42^{a}	53.02 ± 6.41^{a}	63.12 ± 6.17^{b}
Fert	13.68 ± 2.65^{b}	39.83 ± 6.53^{a}	54.34 ± 5.99^{a}	64.09 ± 5.70^{ab}
Fert and comp	14.1 ± 3.1^{b}	37.57 ± 9.63^{b}	53.49 ± 8.25^{a}	67.39 ± 9.47^{a}
Soil	14.36 ± 3.17^{ab}	39.33 ± 8.17^{ab}	54.83 ± 6.24^{a}	64.27 ± 8.39^{ab}
CV	12.99	10.45	9.62	13.0
LSD	0.92	1.99	2.5	4.1

*Means with similar letters has no significant difference at $P < 0.05$.

transplantation, respectively (Table 3). Flower bud number substantially improved by compost supplementation aside from inoculation of Mk-1-25 and Mk-20-20 at 30 and 45 days respectively (Table 3). Similarly, early flower opening, and the total number of opened flowers were significantly induced by compost application and inoculation of K-1-29 (Table 4).

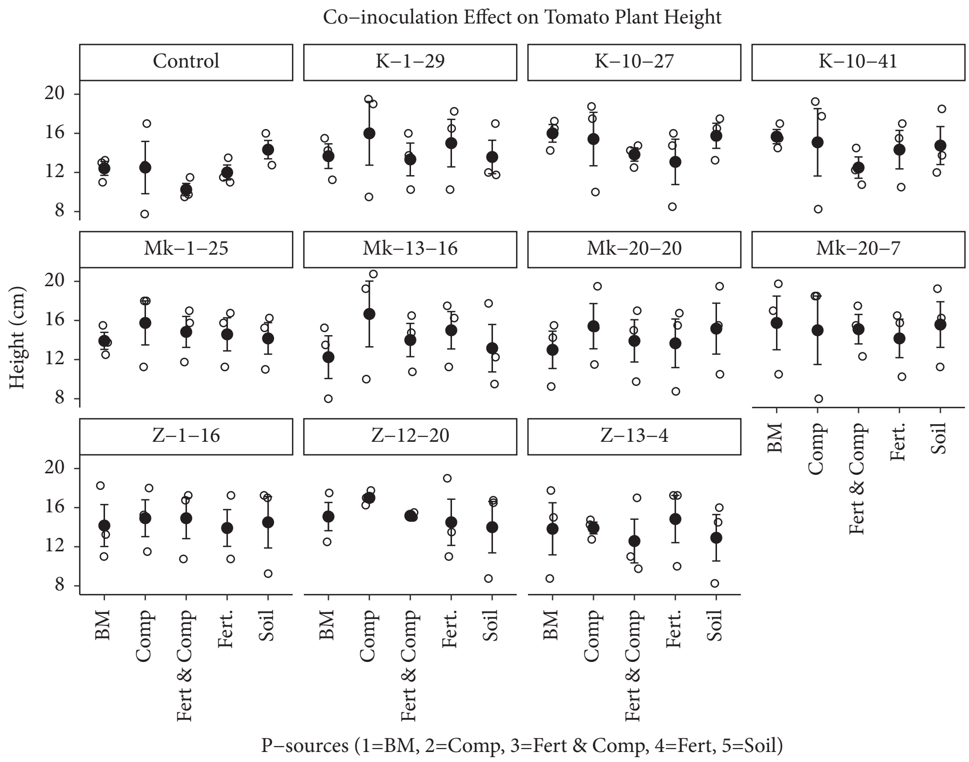
4. Fruit Yield

Starting on 60 days of transplantation, damaged and 50% matured fruits were harvested from three tomato plants per row with frequent farm monitoring (Figure 3). At the time of final harvesting (90 days after transplantation), total fruit number, size, and weight variation were observed (Tables 5 and 6). Even if tomatoes were not faced observable impairment by any infestation, a considerable number of fruits were damaged by blossom end rot. This physiological disorder might be due to the water shortage and limitation (irregular watering time and amount because of supply fluctuation). This irrigation instability resulted in a significant number of unmarketable tomato fruits and loss (Table 5). The total amount of mean fruit variance indicated that K-10-41 inoculated tomatoes induced to produce the highest tomato fruit number (65.6) with significant marketable fruits (31.27). On the other hand, inoculation of K-10-27 produced the second highest (65.47) average fruit number with a considerable amount (37.47) of unmarketable fruits, whereas Mk-20-7 produced a maximum (31.33) marketable fruits and the least (28.07) number of unmarketable fruits (Table 5 and Figure 4). Similarly, K-1-29 ranked the 3rd inoculum in terms of total fruit number (63.93) and number of marketable (30) fruits. Though fruit weight was not exacerbated among isolates, inoculation showed considerable improvement against the control. K-10-41 recorded the maximum overall average fruit weight (2821.6 gm) followed by k-1-29 (2793.3 gm) (Table 5).

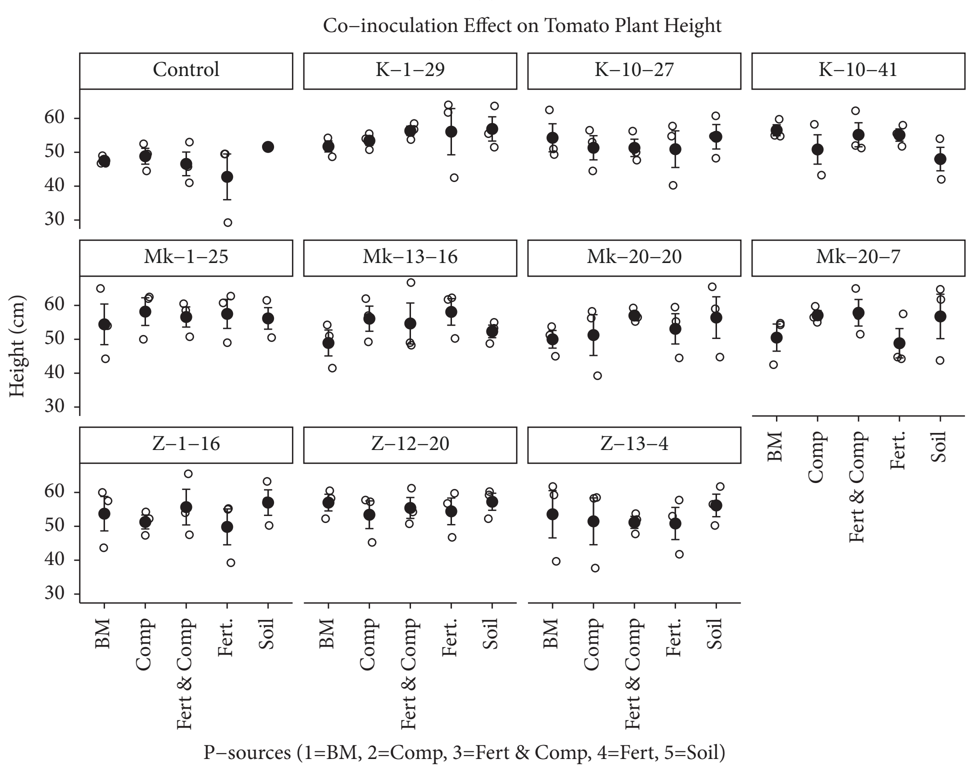
Application of external P-sources promoted tomato-PSB interaction and response and increased fruit yield (Figure 4). For instance, compost application promoted most tomato growth parameters (plant height, flower buds, and flower opening) nevertheless it resulted in the least fruit number (57.88) and the minimum fruit weight (2456 gm) records. Quite the reverse, the bone meal was the least promotor for most tomato plant assays, but it was one of the top fruit development inducers (in average, 20.94 fruits per plant were harvested that recorded the highest fruit weight of 2645.91 gm) (Table 5 and Figure 4). Generally, bone meal and the mixture of 50% of the recommended compost and fertilizer showed a significant effect on overall tomato fruit yield while fertilizer application recorded the least number of unmarketable fruits which might suggest that fertilizer promotes healthy/marketable fruit production next to bone meal.

5. Discussion

According to Manzoore et al., 2017 [20] the application of PSB, rock phosphate, compost, manure or fertilizers increased the amount of P that is accessible to plants. In this field trial, PSB and external P-sources were used in conjunction to tomato growth and yield performance. Based on their prior laboratory and greenhouse performance, a total of 10 PSB isolates were chosen, and they were coinoculated with three distinct supplemental P-sources (compost, bone meal (BM), and synthetic fertilizer). Four growth periods (30, 45, 60, and 90 days) were used after tomato transplantation to evaluate the overall growth and development as well as tomato fruit yield.

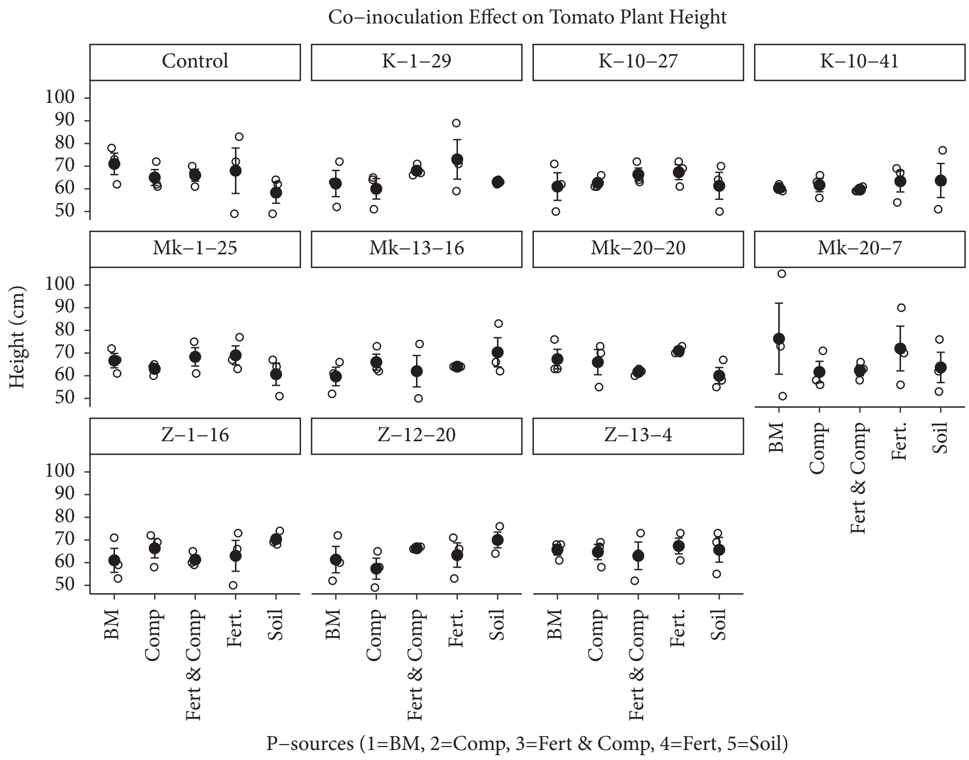


(a)



(b)

Figure 1: Continued.

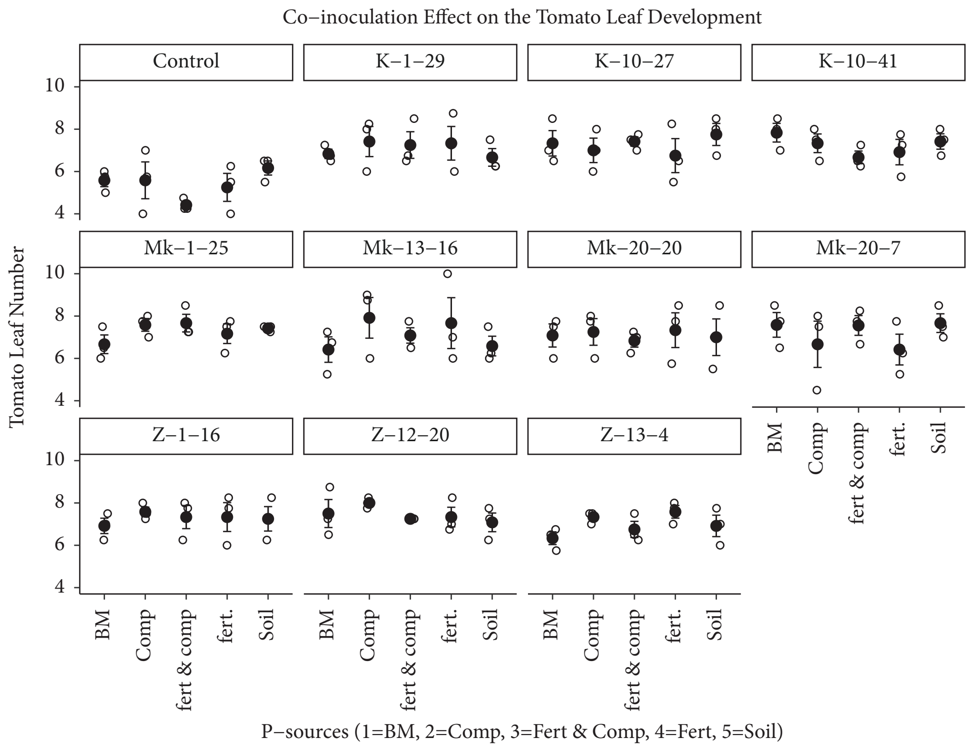


(c)

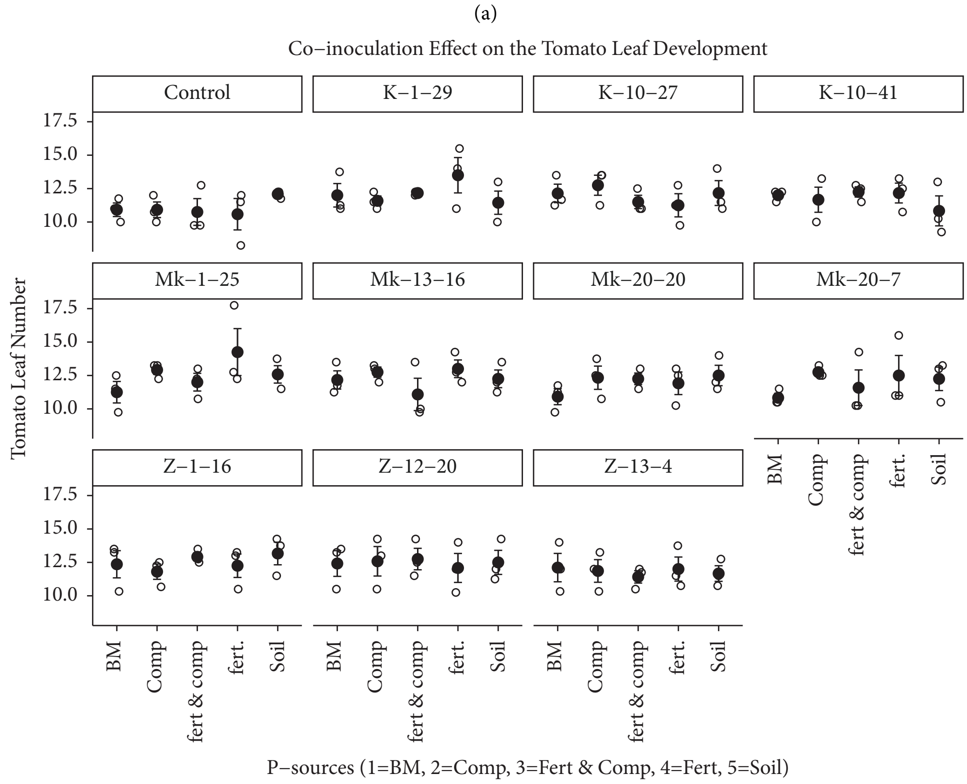
Figure 1: Tomato plant height at different growth periods ((a) = 30 days, (b) = 60 days and (c) = 90 (Harvesting) days) of transplantation. The plant co-inoculated with PSB isolate and external P-supplements.

As shown by Verma et al., 2019 [5] chemical fertilizers control around 95% of the global fertilizer market share, with biofertilizers accounting for the remaining 5%. Plant growth-promoting characteristics were used to filter potential biofertilizer strains from the rhizosphere [2]. Hierarchical screening procedures (lab screening, greenhouse authentication and field evaluation) help to select efficient PSB inoculum. Despite *in vivo* solubilization and greenhouse promotions, PSB application under field conditions is very limited. Laboratory screening, greenhouse, and field trials were used to analyse the effectiveness of PGPR [14]. For a strain to become effective, it should possess good competence, persistence, and stabilization under the provided environmental conditions. Open field evaluation and efficacy confirmation experiments often give a good picture for maximal exploitation of efficient strains. As shown by Kirui et al., 2022 [12] and Khan, 2015 [8] once potential isolates are screened, they would be inoculated into the soil, then stabilize sustainable production and minimize production cost. Given the fact that open field cultivation is exposed to a stressful environment as demonstrated by Bai et al., 2013 [27], the true potential evaluation and efficiency verification provides a practical figure of whether the selected strain is competent or incompetent before distributing to the farmers. Likewise, De Zutter et al., 2022 [31] underlined that field trial is mandatory because most (>90%) of the PSB symbiotic effectiveness studies conducted under greenhouse become unsatisfactory and less effective when tested on field trials. Inoculation of competent PSB strains successfully colonized the root zone and enriched the rhizosphere while some strains failed to succeed [18]. Moreover, it is essential to prove their efficiency and symbiotic effectiveness under various field conditions. This is due to the fact that the environment and soil characteristics have a significant impact on the success of PSM establishment and performance [10, 21]. The interaction and response of inoculants are influenced by plant type, growth stage, root exudates composition, hormone signalling, native microbiota, and climatic conditions [11]. Similarly, Rilling et al., 2019 [13] indicated that PGPR performance should be demonstrated in different soil, crop- and agro-ecological circumstances.

In this study, PSB isolates were inoculated to tomato seeds and root zone to promote inoculum interaction and colonization intended for better stimulation of tomato growth and fruit yield. Supportive publication from De Zutter et al., 2022 [31] described that soil drench, root dip, spray and seed coating mechanisms were used to apply PSB strains nevertheless seed coating and root dip predominantly increased P-uptake and plant biomass. A sympathetic study by Pellegrini et al., 2021 [32] on *Allium cepa* L. showed seed inoculation approach is considered the proven strategy to stabilize inoculum and improve cultivation. In a similar fashion, Egamberdieva et al. 2015 [4] specified that tomato seed inoculation with PGPR have resulted in the induction of wilt resistance both in field and greenhouse trials. Poonia and Dhaka, 2012 [28] also



(a)



(b)

Figure 2: Tomato leaves development at different growth periods ((a) = 30 days, (b) = 60 days) of transplantation.

found PSB inoculation of soil and tomato root (seedling) dip together with the recommended fertilizer rate improved tomato growth and yield. Amaya-Gómez et al., 2020 [14] indicated that successful colonization of the root surface and vicinity (rhizosphere) by the inoculum leads to the release of different compounds that promote plant-bacteria interaction and synchronization and confront indigenous microbes and enhance plant growth.

Table 2: Tomato leaf development at different growth periods.

Isolate	30 days	45 days	60 days
Control	5.4 ± 0.98[b]	10.82 + 0.71[abc]	11.05 + 1.26[c]
K-1-29	7.1 ± 0.92[a]	10.77 + 1.14[abc]	12.14 + 1.43[ab]
K-10-27	7.25 ± 0.92[a]	10.48 + 1.26[bc]	11.96 + 1.24[ab]
K-10-41	7.23 ± 0.77[a]	10.85 + 1.46[abc]	11.78 + 1.24[bc]
Mk-1-25	7.3 ± 0.66[a]	11.2 + 2.24[ab]	12.6 + 1.76[a]
Mk-13-16	7.13 ± 1.3[a]	11.23 + 1.02[ab]	12.25 + 1.32[ab]
Mk-20-20	7.1 ± 0.99[a]	11.02 + 1.5[abc]	11.98 + 1.21[ab]
Mk-20-7	7.18 ± 1.66[a]	10.87 + 0.93[abc]	11.98 + 1.63[ab]
Z-1-16	7.28 ± 0.77[a]	10.22 + 1.18[c]	12.5 + 1.23[ab]
Z-12-20	7.43 ± 0.69[a]	11.37 + 1.24[a]	12.45 + 1.2[ab]
Z-13-4	6.98 ± 0.69[a]	11.25 + 1.63[ab]	11.81 + 11.25[abc]
CV	9.91	10.27	9.18
LSD	0.50	0.81	0.8
P-treatments			
BM	6.92 ± 0.94[a]	10.98 + 1.37[ab]	11.74 + 1.23[b]
Compost	7.24 ± 1.12[a]	10.68 + 1.56[b]	12.17 + 1.17[ab]
Fert	6.93 + 1.03[a]	11.17 + 1.86[a]	11.88 + 1.26[ab]
Fert and comp	7.01 ± 1.23[a]	10.86 + 1.15[ab]	12.32 + 1.87[a]
Soil	7.08 ± 0.85[a]	10.88 + 1.13[ab]	12.13 + 1.3[ab]
CV	9.91	10.27	9.18
LSD	0.34	0.55	0.54

*Means with similar letters has no significant difference at $P < 0.05$.

Table 3: Tomato branch and flower bud development at various growth periods.

	Branch development			Flower bud development		
Isolate	30 days	45 days	60 days	30 days	45 days	60 days
Control	3.5 ± 1.22[b]	3.67 + 1.01[f]	5.43 ± 1.12[ab]	5.98 ± 1.69[ab]	0.75 ± 0.62[ab]	10.82 ± 2.45[a]
K-1-29	4.32 ± 1.11[a]	4.66 + 1.15[bcde]	5.75 ± 0.94[ab]	5.37 ± 1.83[abc]	0.77 ± 0.47[ab]	10.4 ± 1.91[ab]
K-10-27	4.4 ± 1.38[a]	4.53 + 076[cde]	5.77 ± 2.45[ab]	5.07 ± 1.89[abc]	0.67 ± 0.41[ab]	10.51 ± 2.28[ab]
K-10-41	4.77 ± 0.92[a]	4.84 + 1.24[bcd]	6.57 ± 3.94[a]	5.58 ± 1.35[abc]	0.77 ± 0.53[ab]	10.83 ± 1.49[a]
Mk-1-25	4.9 ± 1.11[a]	4.96 + 1.08[bc]	6.27 ± 2.12[ab]	5.23 ± 1.54[abc]	0.83 ± 0.42[a]	10.82 ± 2.32[a]
Mk-13-16	4.87 ± 1.22[a]	4.97 + 0.81[bc]	5.42 ± 0.74[ab]	5.17 ± 1.91[abc]	0.62 ± 0.52[ab]	10.06 ± 2.42[ab]
Mk-20-20	4.84 ± 1.58[a]	4.32 + 1.33[de]	5.42 ± 0.97[ab]	6.29 ± 5.33[a]	0.73 ± 0.45[ab]	10.23 ± 2.61[ab]
Mk-20-7	4.42 ± 1.02[a]	4.52 + 1.22[cde]	5.12 ± 0.71[b]	4.83 ± 2.21[bc]	0.73 ± 0.57[ab]	9.8 ± 1.88[ab]
Z-1-1	4.31 ± 1.30[a]	4.27 ± 1.0[ef]	6.15 ± 2.29[ab]	5.25 ± 1.98[abc]	0.62 ± 0.49[ab]	10.1 ± 2.42[ab]
Z-12-20	4.88 ± 0.97[a]	5.12 ± 1.08[ab]	5.28 ± 1.03[b]	5.28 ± 1.51[abc]	0.77 ± 0.4[ab]	10.78 ± 1.89[a]
Z-13-4	4.63 ± 0.98[a]	5.55 ± 1.54[a]	5.6 ± 1.09[ab]	4.53 ± 1.74[c]	0.57 ± 0.43[b]	9.25 ± 1.22[b]
CV	17.04	16.63	30.83	32.22	51.62	18.77
LSD	0.57	0.56	1.27	1.24	0.27	1.39
P-treatment						
BM	4.45 ± 0.91[bc]	4.71 ± 1.11[ab]	5.09 + 0.88[b]	0.65 ± 0.42[b]	4.81 ± 1.58[bc]	9.4 ± 1.9[c]
Compost	4.67 ± 1.3[b]	4.47 ± 1.44[b]	5.35 + 0.89[b]	0.89 ± 0.58[a]	6.11 ± 3.6[a]	10.30 ± 1.69[abc]
Fert	4.66 ± 1.14[b]	4.49 ± 1.45[b]	5.73 + 1.04[b]	0.65 ± 0.43[b]	5.49 ± 1.47[ab]	10.67 ± 1.74[ab]
Fert and Comp	4.12 ± 1.12[c]	4.85 ± 1.15[a]	5.41 + 1.58[b]	0.64 ± 0.46[b]	4.17 ± 1.58[c]	9.88 ± 2.57[bc]
Soil	5.15 ± 1.35[a]	4.78 ± 1.36[ab]	6.87 + 3.21[a]	0.73 ± 0.47[ab]	6.05 ± 2.12[a]	11.13 ± 2.2[a]
CV	16.55	16.63	30.83	51.62	32.22	18.77
LSD	0.382	0.38	0.85	0.18	0.84	0.938

*Means with similar letters has no significant difference at $P < 0.05$.

In the present study, PSB inoculation of tomatoes showed a significant difference over the control and among the added P-substrates. For instance, tomato plant height was strongly promoted by Z-12-20, Mk-1-25, and Mk-20-7 (Table 1), the number of leaves, branches, and flower buds development were encouraged by Mk-20-20, Mk-1-25, and K-10-41 (Tables 2–4) and fruits development was enhanced by K-10-41, Mk-20-7, and K-10-27 (Tables 5 and 6). Comparable studies demonstrated that PSB strains inoculation such as N3 [15], and MBP 2.1 [33] improved tomato growth parameters (plant height, root length, chlorophyll content, and biomass). The possible reason is perhaps that the PSB stimulated tomato by enhancing P-access, growth hormone production, and biocontrol activity and by reducing toxic chemicals absorption and accumulation in the shoot as well as roots. In line with this, Khan

Table 4: Tomato total number of open flowers.

Isolate	30 days	45 days	60 days
Control	0.13 ± 0.23^{ab}	$1.53 + 0.91^{c}$	$8.18 + 3.78^{a}$
K-1-29	0.21 ± 0.38^{a}	$2.52 + 1.49^{a}$	$9.88 + 3.62^{a}$
K-10-27	0.07 ± 0.18^{ab}	$1.78 + 1.24^{bc}$	$8.39 + 4.36^{a}$
K-10-41	0.00^{b}	$2.61 + 1.54^{a}$	$9.48 + 3.89^{a}$
Mk-1-25	0.13 ± 0.3^{ab}	$2.45 + 1.71^{ab}$	$9.33 + 3.84^{a}$
Mk-13-16	0.07 ± 0.18^{ab}	$2.02 + 1.06^{abc}$	$8.93 + 4.86^{a}$
Mk-20-20	0.2 ± 0.37^{a}	$1.98 + 1.22^{abc}$	$8.77 + 5.01^{a}$
Mk-20-7	0.1 ± 0.28^{ab}	$2.22 + 1.6^{abc}$	$8.1 + 3.9^{a}$
Z-1-16	0.1 ± 0.28^{ab}	$2.0 + 1.84^{abc}$	$8.64 + 3.64^{a}$
Z-12-20	0.1 ± 0.28^{ab}	$2.38 + 1.49^{ab}$	$8.83 + 3.0^{a}$
Z-13-4	0.07 ± 0.18^{ab}	$2.5 + 1.66^{a}$	$8.0 + 4.3^{a}$
CV	206.73	45.0	39.05
LSD	0.18	0.71	2.24
P-treatment			
BM	0.00^{c}	$2.23 + 1.45^{ab}$	$8.69 + 4.46^{ab}$
Compost	0.31 ± 0.42^{a}	$2.4 + 1.69^{a}$	$9.72 + 3.64^{a}$
Fert	0.06 ± 0.17^{bc}	$1.82 + 1.32^{b}$	$9.12 + 3.39^{ab}$
Fert and comp	0.09 ± 0.2^{bc}	$2.2 + 1.47^{ab}$	$7.71 + 4.08^{b}$
Soil	0.14 ± 0.29^{b}	$2.27 + 1.32^{ab}$	$9.47 + 4.29^{a}$
CV	206.73	45.0	38.52
LSD	0.12	0.48	1.68

*Means with similar letters has no significant difference at $P < 0.05$.

Figure 3: PSB and P-substrate co-inoculated tomato growth progress and fruiting at open field trial.

Table 5: Tomato fruit yield.

Isolate	Marketable fruit	Unmarketable fruit	Total fruit no	Total fruit weight (gm)
Control	19.0 ± 11.77^{b}	32.0 ± 9.58^{ab}	51.0 ± 17.36^{b}	1700.0 ± 828.0^{b}
K-1-29	30.0 ± 9.78^{a}	33.93 ± 11.68^{ab}	63.93 ± 11.27^{a}	2793.3 ± 740.36^{a}
K-10-27	28.0 ± 14.72^{a}	37.47 ± 15.57^{a}	65.47 ± 20.31^{a}	2563.4 ± 900.09^{a}
K-10-41	31.27 ± 10.12^{a}	34.33 ± 13.77^{ab}	65.6 ± 19.52^{a}	2821.6 ± 765.85^{a}
Mk-1-25	24.6 ± 11.21^{ab}	34.13 ± 8.65^{ab}	58.73 ± 11.3^{ab}	2268.07 ± 825.79^{ab}
Mk-13-16	28.4 ± 16.32^{a}	31.4 ± 9.4^{ab}	59.8 ± 22.95^{ab}	2781.3 ± 1377.7^{a}
Mk-20-20	27.27 ± 12.2^{ab}	34.8 ± 15.09^{ab}	62.07 ± 19.31^{ab}	2583.47 ± 691.21^{a}
Mk-20-7	31.33 ± 14.68^{a}	28.07 ± 9.36^{b}	59.4 ± 12.66^{ab}	2780.53 ± 964.66^{a}
Z-1-16	25.93 ± 13.51^{ab}	32.27 ± 9.58^{ab}	58.2 ± 12.35^{ab}	2507.2 ± 768.78^{a}
Z-12-20	28.73 ± 15.01^{a}	31.53 ± 9.73^{ab}	60.27 ± 15.18^{ab}	2558.4 ± 1004.15^{a}
Z-13-4	28.8 ± 12.94^{a}	30.93 ± 8.29^{ab}	59.73 ± 12.13^{ab}	2508.93 ± 838.61^{a}
CV	41.87	33.69	26.74	34.23
LSD	8.33	7.97	11.65	625.79
P-treatment				
BM	29.0 ± 17.06^{a}	33.82 ± 9.35^{a}	62.82 ± 20.61^{a}	2645.91 ± 1257.65^{a}
Compost	27.42 ± 15.39^{a}	34.46 ± 11.37^{a}	57.88 ± 16.33^{a}	2456.0 ± 1072.65^{a}
Fert	27.91 ± 11.59^{a}	31.79 ± 8.05^{a}	59.7 ± 13.41^{a}	2474.58 ± 739.31^{a}
Fert and comp	27.61 ± 9.64^{a}	34.46 ± 14.54^{a}	63.06 ± 15.67^{a}	2617.39 ± 660.3^{a}
Soil	25.94 ± 11.04^{a}	32.52 ± 11.42^{a}	58.46 ± 14.92^{a}	2472.61 ± 802.17^{a}
CV	6.02	33.69	26.74	34.23
LSD	44.89	5.38	7.85	421.9

*Means with similar letters has no significant difference at $P < 0.05$.

Table 6: Synergetic application effect of PSB isolates and external P-supplements on tomato fruit yield and fruit size.

Isolate	Fruit yield per plant	Lager fruit		Small fruit	
		Length (cm)	Width (cm)	Length (cm)	Width (cm)
Control	$17.0 + 5.79^{b}$	$9.87 + 0.99^{a}$	$18.93 + 2.12^{ab}$	$3.43 + 0.07^{abc}$	$6.57 + 1.08^{ab}$
K-1-29	$21.31 + 3.76^{a}$	$9.8 + 1.01^{a}$	$19.2 + 2.27^{ab}$	$3.17 + 0.79^{bc}$	$5.53 + 1.2^{c}$
K-10-27	$21.82 + 6.76^{a}$	$9.87 + 1.06^{a}$	$19.87 + 2.23^{a}$	$3.1 + 0.78^{c}$	$5.8 + 1.28^{bc}$
K-10-41	$21.87 + 6.51^{a}$	$10.03 + 0.86^{a}$	$19.27 + 1.67^{ab}$	$3.07 + 0.46^{c}$	$5.7 + 1.1^{bc}$
Mk-1-25	$19.58 + 3.77^{ab}$	$9.87 + 1.13^{a}$	$19.13 + 2.0^{ab}$	$3.43 + 0.75^{abc}$	$6.3 + 1.24^{abc}$
Mk-13-16	$19.93 + 7.65^{ab}$	$9.87 + 1.19^{a}$	$19.13 + 2.97^{ab}$	$3.67 + 1.08^{ab}$	$6.9 + 1.67^{a}$
Mk-20-20	$20.69 + 6.44^{ab}$	$9.8 + 0.78^{a}$	$18.2 + 2.24^{b}$	$3.73 + 0.96^{a}$	$6.93 + 1.79^{a}$
Mk-20-7	$19.8 + 4.22^{ab}$	$9.93 + 0.7^{a}$	$19.0 + 2.20^{ab}$	$3.47 + 0.92^{abc}$	$6.3 + 0.92^{abc}$
Z-1-16	$19.4 + 4.12^{ab}$	$10.0 + 0.85^{a}$	$19.27 + 2.34^{ab}$	$3.5 + 0.71^{abc}$	$6.3 + 1.27^{abc}$
Z-12-20	$20.09 + 5.06^{ab}$	$10.0 + 0.93^{a}$	$19.67 + 2.34^{ab}$	$3.67 + 1.03^{ab}$	$6.53 + 1.46^{ab}$
Z-13-4	$19.91 + 4.05^{ab}$	$9.53 + 1.06^{a}$	$18.47 + 2.13^{ab}$	$3.37 + 0.58^{abc}$	$6.33 + 0.96^{abc}$
CV	26.74	9.9	11.79	22.92	19.93
LSD	3.88	0.71	1.62	0.57	0.91
P-treatment					
BM	$20.94 + 6.87^{a}$	$10.0 + 0.97^{a}$	$18.91 + 2.47^{a}$	$3.55 + 0.94b^{a}$	$6.35 + 1.53^{ab}$
Compost	$19.29 + 5.44^{a}$	$9.85 + 0.97^{a}$	$18.88 + 1.63^{a}$	$3.35 + 0.71^{ab}$	$6.09 + 1.31^{ab}$
Fert	$19.9 + 4.47^{a}$	$9.86 + 1.07^{a}$	$19.33 + 2.01^{a}$	$3.08 + 0.69^{b}$	$5.79 + 1.27^{a}$
Fert and comp	$21.02 + 5.22^{a}$	$9.82 + 0.88^{a}$	$19.15 + 2.66^{a}$	$3.58 + 0.99^{a}$	$6.61 + 1.3^{a}$
Soil	$19.49 + 4.97^{a}$	$9.82 + 0.88^{a}$	$19.06 + 2.29^{a}$	$3.55 + 0.65^{a}$	$6.62 + 1.08^{a}$
CV	26.74	0.48	11.79	22.92	19.93
LSD	2.62	9.9	1.09	0.38	0.61

*Means with similar letters has no significant difference at $P < 0.05$.

et al., 2016 [33] have reported that PGPR promoted plant growth through a wide range of mechanisms (phytohormones production, alleviating environmental stresses, and production of secondary metabolites). A review in [1] strengthens the assumption that soil microorganisms enhance plant nutrient acquisition. In this study, tomato inoculated by Mk-20-7 recorded the highest tomato plant height mean (67.2 cm) which was greater than Etissa et al., 2013 [6] finding (59.2 cm) but lower than Poonia and Dhaka's, 2012 [28] report that found maximum tomato plant height of 86.3 cm from the complemented application of PSB and fertilizer. The Mk-20-7 isolate was also one of the top

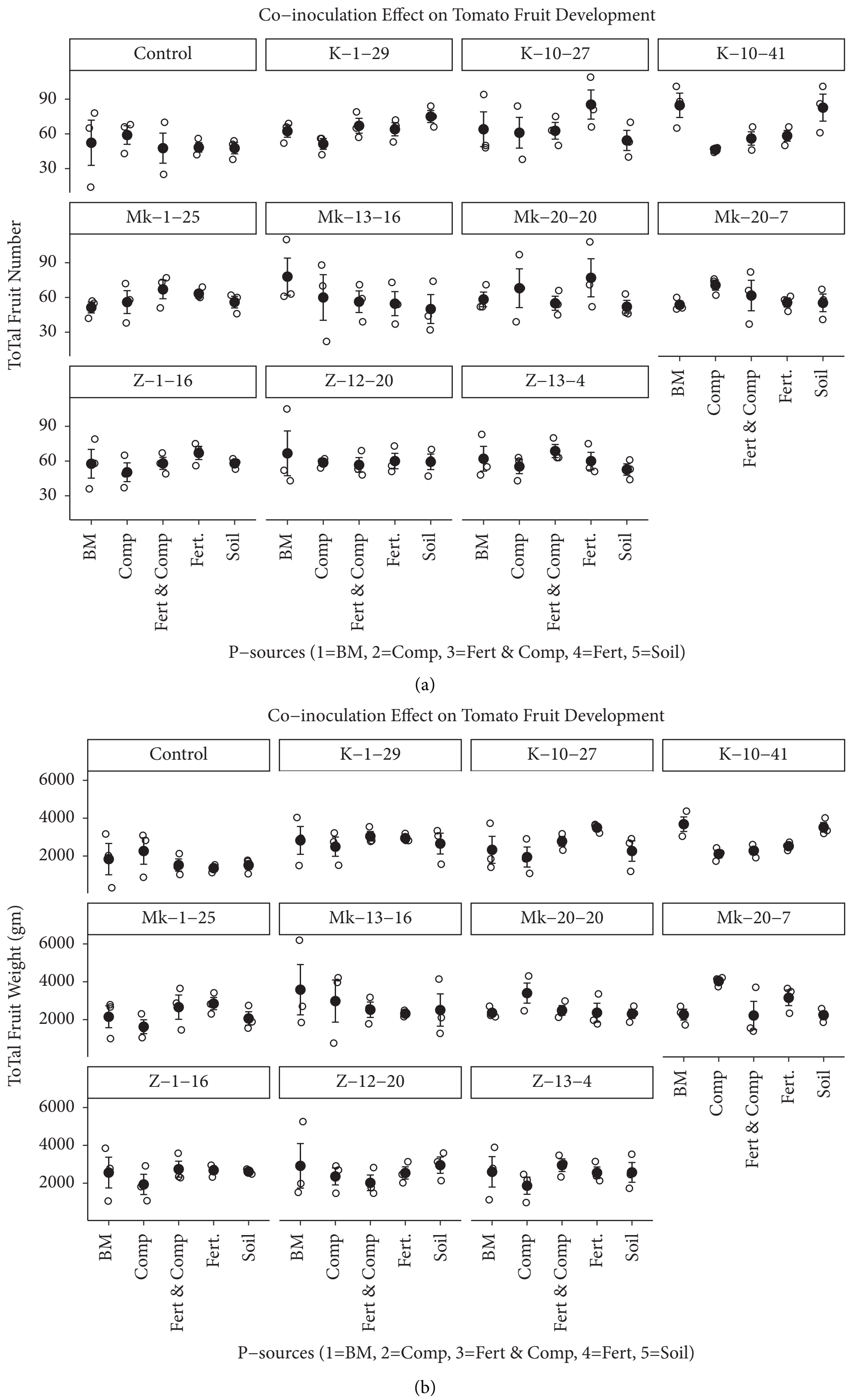


Figure 4: Tomato fruit yield ((a) = Total Fruit Number and (b) = Total Fruit Weight).

tomato inducers to develop more marketable (31.33) fruits inferring that this efficient isolate positively interacted with tomato to increase the height (67.2 cm (Table 1)), and thus it led to the development of more healthy fruits. In the same way, K-1-29 effectively interacted with tomatoes and promoted plant height (Table 1), the overall fruit yield and gross fruit weight (2793.3 gm) (Table 5). Similarly, [1] reviewed the overall benefit of adopting rhizosphere microbes in enhancing plant available nutrients, stimulating root and shoot growth, and increasing height, biomass, and yield. A supportive finding reported by [7] indicated that PSB inoculation increased rice root growth, P uptake, and biomass and grain yield.

Sharon et al., 2016 [34] demonstrated that tomato inoculation with *Pantoea* sp. recorded elevated P incorporation and biomass. In our study, three PSB isolates stimulated tomato growth parameters, fruits yield and response to stress. K-10-27 encouraged to develop a greater number of fruits (65.47), (though the majority of fruits (37.47) were unmarketable due to blossom end rot), while Mk-20-7 improved directly or indirectly physiological response to resist stresses and developed more healthy and marketable fruits (31.33), whereas K-10-41 encouraged tomato to resist water stress as well as increased fruit yield (2821.3 gm fruit weight recorded from a total of 65.6 fruits among them 31.27 were marketable) (Table 5). In agreement to this Verma et al., 2019 [5] reported that the application of PGPR in plants directly (nutrient accessing, phytohormone production) and indirectly (antibiotics response, competition for niche and stress tolerance) increased plant growth, biomass, and yield. The three PSB isolates (K-10-27, K-10-41, and Mk-20-7) demonstrated substantial improvement in fruit number and weight which was a prominent recognition that can possibly be recommended for tomato farm application under repeated efficacy attest and conformation. In line with this, Kumar et al., 2022 [2] reported that the application of biofertilizers improved seed germination, seedling growth, yield, and quality. This might perhaps suggest PSB inoculation induces functional tomato gene expressions as indicated by Zhang et al., 2022 [15] which regulates physiological parameters of chlorophyll synthesis, metabolism, transportation, and resistance, in the reverse tomato modified and released metabolites to promote PSB colonization.

PSM increased plant available phosphorous through solubilization and mineralization of insoluble P-compounds (i.e., both inorganic and organic phosphorous) [1]. Combined application of organic matters, biological inputs, and synthetic chemicals consent integrated soil fertility maintenance for multidimensional benefits. Application of external P-supplements in conjunction with PSB isolates improved interaction and responses between isolates and tomato. Particularly, compost and PSB boosted tomato growth indices (height, number of leaves, flower buds development, and flower openings). These were consistent with the findings of Etissa et al., 2013 [6] and Girshe et al., 2018 [25] which revealed that locally available organic fertilizers such as farmyard and compost application to tomato enhanced growth and development that fortified economic, social, and environmental feasibility. A review by Tamene et al., 2017 [23] also elaborated organic matter amendment (green manures, animal dung, and crop residues) enhanced soil nutrient availability, moisture, microbial activities, and crop production. A study on sugarcane indicated that PSB coinoculation with compost showed significant shoot nutrients (P, N and K) composition over control and other supplements including rock phosphate and TSP [9]. Similarly, Khan, 2015 [8] found that the interaction of compost and PSB significantly increased maize yield and yield components (grain number and weight). Likewise, Yasmeen et al., 2022 [3] found that maize grain yield has been significantly affected by the interaction of a potent PSB strain (*Bacillus cereus* GS6) and rock phosphate. In the current study, PSB coinoculation with a mixture of 50% compost and 50% of the recommended DAP fertilizer significantly improved both tomato vegetative growth (plant height 67.39 cm) and fruit yield (the highest (63.06) total fruit number and the 2nd highest (2617.39 gm) total fruit weight) (Table 5). This assorted coinoculation promoted tomato height, number of leaves, flower buds, fruit number, fruit size, and weight) whereas bone meal strongly encouraged fruit values (recorded a total of 62.82 fruit number among them 29 were marketable, the highest fruit weight (2645.91 gm) and the larger fruit size (Tables 5 and 6)). These results are in line with the findings of Tamene et al., 2017 [23] indicated that combined application of half of the recommended fertilizer rate and compost improved soil pH and micronutrients and strongly increased wheat and teff productivity. In the current experiment, fertilizer was found intermediate inducer compared to other treatments except for leaf development and fruit width. Our results are consistent with the findings of Estrada-Bonilla et al., 2021 [9] which indicated that in contrast to fertilizer amendment, simultaneous application of PSB strains and compost amendment showed significant improvement in physical, chemical, and biological soil properties which improved shoot nutrition and growth. In contrast, many reports have indicated that fertilizer and PSB inoculation among other treatments has shown notable success in different crops production and productivity such as maize [3, 8], *Allium cepa* L. [32], tomato [20], 2017; [28, 34], mung bean [17], rice [7], and wheat [16].

Generally, the current agricultural production requires intensive agricultural practices including improved agro-inputs, plantation, irrigation and phyto-infestation control [11]. Likewise, tomato production needs optimum growing conditions (nutrient-rich soil or growing medium, proper water supply, proper infestation control, mentoring, proper harvest and postharvest management. Soil nutrients could be supplemented as biowastes, organic matter, fertilizers, and/or biofertilizers. Biofertilizers such as nitrogen fixers, PSB, and mycorrhizal fungi application alone or together [2, 17] improve soil nutrients, root and shoot growth as well as maintain plant and soil health.

6. Conclusion

Application of competent PSB strains together with nutrient supplements improved symbiotic effectiveness, sustainable production, and environmental health. Among the 10 PSB isolates K-10-41 strongly stimulated tomato height, branch and flower development besides fruit yield (number, size, and weight (2821.6 gm). Similarly, Mk-20-7 enhanced plant height as well as fruit yield (a total of 59.4 fruits weighing

2780.53 gm with a substantial number of marketable (31.33) fruits were harvested). Likewise, the addition of compost enhanced more of tomato vegetative growth whereas bone meal induced fruit yield (a total of 62.82 fruits with a gross weight of 2645.91 gm were harvested wherein 29 of the fruits were marketable), while the mixture (50% of the recommended rate of compost and fertilizer) improved the overall tomato growth performance. Hence, K-10-41 and Mk-20-7 applications together with bone meal and the mixture of compost and fertilizer were found effective. Consequently, they are recommended for fruitful and sustainable tomato production especially for smallholder farmers. To distribute these promising PSB isolates as inoculants, it is better to confirm their efficacy under different agro-ecologies, characterize them for strain level identification, and evaluate their response to other crops (host range test). Synergetic application of organic supplements (compost, farmyard, bone meal or other biowastes), bioinoculants, and proper agrochemicals maximize production and environmental health. This kind of farm practice is feasible for the economic, social, and ecological sense of balance in line with soil and environmental health maintenance. Therefore, exploring more efficient/competent strains as well as cheap, easily available, and eco-friendly supplements for combined application are the future prospects to improve soil fertility, plant growth, development, and production.

Data Availability

The authors confirm that all the data used to support the findings of this study are included within the article and are made available upon reasonable request to the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors are thankful to Hawassa University and NORAD-IV project for budget allocation and facilitation. The research was financially supported by Hawassa University and NORAD Project-IV.

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