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Foliar application of potassium silicate, potassium fulvate and betaine improve summer-time tomato yield by promoting plant nitrogen and potassium uptake

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ABSTRACT

During the summer months, greenhouse tomato production is challenged by the heat, causing yield reduction; therefore, we conducted a study to test the effectiveness of different foliar spray compositions for the improvement of *Lycopersicon esculentum* var. *cerasiforme* 'Qianxi' nutrition uptake and fruit yield. Two forms of silicon, two kinds of organic nitrogenous compounds and water as the control factor were two-two paired to become nine different recipes, which were as follows: CK (H_2O), ISi (K_2SiO_3), organic silicon (OSi), potassium fulvate (BSFA), BSFA + ISi, BSFA + OSi, betaine (GB), GB + ISi and GB + OSi. The plants were sprayed three times during the period of the first, second and third truss fruit expansions with a 2-week interval. As a result, BSFA or K_2SiO_3 generated higher yield in plants compared with the other compositions. Also, K_2SiO_3 significantly enhanced the total nitrogen, phosphorus and potassium accumulation in fruit and the whole plant. Comparing across the nine recipes, BSFA + ISi, ISi and GB had improved the fruit yield by 17%, 12.7% and 9.5%, performing the best. BSFA + ISi, ISi and GB also improved the plant nitrogen uptake by 8.2%, 18.8% and 9.8%, as well as the potassium uptake by 16.2%, 12.3% and 15.2%, compared with CK, respectively. Thus, K_2SiO_3, BSFA and GB stimulated the plant nitrogen and potassium uptake, which improved the marketable yield.

Keywords: biostimulant, leaf spray, *Lycopersicon esculentum*, macronutrients translocation, tomato fruit quality

Abbreviations: BSFA, potassium fulvate; CK, control group; GB, betaine; ISi, potassium silicate; OSi, organic silicon.

INTRODUCTION

In the north of China, long-time high temperatures from May to August are challenging for the summer greenhouse tomato production. High temperatures suppress plant reproduction, decreasing the fertility of tomato pollen, decreasing the fruit setting rate, and increasing the percentage of abnormal fruits because of the loss of osmosis balance (Pham et al., 2020). More specifically, the heat during the flower stage and pollination phase retards gamete development, sterilises pollens, interferes with pollen tube development and shortens the flower mating time (Hedhly et al., 2009); it reduces the plant seeding rate and induces embryo abortion after fertilisation (León-Osper et al., 2020). Although the reduction of yield due to heat was accompanied with the improvement on some fruit quality (FrQ) parameters like total soluble content or total acid (Vijayakumar et al., 2021; Mesa et al., 2022), it cannot override the loss on the total production.

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It also modulates the nutrients uptake and transportation, causing physiological disorder diseases such as fruit blossom end rot from calcium deficiency (Marcelis and Ho, 1999; Suzuki et al., 2003; Saure, 2014) and yellow shoulder from potassium deficiency (Zhang et al., 2018). Likewise, low vapor pressure deficit could elongate the time of tomato fruit formation and ripening, reducing the fruit number, fruit diameter and yield per truss (Doan and Tanaka, 2022), as well as reduce the N, P, K concentrations in tomato plant stem, leaves and fruits (Suzuki et al., 2015) or the Ca and K uptake in vigorous growing organs (Ding et al., 2022).

Leaf spray is one of the widely accepted methods that help plants to get relief from heat stress. It can be used as an excessive sunlight reflector, metabolism regulator and physical light film (Mphande et al., 2020), or as a biostimulant for improving crop aboveground biomass and photosynthesis-related performance under heat stress (Niu et al., 2022). For instance, leaf sprayed silicon can improve the crop leaf chlorophyll content, maximum quantum transport efficiency of photosystem II (PSII) and the activity of antioxidation enzymes under water deficiency (Verma et al., 2021); promote leaf photosynthesis, leaf total soluble sugar content and biomass accumulation under shading (Hussain et al., 2021); as well as strengthen the leaf cortex wax layer and increase stomatal conductance under heat stress (Hu et al., 2020). Increasing plant silicon uptake under environmental stress can stabilise the epidermal cell lipid layers and maintain membrane function, and polymerised silicon can strengthen the epidermal cell wall (Agarie et al., 1998). Root supply with silicate may mitigate the biotoxicity of antibiotics that remain in soil, reducing root damage and antibiotic absorption (Lv et al., 2021). Under heat stress, silicon improves the plant transpiration, leaf chlorophyll concentration, photosystem core protein, cell wall rigidity and cortical wax thickness without manipulating abscisic acid (ABA) content (Saha et al., 2021). Specifically, for fruiting, silicon can improve the plant anthesis rate, pollen fertility and membrane stability (Nahar et al., 2015). It is also suggested that spraying silicate at low dosage (50–100 mg · dm^{-3}) could enlarge the flower diameter and even accelerate flowering for some Asteraceae species (Attia and Elhawat, 2021, Kamenidou et al., 2010). Similarly, betaine (GB) as a more commonly used organic biostimulant can increase plant stomatal conductance, CO_2 assimilation rate, leaf chlorophyll and relative water content (Denaxa et al., 2012), while cooling down the leaf temperature, increasing quantum yield of PSII and the yield of crop under stress (Khedr et al., 2022). It also improves the activity of catalase, peroxide degrease, superoxide dismutase and nitrate reductase and reduces the concentration of malondialdehyde (MDA), H_2O_2 and $^{\cdot}O_2^-$, increasing crop performance under numerous environmental stresses (Rady et al., 2018; Ahmed et al., 2019; Islam and Mohammad, 2021; Islam et al., 2021,). It also promotes inflorescence formation, shoot and root elongation and their dry mass (DM) accumulation with or without stress (Habib et al., 2012).

Unlike the substances mentioned before, fulvic acid and fulvate are a much more complicated mixture of numerous amino acids, carbohydrates, organic acids, minerals and even some phytohormone-like compounds. When subject to stress, fulvic acid can increase plant mineral nutrients uptake, including Fe, Zn and Mn, and leaf chlorophyll content, increasing the plant photosynthesis capacity (Wang et al., 2019). It accelerates the plant recovery from water stress, maintaining a higher photosynthesis rate and antioxidant enzymes activity, saving yield loss (Do Rosário Rosa et al., 2021). Although fulvic acid also works as an antitranspirant, its ability to increase water use efficiency and leaf water content are in in favour of over-summer production (AbdAllah et al., 2018). Furthermore, leaf spraying fulvic acid can intensify the effect of paclobutrazol (PBZ) on the suppression of gibberellin synthesis, improve the flower uniformity and the accumulation of carbohydrates, protein and amino acids (Dos Santos Silva et al., 2021).

The reduction of mineral nutrient uptake and effective fruit setting are the main challenges in the summer greenhouse tomato production, so guaranteeing the plant nutrition acquisition and marketable yield are the focus of this study. Our objective is to compare the effectiveness of different combinations of silicon, potassium fulvate (BSFA) and GB on yield improvement by foliar spraying. We hypothesised that these contents can enhance the plant uptake of nitrogen, phosphorus and potassium and their translocation to fruit, then improving the fruit yield.

MATERIALS AND METHODS

Experiment site and cultivation method

The experiment was conducted in the gut-connected glass greenhouse of Beijing Academy of Agriculture and Forestry Sciences. Beijing has four distinct seasons in a year. Precipitation mainly happens from May to August, with an average annual precipitation around 500–700. Monthly average temperature is -4.1 °C and 27.6 °C in January and July, which also has the lowest and highest annual temperatures at -15 °C and 41.9 °C, respectively. The frost-free period here is around 180–200 days, with annual cumulative sunlight of 2,000–2,800 h. Greenhouse was equipped with top window and side wall fans for air exchange, top-drop hanging fans blowing horizontally for air circulation, and wet pad for summer cooling. Cherry tomato 'QianXi' seedlings with four true leaves were transplanted on 27 February 2017. The planting area was sized 8 m × 13.5 m, containing 18 flat planting beds with double lines of crop in each bed. The distance between each plant within and between the lines was 30 cm, so the designed planting density was 66,666 plants per hectare. The planting bed was in the south-north direction, equipped with double drip

irrigation lines close to the plants. Plants were irrigated every 3–4 days depending on the weather, and all the plants were under the same fertilisation management through fertigation. Commercial high potassium (5-19-27) and high nitrogen (30-5-15) compound fertiliser containing necessary trace elements were alternatively supplied through irrigation water. Commercial sphagnum-mixed substrate was used, whose properties and analysed nutrition content were as follows: pH –7.43, EC-713 μS · cm^{-1}, organic matter 316 g · kg^{-1}, total N 9.67 g · kg^{-1}, NH_4-N 40.8 mg · kg^{-1}, NO_3-N 298 mg · kg^{-1}, P_2O_5 213 mg · kg^{-1}, K_2O 150 mg · kg^{-1}. Additional base fertiliser of 150 kg · ha^{-1} nitrogen, 120 kg · ha^{-1} phosphorus and 180 kg · ha^{-1} potassium were evenly spread in the planting bed before transplanting.

Experimental design

The experiment was a split plot experiment with random design. The biostimulants were separated into two categories: organic nitrogenous compounds (NSource) and different forms of silicon (SiForm). The BSFA and GB are defined as organic nitrogenous compounds, and the forms of silicon are organic silicon (OSi) and potassium silicate. The compositions and water as control factor were two-two paired to be the final recipe for leaf spray, details are shown in Table 1. The planting area was separated into nine main plots, and each plot was further divided into three subplots as three repetitions within. The plants were treated three times at 2-weeks' interval, which were at the first, second and third truss fruit expansion periods, during the experiment. The concentration of each composition was 0.5 g × dm^{-3}, and the spraying volume was 750 dm^3 · ha^{-1}.

FrQ, water content, yield and DM

Fruit total soluble solids (TSS), fruit vitamin C concentration (Vc), fruit nitrate content (FrNitrate) and fruit water content were measured with the fruits harvested from the third fruit truss with fully red colour and similar size. The TSS, Vc and FrNitrate were measured via anthrone colorimetry, colorimetric method and ultraviolet spectroscopy, respectively. Four repetitions of each treatment were taken for each parameter assessment. Additional fruits were harvested for measuring the fruit water content. All fruits were weighed for fresh mass and sliced into thin pieces for oven drying under 65 °C. After 120 h, the totally dried fruits were weighed for dried mass. All fruits from the experiment plants were harvested at the time when they were just ripened and weighed for yield. In this way, cumulative fruit production and cumulative fruit DM of each treatment were documented gradually until the end of the experiment. The final yield calculation also considered all the fruits harvested for further analysis and assessment.

The macronutrients concentration, accumulation, translocation and partition

On 2 July 2017, six plants were chosen randomly from each treatment for final harvest. Plants were cut at the base of the stem just above the substrate surface after harvesting all fruits. Then, the stem, branch and leaf were sampled at 20% separately of its biomass, weighing for fresh mass. Weighed plant material were preheated under 105 °C for 6 h, then oven dried under 85 °C for 72 h, and weighed for DM. The water content of each part was then calculated. The organs of dried plant were manually ground and sieved. The total nitrogen content was measured using the Kieldahl's method with automatic Kjeldahl nitrogen analyzer (KDY-9820, KETUO, Beijing, China); the total phosphorus was measured using Olsen method with spectrophotometer (Model 722, Modern Science Ltd., Shanghai, China); and the total potassium was determined with Atomic Absorption Spectrometer (6400A, Shanghai Jingmi Ltd, Shanghai, China). The macronutrients accumulation and translocation were calculated as follows:

Nutrients accumulation
= Nutrients concentration in the organ
× Dry mass of the organ

Nutrients translocation
= Nutrients concentration in the fruit/
Nutrients concentration in vegetative organs

The nutrients translocation factors (NTF) are the ratio between the nutrient's concentration of fruit and

Table 1. Experimental design.

NSource	SiForm	Leaf spray content	Treatment	Concentration (g · dm^{-3})
H_2O	H_2O	H_2O	CK	None
	K_2SiO_3	Solely inorganic silicon	ISi	0.5
	$C_8H_{20}O_4Si$	Solely OSi	OSi	0.5
BSFA	H_2O	Solely BSFA	BSFA	None
	K_2SiO_3	BSFA and inorganic silicon	BSFA + ISi	0.5 + 0.5
	$C_8H_{20}O_4Si$	BSFA and OSi	BSFA + OSi	0.5 + 0.5
GB	H_2O	Solely GB	GB	None
	K_2SiO_3	GB and inorganic silicon	GB + ISi	0.5 + 0.5
	$C_8H_{20}O_4Si$	GB and OSi	GB + OSi	0.5 + 0.5

BSFA, potassium fulvate; CK, control group; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

vegetative organs, including stem, branch and leaf. The factor shows the status of the root absorbed nutrients moving from the transportation organs (stem and branch) to the source organs (leaf) and finally to the sink organ (fruit).

Data analysis

The significant effects of the two categories of biostimulants were detected through two-way ANOVA. Duncan Test for Multiple-comparison ($p < 0.05$) was performed for ANOVA analyses. Pearson's correlation was performed between the macronutrient accumulation, partition and translocation of each plant organ. Pearson's correlation and principal components analysis (PCA) were performed using OriginPro 2021 OriginLab Corporation, Northampton, MA, USA. ANOVA analyses was performed using IBM SPSS Statistics 23.0 (SPSS Inc., New York, USA). Figures were plotted in OriginPro 2021 (OriginLab Corporation). All data in the tables are presented as mean.

RESULT

The fruit yield, FrQ, plant DM and partitioning

BSFA + ISi, ISi and GB performed best in yield improvement, increasing fruit fresh mass by 17%, 12.7%, 9.5% compared with CK correspondingly (Table 2). Other treatments did not show obvious advantages in fruit production.

NSource and SiForm had interactive influence on FrQ (Table 2). BSFA + OSi, BSFA and GB + OSi separately produced the highest fruit total soluble solids (FrTSS), fruit Vitamin C (FrVc) and fruit nitrate contents (FrNitrate) among all the treatments and CK. Both BSFA and GB resulted in minimal but significant improvement in FrVc, but ISi, OSi and nearly all compounded treatments had significantly reduced FrVc compared with CK. The lowest FrVc was generated in GB + ISi, which was 22.8% lower than CK.

ISi, BSFA + ISi and GB also produced the highest fruit dry mass (FrDM) among all treatments and CK, and CK produced the least amount of FrDM (Table 3). Only ISi significantly improved FrDM by 18.3%. We noticed that the improvement on FrDM was better than fresh yield, indicating a higher fruit photosynthates accumulation of the relevant treatments.

For canopy biomass (Table 3), only SiForm had impacted branch dry mass (BrDM) significantly. Treatments containing K_2SiO_3 generated significantly higher BrDM than those containing OSi. The former increased BrDM by 11.0% while the latter reduced BrDM by 10.67%. Among all treatments and CK, ISi performed the best on BrDM, and GB + OSi was the worst. Interestingly, solely applied GB or OSi did not hamper the BrDM accumulation as severe as the compounded treatment did. GB and OSi may have interactive effect on branch growth, which led to this aggravation.

The DM partitioning to different organs is also shown in Table 3. Around half DM was partitioned to fruit for all treatments; the best balance was achieved in GB + OSi, which is 5.6% higher than the worst performance of CK. It can be concluded that BSFA + ISi was the optimum in terms of yield improvement among all treatments; ISi was the optimum for promoting general biomass accumulation; GB + OSi shifted

Table 2. The mean ($n = 4$) of FrY, FrTSS, FrVc and FrNitrate of the tomato plants sprayed with nine different recipes.

Treatment	FrY ($kg \cdot m^{-2}$)	FrTSS (%)	FrVc ($mg \cdot 100\ g^{-1}$)	FrNitrate ($mg \cdot kg^{-1}$)
CK	3.67 c	8.2 ab	32.6 b	259.9
ISi	4.14 ab	7.8 c	29.8 cd	209.8
OSi	3.66 c	7.7 c	28.8 de	171.6
BSFA	3.71 c	8.3 ab	34.2 a	310.3
BSFA + ISi	4.29 a	8.0 bc	27.8 ef	219.0
BSFA + OSi	3.91 bc	8.4 a	30.6 c	233.7
GB	4.02 abc	8.2 ab	33.1 ab	256.4
GB + ISi	3.81 bc	8.0 abc	25.5 g	228.9
GB + OSi	3.74 c	8.4 a	26.8 fg	413.0
NSource				
H_2O	3.82	7.9 B	30.8	213.8
BSFA	3.97	8.3 A	31.1	254.3
GB	3.86	8.2 A	28.8	299.4
SiForm				
H_2O	3.80	8.3 A	33.7 A	275.5
K_2SO_3	4.08	7.9 B	27.9 B	219.2
OSi	3.77	8.2 A	29.1 B	272.8

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; FrNitrate, nitrate concentration; FrTSS, fruit total soluble solids; FrVc, fruit vitamin C concentration; FrY, cumulative fruit yield; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogeneous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

Table 3. The mean ($n \geq 4$) of stem, branch, leaf, fruit and total DM, as well as the percentage of DM partitioning to stem, branch, leaf and fruit (Stem%, Br%, Leaf%, Fr%, respectively) of the tomato plants sprayed with different recipes.

Treatments	Stem DM (g)	Branch DM (g)	Leaf DM (g)	Fruit DM (g)	Total DM (g)	Stem%	Branch%	Leaf%	Fruit%
CK	1511 ab	667 ab	1064 ab	3018 d	6260 c	24.2	10.7 a	17.0	48.3 b
ISi	1566 ab	742 a	1233 a	3570 a	7137 a	21.8	10.6 a	17.6	50.0 ab
OSi	1397 b	585 abc	1065 ab	3163 bcd	6168 c	22.2	9.5 ab	16.9	51.4 ab
BSFA	1353 b	541 bc	1136 ab	3303 abcd	6240 c	21.3	8.4 ab	17.5	52.9 ab
BSFA + ISi	1572 ab	599 abc	1127 ab	3465 ab	6923 ab	23.4	9.4 ab	17.0	50.1 ab
BSFA + OSi	1360 b	588 abc	935 ab	3115 cd	6145 c	24.0	9.7 ab	15.6	50.7 ab
GB	1848 a	730 a	1127 ab	3407 abc	6902 ab	25.4	9.2 ab	15.9	49.6 ab
GB + ISi	1549 ab	588 abc	1040 ab	3206 bcd	6402 bc	24.3	9.7 ab	16.0	50.1 ab
GB + OSi	1425 b	427 c	842 b	3213 bcd	5974 c	24.6	7.5 b	14.0	53.9 a
NSource									
H_2O	1481	669	1120	3250	6522	22.7	10.2	17.2	49.9
BSFA	1473	590	1078	3294	6435	22.9	9.2	16.7	51.2
GB	1588	570	990	3275	6426	24.7	8.8	15.3	51.3
SiForm									
H_2O	1528	609 AB	1087 AB	3243 AB	6466 AB	23.6	9.4	16.8	50.2
K_2SO_3	1578	677 A	1152 A	3414 A	6821 A	23.2	9.9	16.9	50.1
OSi	1437	545 B	950 B	3164 B	6096 B	23.6	8.9	15.5	52.0

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; DM, dry mass; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogeneous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

most DM partitioning towards fruit; and nitrogenous compounds can benefit FrQ.

Plant nitrogen content, translocation factor and accumulation

The concentration, translocation factor and accumulation of plant nitrogen are shown in Table 4. SiForm significantly impacted the stem nitrogen concentration (StemN), as the treatments contained K_2SiO_3 which reduced StemN. The leaf nitrogen concentration (LeafN) was significantly increased when the treatments contained BSFA and K_2SiO_3. NSource had an effect on fruit nitrogen concentration (FrN), and the existence of GB significantly decreased the FrN level. It is interesting to note that the nitrogenous compounds could not increase the plant general nitrogen level, but the substance containing potassium benefits plant nitrogen assimilation regardless of its accompanied composition.

Both NSource and SiForm significantly influenced the plant nitrogen translocation factors. Stem nitrogen translocation factor (StemNTF) was significantly improved compared with CK when treatments contained K_2SiO_3. The K_2SiO_3 increased branch nitrogen translocation factor (BrNTF) while GB reduced it, similarly, GB also significantly reduced the leaf nitrogen translocation factor (LeafNTF).

NSource had significant influence on branch nitrogen accumulation (BrTN) so that both of the nitrogenous compounds total BrTN. While SiForm significantly influenced the nitrogen accumulation in all vegetative organs and fruit. The existence of silicon significantly reduced total stem nitrogen accumulation (StemTN), and the OSi reduced the BrTN, StemTN, and the whole canopy and fruit nitrogen accumulation (CTN), while the K_2SiO_3 improved leaf total nitrogen accumulation (LeafTN) and fruit total nitrogen accumulation (FrTN). GB had the highest StemTN than all other treatments and CK. The interactive effect between nitrogenous compounds and silicon exacerbated the reduction of BrTN. ISi, OSi, BSFA, BSFA + ISi, GB and GB + ISi all improved LeafTN compared with CK. FrTN had been increased by ISi, BSFA and BSFA + ISi. Also, the ISi, BSFA, BSFA + ISi and GB improved the CTN compared with CK.

Plant phosphorus content, translocation factor and accumulation

The concentration, translocation factor and accumulation of plant phosphorus are shown in Table 5. Both NSource and SiForm significantly influenced plant phosphorus concentration, and so did their interaction. The existence of GB or OSi significantly increased the stem phosphorus level (StemP). The existence of K_2SiO_3 significantly improved the branch phosphorus concentration (BrP), and OSi could distinctively improve the effect of BSFA on BrP, indicating a superimposed effect. Both BSFA and silicon significantly reduced leaf phosphorus concentration (LeafP). Only the existence of K_2SiO_3 improved fruit phosphorus concentration

Table 4. The mean ($n \geq 3$) of nitrogen concentration, translocation factor and accumulation of different organs of the tomato plants sprayed with different recipes.

Treatments	Nitrogen concentration (g · kg^{-1})				Translocation factor			Nitrogen accumulation (g)				
	Stem	Branch	Leaf	Fruit	Stem	Branch	Leaf	Stem	Branch	Leaf	Fruit	Total
CK	20.0 bcd	22.1 abc	39.8 d	20.5 bc	1.02 bcd	0.93 bc	0.51 ab	30.2 b	14.7 a	42.4 d	61.8 c	149.1 c
ISi	19.3 bcd	20.3 bc	42.2 ab	22.3 a	1.15 ab	1.10 a	0.53 a	30.3 b	15.1 a	52.2 a	79.7 a	177.1 a
OSi	19.7 bcd	21.8 abc	40.8 cd	20.7 bc	1.04 bcd	0.95 bc	0.51 abc	27.7 bc	12.8 c	43.6 c	65.5 c	149.6 c
BSFA	22.7 a	24.1 a	41.8 abc	21.5 ab	0.96 cd	0.90 c	0.52 ab	30.8 b	13.0 bc	47.5 b	71.2 b	162.5 b
BSFA + ISi	17.5 d	20.4 bc	42.7 a	21.1 abc	1.20 a	1.04 ab	0.49 bcd	27.6 bc	12.3 c	48.3 b	73.2 b	161.3 b
BSFA + OSi	21.1 ab	21.6 abc	41.6 abc	20.2 bcd	0.96 cd	0.94 bc	0.49 bcd	28.8 bc	12.7 c	38.9 e	63.1 c	143.5 c
GB	20.4 abc	19.5 c	41.8 abc	18.83 d	0.92 d	0.97 bc	0.45 d	37.9 a	14.3 ab	47.2 b	64.4 c	163.7 b
GB + ISi	18.6 bcd	21.3 bc	41.9 abc	19.70 cd	1.06 abcd	0.93 bc	0.47 cd	28.9 bc	12.6 c	43.7 c	63.4 c	148.6 c
GB + OSi	17.9 cd	22.5 ab	41.3 bc	19.7 cd	1.10 abc	0.88 c	0.48 bcd	25.6 c	9.6 d	34.8 f	63.5 c	133.6 d
NSource												
H_2O	19.7	21.39	41.01 B	21.17 A	1.08	0.99 A	0.52 A	29.4	14.2 A	46.0	69.0	158.6
BSFA	20.5	22.05	42.07 A	20.98 A	1.03	0.86 AB	0.50 A	29.0	12.7 B	44.9	69.2	155.8
GB	19.0	21.15	41.72 AB	19.48 B	1.04	0.93 B	0.47 B	30.8	12.2 B	41.9	63.8	148.6
SiForm												
H_2O	21.1 A	21.9	41.2 B	20.3	0.97 B	0.92 B	0.49	32.9 A	14.0 A	45.7 A	65.8 B	158.4 A
K_2SO_3	18.5 B	20.7	42.3 A	21.1	1.14 A	1.02 A	0.50	28.9 B	13.3 A	48.0 A	72.1 A	162.3 A
OSi	19.6 AB	22.0	41.3 B	20.2	1.04 B	0.93 B	0.49	27.3 B	11.7 B	39.1 B	64.0 B	142.2 B

Note: First row lists the trait, and the second row lists the different organs as stem, branch, leaf, fruit or whole plant (total).

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogeneous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

Table 5. The mean ($n \geq 3$) of phosphorus concentration, translocation factor and accumulation of different organs of the tomato plants sprayed with different recipes.

Treatment	Phosphorus concentration (g · kg^{-1})				Translocation factor			Phosphorus accumulation (g)				
	Stem	Branch	Leaf	Fruit	Stem	Branch	Leaf	Stem	Branch	Leaf	Fruit	Total
CK	2.57 d	1.83 d	2.40 b	2.26 c	0.88 a	1.24 a	0.94 c	3.90 e	1.22 cd	2.56 b	6.85 f	14.5 f
ISi	3.43 b	2.27 a	2.09 cd	2.47 a	0.72 cd	1.09 b	1.18 a	5.38 b	1.69 a	2.58 b	8.84 a	18.5 b
OSi	3.32 b	1.86 d	2.08 cd	2.37 abc	0.71 cd	1.27 a	1.14 ab	4.65 vd	1.09 f	2.22 d	7.51 de	15.5 de
BSFA	3.07 c	1.83 d	2.05 d	2.38 ab	0.77 bc	1.30 a	1.16 a	4.16 e	0.99 g	2.34 d	7.86 c	15.3 e
BSFA + ISi	2.91 c	1.95 cd	2.15 cd	2.42 a	0.83 ab	1.24 a	1.12 ab	4.59 d	1.18 de	2.43 c	8.40 b	16.6 c
BSFA + OSi	3.42 b	2.14 b	2.04 d	2.40 a	0.70 cd	1.12 b	1.18 a	4.66 cd	1.26 c	1.91 e	7.49 de	15.3 e
GB	3.72 a	2.01 c	2.53 a	2.29 bc	0.61 e	1.14 b	0.91 c	6.89 a	1.47 b	2.85 a	7.82 cd	19.0 a
GB + ISi	2.99 c	1.91 cd	2.18 c	2.42 a	0.81 ab	1.27 a	1.11 ab	4.63 d	1.13 ef	2.27 d	7.78 cd	15.8 d
GB + OSi	3.50 b	1.84 d	2.11 cd	2.27 bc	0.65 de	1.23 a	1.08 b	4.99 c	0.79 h	1.78 f	7.32 e	14.9 f
NSource												
H_2O	3.11	1.99	2.19 AB	2.37	0.77 A	1.20 A	1.09 B	4.64 B	1.33	2.46	7.73	16.2
BSFA	3.14	1.98	2.09 B	2.41	0.77 A	1.21 A	1.15 A	4.47 B	1.14	2.23	7.92	15.8
GB	3.41	1.93	2.27 A	2.33	0.69 B	1.22 A	1.03 C	5.50 A	1.13	2.30	7.64	16.6
SiForm												
H_2O	3.13	1.89 B	2.33 A	2.32 B	0.76 A	1.23 A	1.00 B	4.98	1.23 AB	2.58 A	7.51 B	16.3 AB
K_2SO_3	3.11	2.05 A	2.14 B	2.44 A	0.79 A	1.20 A	1.14 A	4.86	1.33 A	2.43 A	8.34 A	17.0 A
OSi	3.42	1.95 AB	2.08 B	2.35 B	0.69 B	1.21 A	1.13 A	4.77	1.05 B	1.97 B	7.44 B	15.2 B

Note: First row lists the trait, and the second row lists the different organs as stem, branch, leaf, fruit or whole plant (total).

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogeneous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

(FrP), regardless of whether it was combined with any nitrogenous compounds.

NSource, SiForm and their interaction influenced the plant phosphorus translocation factor. GB reduced the stem phosphorus translocation factor (StemPTF) and the leaf phosphorus translocation factor (LeafPTF), while BSFA increased LeafPTF. OSi suppressed StemPTF but both forms of silicon improved LeafPTF. No treatments performed better than CK on StemPTF, but all treatments except GB improved LeafPTF.

NSource significantly influenced the stem phosphorus accumulation (StemTP), so that the existence of GB improved StemTP by 18.5% compared with H_2O. SiForm significantly influenced plant phosphorus accumulation in branch, leaf and fruit (BrTP, LeafTP and FrTP, respectively). K_2SiO_3 significantly improved BrTP and FrTP, while OSi reduced LeafTP. The interaction of NSource and SiForm also had a significant effect. All treatments resulted in higher StemTP and FrTP compared with CK, while only ISi and GB improved BrTP. GB increased LeafTP but the combination of nitrogenous compounds and silicon exacerbated their negative effect on LeafTP. For the total phosphorus accumulation (TP) in the whole canopy and fruit (CTP), all the treatments except GB + OSI had a positive effect.

Plant potassium content, translocation factor and accumulation

The concentration, translocation factor and accumulation of plant potassium are shown in Table 6. NSource impacted the stem potassium concentration (StemK) and the branch potassium concentration (BrK), that GB increased both of them while BSFA only increased BrK. SiForm impacted BrK, the leaf potassium concentration (LeafK) and the fruit potassium concentration (FrK). OSi improved BrK and LeafK while K_2SiO_3 improved FrK. All treatments benefited the StemK compared to CK except ISi and BSFA + OSi, and ISi and GB suppressed BrK and LeafK, respectively. GB + ISi was the only treatment elevated FrK compared to CK. Interestingly, neither BSFA or K_2SiO_3 was able to directly increase LeafK, but silicon could be the key of LeafK improvement. FrK was more sensitive to potassium content in the sprays. Hence, the K_2SiO_3 can inverse the negative effect of GB on FrK and the combination even resulted in highest FrK.

Plant potassium translocation factor (StemKTF, BrKTF and LeafKTF) was also impacted by NSource, SiForm and their interaction, respectively. GB decreased StemKTF, and BrKTF, and BSFA only reduced BrKTF. At the meanwhile, K_2SiO_3 increased BrKTF and OSi reduced LeafKTF. Almost all treatments had lower StemKTF than CK, except BSFA + OSi. Different from StemKTF, most treatments had lower BrKTF than CK, except ISi. LeafKTF was elevated by the K_2SiO_3 and nitrogenous compounds, especially by the GB, but organic compounds would reduce LeafKTF and attenuated the positive effect of K_2SiO_3 and nitrogenous compounds.

Both NSource and SiForm had significant effect on plant total potassium accumulation (TK), and so did their interaction. GB improved total stem potassium

Table 6. The mean ($n \geq 3$) of potassium concentration, translocation factor and accumulation of different organs of the tomato plants sprayed with different recipes.

Treatment	Potassium concentration ($g \cdot kg^{-1}$)				Translocation factor			Potassium accumulation (g)				
	Stem	Branch	Leaf	Fruit	Stem	Branch	Leaf	Stem	Branch	Leaf	Fruit	Total
CK	24.4 d	31.7 d	27.4 ab	25.4 bcd	1.05 a	0.80 b	0.93 bcd	36.9 g	21.2 b	29.2 bc	76.8 f	164.2 c
ISi	26.1 cd	25.8 e	26.1 b	25.8 bc	0.99 ab	1.00 a	0.99 ab	40.9 de	19.2 d	32.2 a	92.1 a	184.4 a
OSi	31.4 a	34.1 c	28.4 a	25.4 bcd	0.81 cd	0.75 bcd	0.90 cd	44.0 cd	20.0 cd	30.3 bc	80.6 def	174.8 b
BSFA	28.4 bc	36.7 a	27.0 ab	26.0 b	0.92 bc	0.71 de	0.96 bc	38.5 ef	19.9 cd	30.8 ab	86.1 bc	175.3 b
BSFA + ISi	30.4 ab	35.1 bc	26.8 ab	26.4 b	0.86 cd	0.75 bcd	0.99 ab	48.0 b	21.1 b	30.2 bc	91.5 a	190.8 a
BSFA + OSi	25.4 d	36.1 ab	28.1 a	26.7 ab	1.05 a	0.74 cd	0.95 bc	34.6 g	21.3 b	26.3 d	83.5 cd	165.7 c
GB	29.80 ab	35.7 ab	22.7 c	24.1 d	0.81 cd	0.67 e	1.06 a	55.1 a	26.2 a	25.7 d	82.2 cde	189.1 a
GB + ISi	31.4 a	35.1 bc	27.7 ab	27.9 a	0.88 bc	0.79 bc	1.01 ab	48.8 b	20.7 bc	28.9 c	89.6 ab	187.9 a
GB + OSi	31.8 a	36.1 ab	28.4 a	24.4 cd	0.77 d	0.68 e	0.86 d	45.3 bc	15.4 e	23.9 e	78.5 ef	163.2 c
NSource												
H_2O	27.4 B	30.6 B	27.3	25.6	0.95 A	0.85 A	0.94	40.6 B	20.1	30.6 A	83.2	174.5
BSFA	28.1 B	36.0 A	27.3	26.4	0.95 A	0.73 B	0.97	40.4 B	20.8	29.1 A	87.0	177.2
GB	31.1 A	35.7 A	26.0	25.5	0.82 B	0.71 B	0.98	49.8 A	20.8	26.2 B	83.4	180.1
SiForm												
H_2O	27.6	34.8 B	25.8 B	25.2 B	0.93	0.73 B	0.98 A	43.5	22.4 A	28.6 AB	81.7 B	176.2 B
K_2SO_3	29.4	32.0 AB	26.9 AB	26.7 A	0.91	0.85 A	0.99 A	45.9	20.3 AB	30.4 A	91.1 A	187.7 A
OSi	29.6	35.5 A	28.3 A	25.6 B	0.88	0.72 B	0.90 B	41.3	18.9 B	26.8 B	80.8 B	167.9 C

Note: First row lists the trait, and the second row lists the different organs as stem, branch, leaf, fruit or whole plant (total).

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogenous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

accumulation (StemTK) but reduced total leaf potassium accumulation (LeafTK). K_2SiO_3 decrease total branch potassium accumulation (BrTK), and the elevated the LeafTK, total fruit potassium accumulation (FrTK) and the total potassium accumulated in whole canopy and fruit (CTK). Also, OSi reduced the CTK. All treatments increased StemTK compared with CK except BSFA + OSi. Whilst GB and ISi improved BrTK and LeafTK compared with CK, respectively. All the treatments except OSi and GB + OSi increased FrTK compared to CK, and all treatments except BSFA + OSi and GB + OSi increased CTK.

Macronutrients partitioning

The plant macronutrients partitioning to different organs are shown in Table 7. Nsource and Siform manipulated the nitrogen, phosphorus and potassium partitioned to the stem (StemN%, StemP% and StemK%, respectively). GB increased StemN%, StemP% and StemK%, while OSi reduced StemN%. Almost all treatments decrease StemN% excepted for GB, and all treatments promoted StemP% except BSFA. The Isi, BSFA + OSi, GB, GB + ISi and GB + OSi also increased StemK%.

For macronutrients partitioned to branch, both nitrogenous compounds and silicon tend to have negative impact. The nitrogen, phosphorus and potassium partitioned to branch (BrN%, BrP% and BrK%, respectively) were reduced by most of the treatments. All treatments had decreased BrN%, especially when contained nitrogenous compounds. All treatments except OSi reduced BrP%, and only GB increased BrK%.

The macronutrients partitioned to leaf also tended to be suppressed by nitrogenous compounds and silicon. Two nitrogenous compounds significantly reduced the potassium partitioned to leaf (LeafK%), and GB showed more extensively effect. And K_2SiO_3 reduced the nitrogen and phosphorus partitioned to leaf (LeafN% and LeafP%, respectively), while OSi only suppressed LeafP%. None of the treatments elevated the LeafP% or LeafK% compared to CK, and only BSFA + OSi increased LeafN%.

In all treatments, a major part of macronutrients assimilated by plants were partitioned to fruits. NSource did not have significantly influence to the macronutrients partitioned to fruit, but SiForm impacted total fruit nitrogen partitioning (FrN%), that both forms of silicon elevated FrN%. All treatments excepted GB had higher FrN% than CK, and all treatments excepted ISi and OSi increased FrP% compared to CK. Also, OSi, BSFA and BSFA + ISi increased FrK%.

The performance of yield preferable treatments on plant macronutrient content, translocation factor, accumulation and partitioning

BSFA + Isi generated significantly higher FrTN, FrTP and FrTK, which are 18.4%, 22.6% and 19.2% more than CK fruit. The StemNTF of BSFA + ISi is competitive among all treatments and CK, at the meanwhile, its BrTN is16.7% lower than CK. Its best performances were presented in LeafTN and CTK, which were 13.8% and 16.2% higher than CK. ISi generated highest FrP, which was 9.3% higher than CK, and it also resulted

Table 7. The mean ($n \geq 3$) of the partitioning of total nitrogen, phosphorus and potassium to the different organs of the tomato plants sprayed with different recipes.

Treatment	Total nitrogen partitioning to				Total phosphorus partitioning to				Total potassium partitioning to			
	Stem (%)	Branch (%)	Leaf (%)	Fruit (%)	Stem (%)	Branch (%)	Leaf (%)	Fruit (%)	Stem (%)	Branch (%)	Leaf (%)	Fruit (%)
CK	20.3 b	9.9 a	28.4 b	41.4 d	26.8 e	8.4 b	17.6 a	47.1 d	22.5 c	12.9 b	17.8 a	46.8 cd
ISi	18.5 bc	8.6 b	29.1 ab	43.8 bc	30.0 c	7.1 d	14.4 bc	48.5 cd	25.2 b	11.4 c	17.3 a	46.1 d
OSi	17.1 c	8.5 b	29.5 ab	45.0 b	29.1 cd	9.1 a	14.0 c	47.8 cd	22.2 c	10.4 d	17.5 a	49.9 a
BSFA	18.9 bc	8.0 c	29.2 ab	43.8 bc	27.1 e	6.5 e	15.2 b	51.2 a	21.9 c	11.4 c	17.6 a	49.1 ab
BSFA + ISi	20.0 b	8.9 b	27.2 c	44.0 bc	30.4 c	8.2 b	12.5 d	48.9 bc	20.9 c	12.9 b	15.9 b	50.4 a
BSFA + OSi	17.1 c	7.6 c	29.9 a	45.4 b	27.6 de	7.1 d	14.7 bc	50.6 ab	25.1 b	11.0 cd	15.9 b	48.0 bc
GB	23.1 a	8.7 b	28.8 ab	39.3 e	36.2 a	7.7 c	15.0 b	41.1 e	29.1 a	13.8 a	13.6 d	43.5 e
GB + ISi	19.2 bc	7.2 c	26.1 c	47.6 a	33.6 b	5.3 e	11.9 d	49.2 bc	27.8 a	9.5 e	14.7 c	48.1 bc
GB + OSi	19.5 b	8.5 b	29.4 ab	42.7 c	29.3 cd	7.1 d	14.4 bc	49.2 bc	26.0 b	11.0 cd	15.4 bc	47.7 bcd
Nsource												
H_2O	18.6 B	9.0 A	29.0	43.4	28.7 B	8.2 A	15.33	47.8 AB	23.3 A	11.6	17.5 A	47.6 AB
BSFA	18.7 B	8.2 B	28.8	44.4	28.4 B	7.3 B	14.13	50.3 A	22.7 A	11.8	16.4 B	49.2 A
GB	20.6 A	8.1 B	28.1	43.2	33.0 A	6.7 B	13.77	46.5 B	27.6 B	11.4	14.5 C	46.4 B
SiForm												
H_2O	20.8 A	8.9	28.8 A	41.5 B	30.0	7.5	15.95 A	46.5	24.5	12.7 A	16.3	46.5
K_2SO_3	19.2 AB	8.2	27.5 B	45.1 A	28.7	6.9	12.93 C	48.9	24.6	11.3 B	16.0	48.2
OSi	17.9 B	8.2	29.6 A	44.3 A	31.3	7. 8	14.34 B	49.2	24.4	10.8 B	16.2	48.5

BSFA, potassium fulvate; CK – H_2O, ISi – K_2SO_3; GB, betaine; ISi, potassium silicate; OSi, organic silicon; SiForm, different forms of silicon.

The different letters following each number stand for the different Duncan's homogenous subsets of the corresponding mean. The lowercase, uppercase and italic uppercase letters are used for the interactive effect, main effect of silicon forms and main effect of nitrogen source, respectively. The letters are not indicated if no significance was found.

Table 8. Principle components analysis comprehensive scores of the growth, nutrients and fruiting traits.

	CK	ISi	OSi	BSFA	BSFA + ISi	BSFA + OSi	GB	GB + ISi	GB + OSi
General growth	−1.68	3.03	−0.74	0.12	1.46	−0.99	1.19	−0.04	−2.35
Fruiting performance	−0.73	1.62	−0.37	0.28	1.15	−0.51	0.20	−0.24	−1.41
Vegetative organs performance	−0.33	2.15	−0.97	−0.84	0.60	−0.66	2.07	−0.25	−1.77

Note: General growth includes the N, P, K concentration and accumulation in each organ and DM of each organ; fruiting performance includes the vitamin C, TSS, water content, DM, fresh yield, and the N, P, K concentration, accumulation and partitioning of fruit; vegetative organ performance includes the N, P, K concentration and accumulation in vegetative organs, DM of vegetative organs, leaf SPAD index (data not shown), leaf net photosynthesis rate (data not shown) and leaf temperature (data not shown).

BSFA, potassium fulvate; DM, dry mass; GB, betaine; ISi, potassium silicate; OSi, organic silicon; TSS, total soluble solids.

in highest FrTN, FrTP and FrTK, which were 28.9%, 29.1%, 19.9% more than CK did. Its StemP and LeafN are significantly higher than CK for 33.5% and 6.0% correspondingly. But its general potassium concentration was relatively low among all treatments, especially for BrK. The ISi had highest BrNTF, BrKTF and LeafPTF among the treatments and CK. It also accumulated more LeafTN (+23.5%), BrTP (+38.5%), LeafTK (+10.1%), CTN (+18.8%) and CTK (+12.3%) than CK did. GB generated low FrN, but it had highest StemP and LeafP which are 44.7% and 5.4% higher than CK. Its LeafKTF is highest among all treatments and CK, too. GB results in highest amount of N, P, K accumulation in stem, highest amount of K in branch and highest amount of P accumulation in leaf among all treatments and CK, which improved StemTN by 25.2%, StemTP by 76.7%, StemTK by 49.2%, LeafTP by 11.3%, and BrTK by 23.3% compared to CK. The CTN, CTP and CTK of GB are ranking highest or second highest, which are 9.8%, 31.1% and 15.2% more than CK. The performance of yield preferable treatments on fruit macronutrients partitioning are not outstanding.

PCA and correlation matrix

The PCA comprehensive scores are shown in Table 8. The comprehensive scores were assessed from three different emphasis, which are general growth, fruiting performance and vegetative organs growth with leaf status. Among all treatments and CK, ISi performed best from all three aspects, especially in general growth. BSFA + ISi is comparable to ISi in terms of fruiting performance, but the difference is still obvious. GB's comprehensive influence on plant vegetative organs growth and performance is very close to that of ISi, and the gap is minimal. Thus, ISi, BSFA + ISi and GB are the top three ranking treatments considering both fruiting and plant growth.

The Figure 1 shows the PCA result of the N, P, K accumulation of different organs, DM of different organs, FrQ parameters, and the total N, P, K partitioned to fruit. The green, blue and red symbol cluster represent difference NSource, which are water (no nitrogenous compound), BSFA and GB, respectively. The FrN%, FrP%, FrK%, FrVc, StemDM, Stem TN, StemTP, StemTK and BrTK contribute more to the GB clustering, while the FrTSS, FrTN, FrTP, FrTK, LeafTK and FrDM contribute more to the water and BSFA clustering. The two major components explained 36.3% (PC1) and 23.2% (PC2) of the combined influence to all the experiment factors. The different organs' DM accumulation, LeafTN, BrTP, BrTN and LeafTP are more positively influenced by component 1, while the fruit nutrients accumulation, fruit nutrients partition and LeafTK are more positively influenced by component 2. The FrVc, BrTK and nutrients accumulation of stem are more positively influenced by component 1 but negatively influenced by component 2. Only the FrTSS is negatively influenced by both components 1 and 2. Attractively, LeafTN has the strongest consistency with FrDM, BrDM and LeafDM, whereas the FrVc has the strongest consistency with the total nutrient accumulation in stem. Besides, FrTSS has the total conversed response to the experiment factors compared with FrTN, FrTP and FrTK and so does the FrVc concentration compared with FrTN%, FrTP% and FrTK%.

The correlation matrix of plant macronutrient translocation factors, accumulation and their partitioning to fruit are shown in Figure 2. The FrTSS has negative correlation with FrDM, FrTN, FrTP, FrTK, LeafTN, LeafTP and LeafTK. But the FrDM, FrTN, FrTP and FrTK have a positive correlation with LeafTN, LeafTP and LeafTK. The macronutrients accumulated in stem and branch and LeafTP are negatively correlated to the FrTN%, FrTP% and FrTK%, but LeafTN and LeafTK had no correlation with those. On the contrary, the macronutrients concentration of stem of branch had no impact on FrTN%, FrTP% and FrTK%, but LeafP and LeafK have negative and positive correlation with them, respectively.

DISCUSSION

As the treatments generated the highest yield and most fruit DM, it drew our attention that the BSFA + ISi and ISi increased LeafN and LeafTN more extensively, and the percentage improved by BSFA + ISi and ISi on fruit total nutrient accumulation is much higher than its impact on fruit DM, showing a further enrichment effect on the N, P, K in fruit. The common point shared by BSFA + ISi and ISi in the stimulation of fruit yield and photosynthates accumulation is it improves the plant nitrogen uptake and accumulation. Potassium

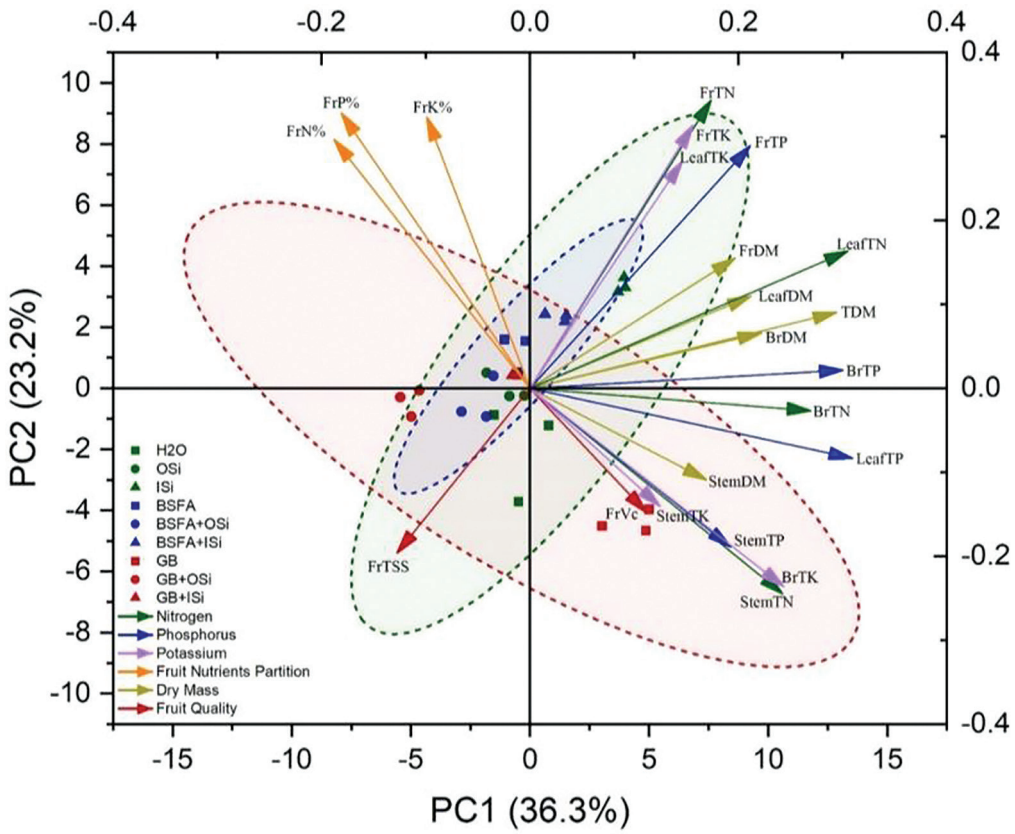

Figure 1. Principle components analysis of plant macronutrients accumulation, fruit macronutrients partitioning, FrTSS content and FrVc concentration. The green, blue and red circles represent the confidential eclipses of the treatments having water (control), BSFA and GB as the source of nitrogen, respectively. The square, round and triangle dots represent the treatments having water (control), ISi and OSi as the form of silicon, respectively. The green, blue and purple vectors show the N, P, K accumulation in different plant organs, and the orange, dark yellow and red vectors show the fruit nutrients partitioning, DM of different plant organs and FrQ, respectively. *FrN%, the percentage of TN partitioned to fruit, similar for FrP% and FrK%, which indicate the percentage of total phosphorus and potassium accumulation partitioned to fruit, respectively. Br, branch; BSFA, potassium fulvate; DM, dry mass; Fr, fruit; FrN, fruit nitrogen concentration; FrQ, fruit quality; FrTSS, fruit total soluble solids; GB, betaine; ISi, potassium silicate; OSi, organic silicon; TK, total potassium accumulation; TN, total nitrogen accumulation; TP, total phosphorus accumulation; TSS, total soluble solids; Vc, vitamin C.

fertiliser amendment to field can improve plant SPAD, photosynthesis, transpiration and fruit yield (Yang et al., 2017), while lack of potassium retards leaf growth and expansion (Jordan-Meille and Pellerin, 2004). Nitrogen was the primary element in plant used for synthesis of amino acids, chlorophyll, enzyme and DNA, and potassium is vital for enzyme activation, ATP synthesis and stomatal opening (Hasanuzzaman et al., 2018). The stimulation on nitrogen and potassium uptake benefits plant biomass accumulation. It has been proved that under the same level of nitrogen source, higher potassium supply stimulates plant photosynthesis, stomatal conductance, transpiration and biomass accumulation, and vice versa (Guo et al., 2019). Early serial studies revealed the efficacy of potassium on nitrate absorption, root to shoot translocation and assimilation of plant, specifically, higher potassium supply increases shoot nitrate concentration and the nitrate reductase activity (Blevins et al., 1978); in the meantime, nitrate supply also stimulates the absorption and assimilation of potassium, in condition of the presence of light (Blevins et al., 1974). The difference is, early studies supplied potassium or nitrogen through root system while our study considered foliar application (BSFA: K in solution for appr. > 46.8 ppm, N in solution for appr. ≥ 15 ppm; GB: N in solution for appr. 59.8 ppm; K_2SiO_3: K in solution for 253 ppm). Although leaf sprayed potassium fertiliser was able to improve crop yield and whole plant biomass under stress condition (Amanullah et al., 2016), its relation with nitrogen uptake is unclear. Thus, the function of potassium inside ISi and BSFA was to promote the nitrogen and photosynthates accumulation in leaf but not increase the local potassium content. Thus, it can be seen that potassium or nitrogen source given from the foliar is also able to improve the acquisition of the other, with the only ambiguity being the efficacy.

The influence of GB on plant growth and nutrient metabolism of GB could be through another mechanism.

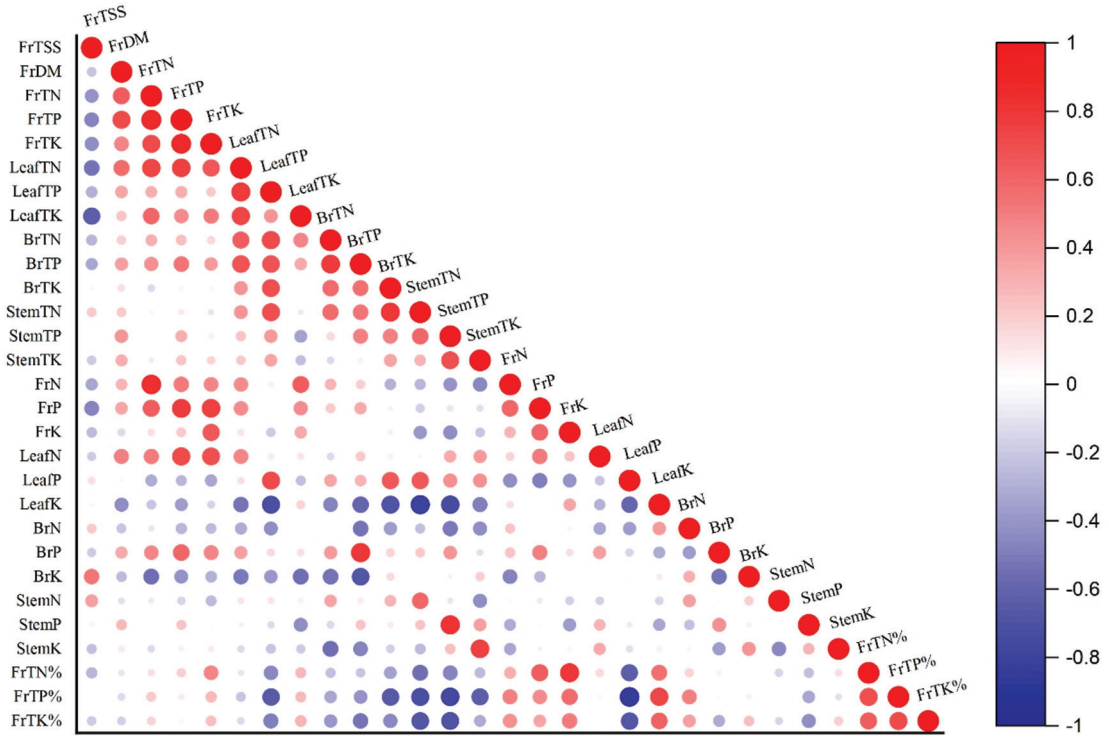

Figure 2. Correlation matrix of macronutrients concentration and accumulation in different plant organs, as well as the fruit DM, FrTSS content and the macronutrients partition to fruit. *FrN%, the percentage of TN partitioned to fruit, similar for FrP% and FrK%, which indicate the percentage of total phosphorus and potassium accumulation partitioned to fruit, respectively; Br, branch; DM, dry mass; Fr, fruit; FrN, fruit nitrogen concentration; FrTSS, fruit total soluble solids; TK, total potassium accumulation; TN, total nitrogen accumulation; TP, total phosphorus accumulation; TSS, total soluble solids; Vc, vitamin C.

With no additional potassium content, GB produced the highest CTP, the second highest CTN and CTK and also the highest biomass on aboveground vegetative organs (data not shown). Its PCA comprehensive score is more advanced on the vegetative growth, especially the biomass, but its fruiting performance is not competitive. Plant membrane stability, chloroplast function and Rubisco activity can be shifted by high temperature (Maestri et al., 2002), gas exchange and the effectiveness of PSII would decrease and the chlorophyll will decompose under heat stress (Morales et al., 2003). While GB can improve crop leaf both chlorophyll content and relative water content through leaf spray (Denaxa et al., 2012; Sofy et al., 2020; Islam and Mohammad, 2021; Islam et al., 2021; Khedr et al., 2022), which is different from the regulation mechanism of potassium. Although GB benefits plant growth more extensively in the vegetative stage, it can increase the source to sink (leaf to fruit or seed) transportation (Osman, 2015). Moreover, one of the potassium metabolism functions is to strengthen the positive transportation of photosynthate in phloem by promoting ATP production, which increases the photosynthates moving from source organ (leaf) to sink organ (fruit) (Mengel, 1980). The shifting on source-sink transportation brought by GB and potassium shares a common point; thus, the way of GB improving plant potassium uptake deserves further study. It also proposed that GB improves crop nutrient uptake and photosynthesis ability mainly by recovering the osmosis balance but not regulating the stress resistance mechanism under stress (Sofy et al., 2020). Early study also suggested that GB helps plants to maintain the leaf water potential and CO_2 assimilation while slowing down wilting under stress, it was not able to increase shoot biomass (Xing and Rajashekar, 1999). As a phytohormone which can be synthesised from plant body, GB can function as a signal molecule or an indicator of plant resisting to environmental stress, whose synthesis can also be triggered by exogenous ABA or itself (Xing and Rajashekar, 2001). Thus, GB may increase the efficiency of plant response to heat stress or interactively work with phytohormone like ABA on modulating plant nutrient uptake and assimilation. Although BSFA + ISi, ISi and GB have significant higher fruit yield and whole aboveground macronutrients accumulation, their FrDM% is not different or improved from CK. Therefore, the yield improvement is the company of aboveground biomass enlargement, but not better photosynthates allocation.

Beyond the effects shown in fruiting and biomass accumulation, the nutrient balance between different organs tells the potential on the direction of further study. LeafN and LeafTN show a strong positive correlation with the macronutrients pool in fruits, and

LeafK has a positive correlation with fruit nutrients partitioning, which means high leaf nitrogen and potassium content benefit fruit biomass. However, high stem macronutrients accumulation, high LeafP and LeafTP reduced fruit macronutrients partitioning. The mechanism of how leaf phosphorus content hampers fruit growth deserves further study. Besides, silicon is also able to elevate plant nitrogen uptake, strengthening its photosynthesis, transpiration and biomass accumulation (Xu et al., 2018); increase K^+-ATPase activity, then enlarge plant potassium uptake (Ahmad, 2014). Thus, separating silicon from potassium or nitrogen to be a single study subject may give new direction on production improvement by leaf spray.

CONCLUSION

For the greenhouse cherry tomato summer production, periodically spraying the plant with ISi, GB and BSFA combined ISi are more effective than the sole use of organic silicate, BSFA or other combinations between the compositions above. Foliar application of ISi or BSFAs increase tomato yield by stimulating the nitrogen and potassium uptake and accumulation of leaf and whole plant, while GB increase yield by improving plant nitrogen, phosphorus and potassium uptake and accumulation potentially through improving plant osmosis balance and interacting with endogenous phytohormone. All the three recipes improve fruit yield with general increase of the aboveground biomass but not higher biomass partitioning towards fruit. Further study targets of the dosage and refined combinations between ISi, BSFA and GB are still needed. Furthermore, silicon could also be an independent subject to be studied in terms of yield promotion through foliar application.

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AUTHOR CONTRIBUTIONS

Y.Z. – data collection. X.X. – manuscript drafting, editing, revising and figures plotting. S.L. – site support and data collection. X.L. – funding acquisition. Y.L. – conceptualisation and data collection. Y.S. – conceptualisation and funding acquisition.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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