scientific reports

OPEN

Effects of Bio and water-soluble fertilizers on sweet potato yield, quality and soil properties in a continuous cropping system under plastic film-mulched drip-fertigated field conditions

Wenxue Duan[1,2,3,4], Haiyan Zhang[1,2,3,4]✉, Qingmei Wang[1,3,4], Beitao Xie[1,3,4], Fuyun Hou[1,3,4] & Liming Zhang[2,3,5]✉

To verify an effective approach for alleviating problems associated with the consecutive monoculture of sweet potato, five fertilizer treatments were designed under plastic film-mulched, drip-fertigated conditions in fields continuously planted with sweet potato over five years. These treatments included: (1) no fertilizer application, (2) basic application of water-soluble (WS) fertilizer, (3) basic application of biofertilizer (BF) and WS fertilizer, (4) split application of WS fertilizer, and (5) combined basic application of BF and split application of WS fertilizer. The effects of BF and WS fertilizer applications on yield, quality, and soil properties were evaluated. Fertilizer applications had positive effects on increasing soil activities and nutrients compared with no fertilizer application. Split fertigation with WS fertilizer increased the activities of soil dehydrogenase (DHA) by 10.94 ~ 14.74%, alkaline phosphatase (ALP) by 4.97 ~ 5.13%, and soil organic matter (SOM) by 10.43 ~ 12.47% in the second year compared with a single application. In both years, split fertigation exerted positive effects on increasing dry matter (DM) accumulation in tuberous roots and increased the productive efficiency in nitrogen (N), phosphorus (P), and potassium (K) fertilizers. BF application for two consecutive years increased the activities of soil sucrase by 7.05 ~ 17.83%, DHA by 18.65 ~ 21.34%, ALP by 6.87 ~ 7.03%, soil available P by 18.34 ~ 28.10%, and SOM by 8.18 ~ 10.17% compared with the no BF application. BF also increased the root yield by 8.88 ~ 14.14%, the carotenoid content in tuberous roots by 20.38 ~ 30.64%, and the K utilization efficiency by 11.09 ~ 14.97%. The combination of BF and split fertigation for two consecutive years was most conducive to the activation of soil nutrients, maintenance of soil fertility, and improvement in yield and quality, which could mitigate problems associated with the consecutive monoculture of sweet potato.

Keywords Biofertilizer, Soil properties, Split fertigation, Sweet potato continuous cropping, Water-soluble fertilizer, Yield

Continuous cropping is a modern commercial production method and has become one of the major issues of sustainable agricultural development[1]. Many kinds of crops, such as wheat, soybean, cotton, and peanut, can cause continuous cropping obstacles[2–5]. The yield and quality decrease, and poor soil fertility occurs in continuous cropping systems, resulting in economic losses and reducing agricultural product safety. Sweet

[1]Crop Research Institute, Shandong Academy of Agricultural Sciences, No. 23788 Gongyebei Road, Jinan 250100, Shandong, People's Republic of China. [2]State Key Laboratory of Nutrient Use and Management, Jinan 250100, People's Republic of China. [3]Scientific Observation and Experimental Station of Tuber and Root Crops in Huang-Huai-Hai Region, Ministry of Agriculture and Rural Affairs, Jinan 250100, People's Republic of China. [4]Featured Crops Engineering Laboratory of Shandong Province, Jinan 250100, People's Republic of China. [5]Shandong Academy of Agricultural Sciences, No.23788 Gongyebei Road, Jinan 250100, Shandong, People's Republic of China. ✉email: zhanghy2020saas@163.com; zhanglm2016saas@163.com

potato has strong adaptability and is widely planted in China. The area used for the continuous cropping of sweet potato is increasing due to the limited arable land. Thus, continuous cropping obstacles can become a bottleneck problem, restricting the sustainable development of the sweet potato industry[6]. The continuous cropping of sweet potato seriously affects the yield and quality, reduces beneficial soil microorganisms, and causes the deterioration of soil physical properties[6,7]. Alleviating continuous cropping obstacles is important for the sustainable ecological planting of sweet potato.

Drip irrigation can deliver water and nutrients to the desirable root zone; reduce water loss; soil evaporation and degradation; and save water and fertilizers[8,9]. Önder et al.[10] have shown that drip irrigation significantly increases the tuber yield of sweet potato and provides high crop water use efficiency. Fertigation is an agronomic operation in which fertilizer is dissolved in irrigation water and delivered to the root zone by an irrigation system. It has been documented that soil mulching keep soil moisture, adjust nutrient balance and suppress weeds, hence crop yield improved[11,12]. In recent years, plastic film mulching has been increasingly used in sweet potato cultivation in northern China because of the increase in yield through the improvement of the soil environment[13,14]. Plastic film mulching with drip fertigation can play a positive role in increasing yield and saving water and fertilizer; thus, this technique is widely used in the cultivation of crops, such as maize, cotton and tomato[15–17]. Although this technology has been used in sweet potato cultivation in northern China, the optimal scheme for high yield and good quality is lacking in systematic research, especially in the hilly land planting of sweet potato with serious continuous cropping obstacles.

Biofertilizer (BF) refers to a kind of fertilizer that has the effects of both microorganisms and organic fertilizer and is composing of microorganisms with specific functions and organic materials[18]. The reasonable application of BF can improve soil quality, promote plant growth, and suppress soil-borne diseases and weeds[19–21], which can effectively alleviate continuous cropping obstacles and be significantly beneficial for sustainable agricultural development[22,23]. Potential benefits of using *Trichoderma* or *Bacillus* species to increase plant growth and/or to control plant diseases have widely been reported[5,24]. Several possible growth-promoting mechanisms, such as an increase in nutrient uptake[25,26], control of plant fungal pathogens[27], and release of soil nutrients[28], have been suggested to explain the phenomenon behind enhanced plant growth. However, the effects of BF on soil fertility, sweet potato root yield and quality are rarely reported, especially in alleviating continuous cropping obstacles.

Based on the above summary, methods for determining suitable techniques for continuous cropping of sweet potato under plastic film-mulched, drip-fertigated field conditions that improve soil fertility, root yield, and quality have not yet been reported. Therefore, an experimental site in which sweet potato was continuously planted for five years was chosen for this study. A split application of water-soluble (WS) fertilizer and a basic application of BF containing *Trichoderma* or *Bacillus* species were used. The following scientific hypotheses are proposed in this study: (i) root yield will increase with split application or basic application of BF by increasing dry matter (DM) accumulation in plants, driven by the ability of fertilizers to meet nutrient requirements and increase crop growth; (ii) soil fertility will increase after BF application due to the increased in soil enzyme activities; (iii) soil nutrients and plant nutrient absorption will improve in response to split application or BF application, which will impact nutrient contents in tuberous roots, may influence root properties, and increase yield, which is also beneficial for improving nutrient utilization efficiency. The main objectives of this study were to evaluate the effects of the application of BF and WS fertilizers on root yield, root quality, and soil properties under plastic film-mulched drip-fertigated sweet potato field conditions and to verify an optimal approach for alleviating continuous cropping obstacles.

Materials and methods

Experimental site

The field experiment was conducted in Dazhai village (36° 09′ N, 116° 35′ E), Jinan, Shandong Province, China, from 2018 to 2019. The experimental field was planted with sweet potato continuously for five years prior to 2018. The study area had a mean yearly temperature of 14.5 °C, average rainfall of 726.2 mm, and 60–70% precipitation during the summer months (June–August). The soil at this site is classified as a Cambisol according to the World Reference Base (WRB) for Soil Resources[29], with a silt loam texture consisting of 175 g kg^{-1} clay, 560 g kg^{-1} silt and 265 g kg^{-1} sand. The 0–20 cm soil layer in the field contained 10.3 g kg^{-1} organic matter, 65.3 mg kg^{-1} alkali-hydrolyzable N, 25.9 mg kg^{-1} available P, and 75.2 mg kg^{-1} available K before planting in 2018.

Experimental design

The cultivar 'Jishu 26' was used for assessment. Five treatments were established in the experiment as follows: (1) no fertilizer application (T0), (2) 450 kg ha^{-1} WS fertilizer applied by drip irrigation as basal fertilizer (T1), (3) 60 L ha^{-1} BF and 450 kg ha^{-1} WS fertilizers applied by drip irrigation as basal fertilizer (T2), (4) 450 kg ha^{-1} WS fertilizer by drip irrigation in accordance with the ratio of 2:5:3 in stages of root branching, ridge covering, and tuberous root expansion, respectively (T3), and (5) 60 L ha^{-1} BF applied by drip irrigation as basal fertilizer and split application of WS fertilizer as the same description as T3 (T4). A high-density black polyethylene film was used as mulching plastic for all treatments, and the same amount of drip irrigation water was used among the five treatments. Before planting sweet potato seedlings, the operation of ridging, mulching, and spreading drip irrigation belts was completed using machinery at one time. Basal fertilizers were applied with drip irrigation on the planting day. The five treatments were arranged in a randomized complete block design. Each treatment had three replicates, and a total of 15 plots were arranged. Each plot was designed to have dimensions of 8 m × 10 m. In the 2019 growing season, all treatments were performed in the same plot as those in the 2018 growing season. The sweet potato seedlings were planted with a spacing of 80 cm × 24 cm (row × plant) on 18 May 2018 and 16 May 2019 and harvested on 22 October 2018 and 20 October 2019, respectively. The other cultivation management practices were the same as in a regular field.

The WS fertilizer used in this study was a granulated compound fertilizer manufactured by Shandong Agricultural Fertilizer Technology Co., Ltd, China. The total N, P_2O_5, and K_2O contents of the fertilizer were 10%, 10%, and 30%, respectively. WS fertilizer was applied through a fertigation system with a fertilizer tank and venturi. The BF applied in the experiment was a liquid mixing fertilizer manufactured by Shandong Kaoshan Biotechnology Co., Ltd, China. The quantity of each component of BF was 40% *Bacillus subtilis* fermentation liquid, 40% *Trichoderma pseudokangensis* fermentation liquid, 1% WS chitin, 1% K fulvic acid, 10% decomposed organic matter, 4.5% surface-active agent, and 3.5% stabilizing agent. The number of viable bacteria in the fermentation broth of *B. subtilis* was $\geq 1 \times 10^9$ per ml, and the effective spore concentration in *T. pseudokangensis* fermentation broth was $\geq 3 \times 10^8$ per ml.

Sampling methods

Soil samples were collected from each plot. Five soil cores with a diameter of 5 cm were collected using a soil auger from the 0–20 cm depth of each plot in an 'S' shape and mixed thoroughly to form a composite sample. Each sample was placed in a sterilized plastic bag, sealed, stored in a cold container, and transported to the laboratory. The composite sample was sieved (< 2 mm) to remove large rocks, visible roots, and debris and separated into air-dried and fresh samples. The air-dried samples were finely ground and stored at room temperature prior to analysis of soil chemical properties, whereas the fresh soil samples were kept at 4°C prior to the analysis of soil enzyme activity[30].

Variable measurements

Random plants, which were divided into stems, leaves, petioles and root tubers, were selected at harvest. The plant samples were placed in the oven and dried to constant weight. The dry weight of each organ of the plant sample was recorded. The proportion of the dry matter (DM) distribution of each part was the dry weight of the part divided by the total dry weight[31]. The efficiency of N, P, and K fertilizers expressed in harvest index, N/P_2O_5/K_2O productive efficiency and N/P/K utilization efficiency was determined using Eqs. [32,33].

(1) Harvest index (%) = ((amount of N/P/K absorption of the root tuber)/(amount of N/P/K absorption of the whole plant)) × 100%,
(2) N/P_2O_5/K_2O productive efficiency (kg/kg) = (fresh yield of root tuber)/(amount of N/P_2O_5/K_2O fertilizer),
(3) N/P/K utilization efficiency (kg/kg) = (fresh yield of root tuber)/(amount of N/P/K absorption of the whole plant).

The soil urease activity was determined using sodium phenol–sodium hypochlorite colorimetry. The soil alkaline phosphatase (ALP) activity was measured using disodium phenyl phosphate colorimetry. The soil dehydrogenase (DHA) activity was determined using triphenyl tetrazolium chloride colorimetry. The soil sucrase activity was determined using the 3,5-dinitrosalicylic acid colorimetric method[34–36].

The soil organic matter (SOM) content, alkali-hydrolyzable N, available P, and available K were measured using the $K_2Cr_2O_7$ solution heating method, alkaline diffusion method, molybdenum-antimony colorimetry, and flame photometry, respectively[37].

All storage roots were harvested and weighed in the yield measurement area. Storage roots and plants were counted. The number of storage roots per plant and the average fresh weight per storage root were also calculated. The storage root was preserved for quality index determination.

The protopectin and WS pectin were measured using H_2SO_4–carbazole colorimetry[38]. The soluble sugar and starch contents were measured using anthrone colorimetry[39]. The carotenoid content was measured using the method of Sumanta et al.[40]. N was determined using the micro-Kjeldahl technique, and the crude protein content ($N \times 6.25$) was calculated[41].

Statistical analysis

Microsoft Excel (Microsoft Cooperation, Redmond, WA, USA) was used for data preprocessing, and the means of three replicates are presented. The statistically significant differences between treatment groups were determined via Duncan's multiple range test at $P < 0.05$ via ANOVA with SPSS 22.0 (SPSS Inc., Chicago, IL, USA). The correlation coefficients were calculated via Pearson's correlation coefficients among various parameters.

Results

DM accumulation and distribution

In 2018, the DM accumulation in leaves (DMAL) under T4 was not significantly different than that under T2 and T3, but it was significantly greater than that under the other treatments. In 2019, T2 and T4 resulted in significantly greater DMAL values than did the other treatments (Fig. 1a). In 2018, the DM accumulation in tuberous roots (DMAT) under T4 was the highest. T4 resulted in significantly greater DM accumulation in the tuberous roots (DMAT) than did T1 and T2. In 2019, the DMAT under T4 was not significantly different from those under T2 and T3 but was significantly greater than that under T1. The DM distribution ratio in the tuberous roots did not significantly differ among the fertilizer treatments in either year (Fig. 1b).

The results suggested that split fertigation was conducive to the improvement of DMAS and DMAT in both years compared with single fertigation. The combination of BF and split fertigation effectively improved DMAT. The application of BF or split fertigation had no significant effect on the DM distribution ratio in the tuberous roots.

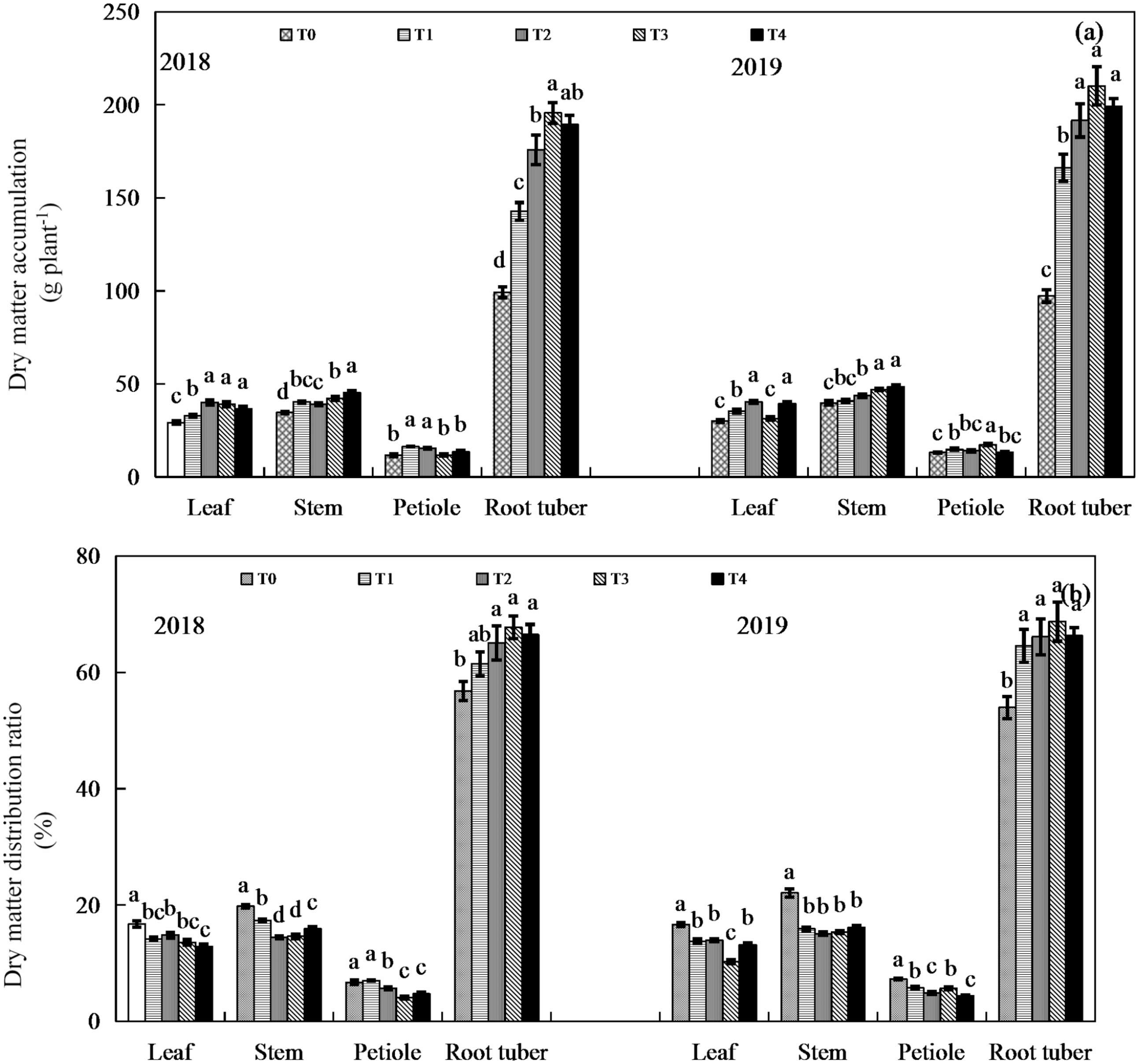

Fig. 1. Dry matter accumulation (a) and distribution ratio of dry matter (b) in different organs at harvest under different treatments. Means denoted by different letters are significantly different at $P < 0.05$ as determined by ANOVA-Duncan's multiple range test.

Soil enzyme activities

In 2019, the soil urease activity (URE) under T2, T3, and T4 was significantly greater than that under T0 and T1 (Fig. 2a). The soil sucrase activity (SUC) and DHA activity under T4 were the highest in both years (Fig. 2b and c). T2 resulted in significantly greater soil SUC than did T0, T1 and T3 in 2019. In 2018, the soil DHA activity under T2 and T3 was significantly greater than that under T0 and T1. In 2019, with the exception of T4, T2 resulted in the highest soil DHA activity, followed by T3. In 2018, the soil ALP activity under T4 was significantly greater than that under T1 and T3 (Fig. 2d). In 2019, the soil ALP activity under T4 was the highest, followed by that under T2 and that under T3.

The results revealed that the BF application significantly increased the activities of soil SUC and ALP in the second year and soil DHA activity in both years. Split fertigation significantly increased the activities of soil ALP in the second year and soil DHA activity in both years in comparison to single fertigation. The combined BF and split fertigation was the most conducive to improving the activities of soil SUC, DHA, and ALP, especially in the second year.

Soil fertility

There is no significant difference in the parameters of soil fertility in the 0–20 cm soil layer between years (Table 1). The impact of fertilizer treatments on the alkaline hydrolysis N (AN) content varies between the

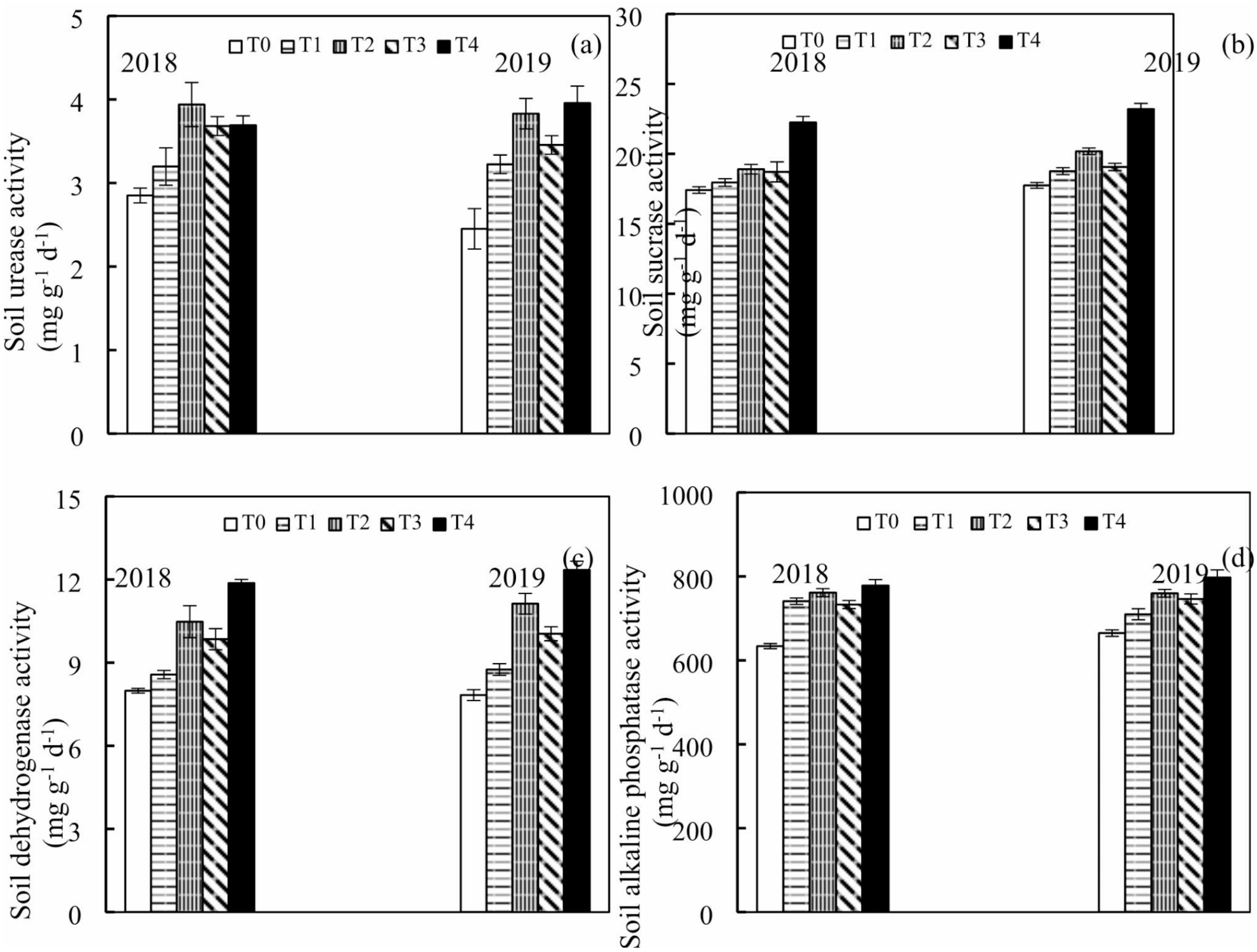

Fig. 2. Activities of soil urease (a), soil sucrase (b), soil dehydrogenase (c), and soil alkaline phosphatase (d) at in 0–20 cm soil layer at harvest under different treatments. Means denoted by different letters are significantly different at $P < 0.05$ as determined by ANOVA-Duncan's multiple range test.

two years. No significant difference in AN was detected among fertilizer treatments in 2018. In 2019, the AN under T4 was significantly greater than that under T0 and T1. The available P contents (AP) under T2 and T4 were significantly greater than those under the other treatments in both years. In 2019, the AP under T3 was significantly greater than that under T1. T4 resulted in a significantly greater available K content (AK) than T1 in 2018 and both T1 and T2 in 2019. T4 resulted in a significantly greater SOM content than did T1 and T2 in both years as well as the highest SOM content in 2019.

The results showed that BF or split fertigation improved the contents of AP and SOM in the second year. The combination of BF and split fertigation for two consecutive years effectively improved the AP, AK and SOM.

Root yield

There is no significant difference in the root yield (RT) between years (Table 2). In both years, there was no significant difference in the number of tuberous roots per plant between T1 and T2 or between T3 and T4, suggesting that BF had no significant effect on the number of tuberous roots per plant. In both years, the lowest RT was observed under T0, followed by T1. In 2018, there was no significant difference in RT between T4 and T3, and T4 resulted in significantly greater RT than did T2. In 2019, T4 resulted in the highest RT. The tuberous root weight per plant tended to be similar to that of RT.

The results revealed that split fertigation or BF increased the tuberous root weight per plant and the RT. The combination of BF and split fertigation was the most conducive to improving RT, especially in the second year.

Index of quality

There is no significant difference in the contents of protopectin, soluble pectin, carotenoids or crude protein between years (Table 3). However, the contents of starch and soluble sugar in 2018 were significantly lower than those in 2019. In 2018, the fertilization treatments showed no significant effects on the contents of protopectin or soluble pectin. The contents of starch and carotenoids under T2, T3, and T4 were significantly greater than those under T0 and T1. In 2019, T4 resulted in a significantly greater protopectin content than did T1 and T2.

Year	Treatments	Alkali-hydrolyzable nitrogen content (mg kg^{-1})	Available phosphorus content (mg kg^{-1})	Available potassium content (mg kg^{-1})	Organic matter content (g kg^{-1})
2018	T0	45.53 b	15.13 c	67.27 c	8.50 d
	T1	49.76 ab	17.07 bc	73.13 b	9.10 c
	T2	51.49 ab	21.03 a	76.98 ab	9.32 bc
	T3	51.87 a	18.97 b	77.91 ab	9.79 ab
	T4	48.12 ab	22.34 a	81.07 a	10.18 a
2019	T0	41.15 c	14.54 d	61.53 c	8.26 d
	T1	47.39 b	17.67 c	75.95 b	9.03 c
	T2	54.49 a	22.64 a	75.22 b	9.77 b
	T3	54.91 a	20.47 b	79.39 ab	9.98 b
	T4	56.41 a	24.22 a	84.36 a	10.99 a
ANOVA					
Year		ns	ns	ns	ns
Treatment		ns	**	*	*
Year×Treatment		*	ns	ns	ns

Table 1. Soil fertility at 0–20 cm soil layer at harvest under different treatments. T0: no fertilizer application, T1: basic application of 450 kg ha^{-1} WS fertilizer, T2: basic application of 60 L ha^{-1} BF and 450 kg ha^{-1} WS fertilizer, T3: split application of 450 kg ha^{-1} WS fertilizer, T4: combined basic application of 60 L ha^{-1} BF and split application of 450 kg ha^{-1} WS fertilizer. Values within the same column of the same year with different letters differ significantly as determined by ANOVA-Duncan's multiple range test ($p < 0.05$). *, $P \leq 0.05$; **, $P \leq 0.01$; ns, not significant.

Year	Treatments	Number of tuber roots per plant	Tuber root weight per plant (g)	Root yield (kg ha^{-1})
2018	T0	3.18 b	446.85 d	24284.29 d
	T1	3.71 a	536.44 c	29152.65 c
	T2	4.07 a	611.03 b	33206.42 b
	T3	3.82 a	657.58 ab	35736.43 ab
	T4	3.93 a	680.51 a	36982.27 a
2019	T0	3.38 c	433.10 d	23536.78 d
	T1	3.96 b	579.82 c	31510.16 c
	T2	3.98 b	661.82 b	35966.43 b
	T3	4.36 a	683.51 b	37145.19 b
	T4	4.02 ab	744.17 a	40441.87 a
ANOVA				
Year		ns	ns	ns
Treatment		*	**	**
Year×Treatment		ns	ns	ns

Table 2. Number of tuber roots per plant, tuber root weight per plant and root yield at harvest under different treatments. T0: no fertilizer application, T1: basic application of 450 kg ha^{-1} WS fertilizer, T2: basic application of 60 L ha^{-1} BF and 450 kg ha^{-1} WS fertilizer, T3: split application of 450 kg ha^{-1} WS fertilizer, T4: combined basic application of 60 L ha^{-1} BF and split application of 450 kg ha^{-1} WS fertilizer. Values within the same column of the same year with different letters differ significantly as determined by ANOVA-Duncan's multiple range test ($p < 0.05$). *, $P \leq 0.05$; **, $P \leq 0.01$; ns, not significant.

The soluble pectin content under T3 and T4 was significantly greater than that under T1 and T2. Similar results were observed for the starch content.

The impact of fertilizer treatments on the contents of soluble sugar, carotenoids and crude protein varied between the two years. In 2018, the soluble sugar content under T3 was the highest. In 2019, the soluble sugar content under T3 was not significantly different from that under T4 but was significantly greater than that under T1 and T2. In 2018, the carotenoid contents under T2, T3 and T4 were significantly greater than those under T0 and T1. However, in 2019, T4 resulted in the highest carotenoid content, followed by T3. In both years, T3 and T4 resulted in a significantly greater crude protein content than did T0 and T1.

The results revealed that the effects of fertilizer application on the quality indices gradually increased. Compared with single fertigation, two consecutive years of split fertigation was conducive to increasing the contents of pectin, starch, carotenoids, and crude protein. However, BF application only increased the contents

Year	Treatments	Protopectin content (mg g^{-1} FW)	Soluble pectin content (mg g^{-1} DW)	Starch content (mg g^{-1} FW)	Soluble sugar content (mg g^{-1} FW)	Carotenoid content (μmg g^{-1} FW)	Crude protein content (%)
2018	T0	155.59 b	27.57 b	113.43 c	41.57 c	7.45 b	2.97 c
	T1	177.65 a	32.19 a	140.46 b	63.02 b	8.22 b	3.57 b
	T2	193.27 a	33.10 a	154.79 a	61.19 b	10.49 a	4.15 a
	T3	193.16 a	32.79 a	153.84 a	74.98 a	10.93 a	4.32 a
	T4	196.49 a	33.21 a	157.12 a	62.05 b	11.39 a	4.11 a
2019	T0	146.98 d	28.45 b	123.43 c	44.16 d	7.07 d	3.01 c
	T1	171.85 c	31.50 b	153.03 b	64.60 c	7.67 d	3.96 b
	T2	188.27 bc	32.42 b	162.21 b	70.98 b	10.02 c	4.18 b
	T3	206.84 ab	39.11 a	181.08 a	80.40 a	11.16 b	4.81 a
	T4	203.33 a	38.21 a	180.48 a	76.27 ab	13.43 a	4.65 a
ANOVA							
Year		ns	ns	*	*	ns	ns
Treatment		**	ns	**	**	*	**
Year×Treatment		ns	ns	ns	*	*	*

Table 3. Index of quality at harvest under different treatments. T0: no fertilizer application, T1: basic application of 450 kg ha^{-1} WS fertilizer, T2: basic application of 60 L ha^{-1} BF and 450 kg ha^{-1} WS fertilizer, T3: split application of 450 kg ha^{-1} WS fertilizer, T4: combined basic application of 60 L ha^{-1} BF and split application of 450 kg ha^{-1} WS fertilizer. Values within the same column of the same year with different letters differ significantly as determined by ANOVA-Duncan's multiple range test ($p < 0.05$). *, $P \leq 0.05$; **, $P \leq 0.01$; ns, not significant.

Year	Treatments	*N* harvest index	*N* utilization efficiency (kg kg^{-1})	*N* productive efficiency (kg kg^{-1})	*P* harvest index	*P* utilization efficiency (kg kg^{-1})	P_2O_5 productive efficiency (kg kg^{-1})	K harvest index	K utilization efficiency (kg kg^{-1})	K_2O productive efficiency (kg kg^{-1})
2018	T0	41.74 c	225.64 a		47.99 c	978.00 ab		49.84 b	208.64 a	
	T1	46.96 b	192.33 b	647.84 c	53.03 b	961.31 b	647.84 c	50.73 b	145.13 c	215.60 c
	T2	49.65 ab	194.02 b	737.92 b	52.46 b	1034.51 a	737.92 b	49.58 b	149.81 bc	245.58 b
	T3	50.22 a	202.18 b	794.14 a	54.00 b	982.02 ab	794.14 a	50.51 b	155.52 b	264.29 a
	T4	52.67 a	199.29 b	821.83 a	60.91 a	1031.01 a	821.83 a	54.41 a	157.80 b	273.50 a
2019	T0	37.87 d	214.10 ab		46.36 c	803.82 c		47.89 b	194.98 a	
	T1	45.12 c	202.07 b	700.23 c	56.97 b	839.72 bc	700.23 c	53.96 a	144.99 c	233.03 c
	T2	51.03 b	201.78 b	799.25 b	56.04 b	917.37 a	799.25 b	48.60 b	166.70 b	265.99 b
	T3	49.44 b	205.59 b	825.45 b	55.60 b	872.96 ab	825.45 b	55.84 a	145.31 c	274.70 b
	T4	56.69 a	219.39 a	898.71 a	64.41 a	942.90 a	898.71 a	53.26 a	161.42 b	299.08 a
ANOVA										
Year		ns	ns	*	ns	**	*	ns	ns	*
Treatment		*	ns	**	**	*	**	ns	*	**
Year×Treatment		ns	ns	ns	ns	ns	ns	ns	*	ns

Table 4. The harvest indexes, utilization efficiency and productive efficiency of N, P and K under different treatments. T0: no fertilizer application, T1: basic application of 450 kg ha^{-1} WS fertilizer, T2: basic application of 60 L ha^{-1} BF and 450 kg ha^{-1} WS fertilizer, T3: split application of 450 kg ha^{-1} WS fertilizer, T4: combined basic application of 60 L ha^{-1} BF and split application of 450 kg ha^{-1} WS fertilizer. Values within the same column of the same year with different letters differ significantly as determined by ANOVA-Duncan's multiple range test ($p < 0.05$). *, $P \leq 0.05$; **, $P \leq 0.01$; ns, not significant.

of soluble sugars and carotenoids. The combination of BF and split fertigation was beneficial for improving root quality as demonstrated by relatively high values of these parameters.

Nutrient use efficiency

The productive efficiencies of N, P_2O_5 and K_2O in 2019 were significantly greater than those in 2018 (Table 4). In 2019, the N harvest index (NHI) under T4 was the highest. T2 and T3 resulted in significantly higher NHIs than did T1 (Table 4). The P harvest index (PHI) under T4 was the highest in both years. There was no significant difference among the other fertilizer treatments. There was no significant difference in the K harvest index (KHI) under T1, T2 and T3 in 2018 or under T1, T3 and T4 in 2019.

There was no significant difference in N utilization efficiency (NUE) among T1, T2 and T3 in either years. However, the P utilization efficiency (PUE) under T2 and T4 was significantly greater than that under T1. In 2019, the K utilization efficiency (KUE) under T2 and T4 was significantly greater than that under T1 and T3. In 2018, the N production efficiency values under T3 and T4 were significantly greater than those under the other treatments, and T2 resulted in greater N production efficiency than did T1. In 2019, the N production efficiency under T4 was the highest, and T2 and T3 resulted in significantly higher N production efficiencies than did T1. The productive efficiency of P_2O_5 and K_2O showed similar changes to those of the N productive efficiency.

The results suggested that split fertigation or BF application effectively improved the NHI and the productive efficiency of N, P_2O_5 and K_2O in the second year. The combination of BF and split fertigation resulted in the highest NHI, PHI, and productive efficiency of N, P_2O_5, and K_2O after two years of application.

Correlation analysis

We used correlation coefficients to assess the relationships among the parameters of root yield (RT), biomass accumulation, NUE, PUE, KUE, soil fertility, and soil enzyme activity (Table 5). The DMAL, DMAS, DMAT, KUE, AN, AP, AK, SOM, URE, SUC, DHA, and ALP were significantly positively correlated with RT. Similar correlations were observed among DMAT, AN, AP, AK, SOM, and all soil enzymes. AN, AP, AK, SOM, SUC, DHA, and ALP were positively correlated with PUE. Significant correlations were observed among AN, URE, SUC, DHA, and ALP. Similar correlations were observed among AP, AK, SOM and all soil enzymes.

Discussion

According to Li et al.[42], split fertilizer application is conducive to increasing soil available N, P, and K in tobacco fields. In the present study, split fertigation for two continuous years increased the activities of soil DHA and ALP, thereby promoting soil nutrient activation and exhibiting positive increased effects on soil available P and SOM. Split fertigation ameliorated soil nutrients in the continuous sweet potato cropping field. In a continuous maize and lettuce cropping systems, manure application is conducive to the enhancement of soil quality[43,44]. In a sweet potato field, the combined application of NPK fertilizer and poultry manure gives higher soil available N and P[45]. The application of BF that contains living microorganisms is one of the management practices that can improve soil fertility in arable soils[46]. The combination of chemical fertilizer and BF increases the soil chemical properties of available P and K and SOM in a continuous cropping cotton system[47,48]. The BF applied in the present study contained *B. subtilis*, *T. pseudokiningii*, and K fulvic acid and decomposed organic matter. The BF applied for two consecutive years significantly increased the activities of soil sucrase, DHA, and ALP, and significantly improving the soil available P and SOM. These results verified that the soil activity of ALP is positively correlated with the contents of soil available P and SOM[49]. Most of the microbial species in the soil are positively correlated with the nutrient content in the soil[50]. Li et al.[47] showed that soil organic carbon and available P are positively correlated with the abundances of *Bacillus* and *Trichoderma* in monocropping cotton fields. In a sweet potato continuous cropping field, the increased soil available P may be attributed to the increased abundances of *Bacillus* and *Trichoderma* added in the BF. Moreover, the SOM provided by K fulvic acid and decomposed organic matter may increase SOM and exhibit a priming effect on increasing soil available N and mineralize with time, in which the inorganic P available from the WS fertilizer increases the available P[3,51]. In a continuous monocropping sweet potato field, the recommended utilization of combined WS and BF is considered useful for the preservation of high soil biological activity and fertility.

Application timing is one of the management strategies that can influence the efficiency in which the applied fertilizer is utilized by crops. Tarkalson and Payero[52] found that increased N is supplied to plants with multiple in-season fertigations compared with a single fertigation. Liu et al.[53] reported that split fertigation increases aboveground N uptake compared with single fertigation. According to Yin et al.[54], split fertigation can be used to replace single broadcast applications on the soil surface of pear orchards and improve the NUE and PUE. In sweet potato, compared with basal application, split K fertigation (half at planting and half at the tuberous root expansion stage) increases N and K accumulation and NUE and KUE[55]. In the present study, compared with single fertigation, split fertigation at a ratio of 2:5:3 in the stages of root branching, ridge covering, and tuberous root expansion increased the productive efficiency of N, P_2O_5, and K_2O in both years. This finding was attributed to the higher root yield obtained using split fertigation. No significant change in the NUE, PUE, and KUE may be related to the simultaneous increase in the absorption of N, P, and K in sweet potato plants. The application of BF can increase the nutrient uptake efficiency and minimize the negative effects of consuming too much fertilizer[56]. Increases in N concentrations were observed in the leaves of plants inoculated with *Trichoderma* and *Bacillus* isolates[57]. The BF containing *Bacillus subtilis* regulated the microbial N transformation process and reduced N loss in soil; it also significantly increased N use efficiency[18]. In potato, the use of the bacteria *Bacillus subtilis* promoted greater P uptake kinetics and increased the production of P fertilizer efficiency[58]. Similar results were observed in wheat plants[59]. In the present study, the BF applied in drip irrigation for two consecutive years had positive effects on NUE and PUE. This strategy significantly increased the KUE and the productive efficiency of N, P_2O_5, and K_2O. Positive effects on biological parameters in a monoculture banana field were observed in the BF application only for a 1-year period[60]. These effects may be attributed to the different crops and soil environments. The BF consisting of *B. subtilis* and *T. pseudokiningii* in the present study may alter the microbial community structure and stimulate the population of beneficial microorganisms[61], which increased the activities of soil sucrase, DHA and ALP, resulted in soil nutrient improvement (soil available P and SOM) and finally increased yield and element utilization efficiency, especially PUE and KUE. The combination of BF and split fertigation was the most conducive to obtaining higher root yield and higher productive efficiency in N, P_2O_5, and K_2O fertilizers in sweet potato continuous cropping fields.

	RT	DMAL	DMAS	DMAP	DMAT	NUE	PUE	KUE	AN	AP	AK	SOM	URE	SUC	DHA	ALP
RT	1															
DMAL	0.63*	1														
DMAS	0.67**	0.49*	1													
DMAP	0.16	0.05	0.26	1												
DMAT	0.84**	0.71**	0.75**	0.3	1											
NUE	-0.09	-0.41	-0.35	-0.50*	-0.50*	1										
PUE	0.36	0.49*	0.19	-0.21	0.32	0.02	1									
KUE	-0.63*	-0.62*	-0.61*	-0.39	-0.73**	0.59*	-0.26	1								
AN	0.54*	0.69**	0.63*	0.08	0.76**	-0.62**	0.42*	-0.63*	1							
AP	0.71**	0.75**	0.72**	0.15	0.77**	-0.46*	0.54*	-0.63*	0.80**	1						
AK	0.81**	0.68**	0.75**	0.07	0.81**	-0.39	0.46*	-0.80**	0.81**	0.83**	1					
SOM	0.77**	0.61*	0.87**	0.07	0.82**	-0.35	0.46*	-0.67**	0.75**	0.88**	0.89**	1				
URE	0.64*	0.76**	0.67**	0.23	0.83**	-0.65**	0.34	-0.69**	0.83**	0.88**	0.78**	0.79**	1			
SUC	0.65**	0.59*	0.73**	-0.12	0.61*	-0.17	0.50*	-0.53*	0.57*	0.83**	0.79**	0.87**	0.70**	1		
DHA	0.80**	0.73**	0.72**	-0.03	0.74**	-0.23	0.58*	-0.59*	0.68**	0.93**	0.84**	0.89**	0.80**	0.92**	1	
ALP	0.79**	0.78**	0.77**	0.2	0.81**	-0.49*	0.49*	-0.80**	0.81**	0.93**	0.92**	0.89**	0.85**	0.81**	0.89**	1

Table 5. Correlation coefficients to assess the relationships among the parameters of RT, biomass accumulation, NUE, PUE, KUE, soil fertility, and soil enzyme activity. RT: root yield, DMAL: DM accumulation in leaves, DMAS: DM accumulation in stems, DMAP: DM accumulation in petioles, DMAT: DM accumulation in tuberous roots, NUE: N utilization efficiency, PUE: P utilization efficiency, KUE: K utilization efficiency, AN: alkali-hydrolyzable N content, AP: available P content, AK: available K content, SOM: soil organic matter, URE: urease activity, SUC: sucrase activity, DHA: dehydrogenase activity, ALP: alkaline phosphatase activity.

The improvement in DM accumulation with humic acid could be attributed to it potential effect to enhance plant piments, stomatal conductance and photosynthesis process[62]. Chen et al.[63] reported that humic acid urea fertilizer increases the DM accumulation of storage roots and aboveground parts in sweet potato plants during the growth stages. In the present study, compared with the control, fertilizer application increased DM accumulation in leaves, stems, and tuber roots and decreased the distribution ratio of DM in leaves and stems at harvest. Split fertigation or BF application was beneficial in increasing DM accumulation in tuberous roots, which was the material basis for increasing yield production. The maize yield under split fertigation is significantly greater than that under single fertigation[53]. Compared with the broadcast application of N and P, split fertigation increases the marketable fruit of pear[54]. Kelling et al.[64] reported that splitting N fertilizer into stages of emergence, early tuberization, and tuberization can increase potato yield in sandy soil. However, Zebarth et al.[65] have shown that split N application exhibits limited benefits on tomato yield. In the present study, the split fertigation of WS fertilizer in stages of root branching, ridge covering, and tuberous root expansion increased root yield in both years. This phenomenon was related to meeting the nutrient needs at different periods for sweet potato plants. The combined application of organic and inorganic fertilizers provided greater crop productivity. Choudhary et al.[66] showed that a significantly higher yield was observed in plots receiving NPK combined with manure in a soybean–wheat cropping system. In sweet potato, the combined application of NPK fertilizer and poultry manure exhibits higher tuber yield[45]. Bonanomi et al.[24] found that combining photoselective mulching films with beneficial microbes (i.e., *Trichoderma* and *Bacillus subtilis*) promotes crop yield. In cucumber, *Trichoderma pseudokoningii* inoculations stimulate metabolism in plants and enhance the activities of stress-resistance enzymes, which consequently promote plant growth and improve yield[67]. Ding et al.[68] showed that BFs containing *B. subtilis* increase potato yield. In the present study, BF consisting of *B. subtilis*, *T. pseudokiningii* and organic matter improved root yield by increasing tuberous root weight per plant. The combination of BF and split fertigation with WS fertilizer exhibited the highest root yield after continuous application for two years. Huang et al.[50] reported that a high concentration of BF increased cucumber production after continuous cropping, possibly through improving soil chemical conditions and manipulating the composition of the soil microbial community. In the sweet potato continuous cropping field, the BF consisting of *B. subtilis* and *T. pseudokiningii* also exhibited soil nutrient improvement, especially in soil available P and SOM. The yield increase was related to the soil nutrient improvement by the soil microenvironment regulation altered by beneficial microbes added in this kind of BF. The combination of BF and split fertigation with WS fertilizer was the most conducive to the improvement of sustainable productivity under continuous sweet potato cropping.

The fruit quality of pineapple was influenced by the split application of N and K[69]. Compared with all N fertilizers applied at sowing alone, the application of half or one-third of the total N fertilizer at stem elongation improves the grain protein content of spring wheat[70]. For white cabbage, split N increases indole and total glucosinolate concentrations compared with nonsplit N[71]. In the present study, the split fertigation of N, P, and K for two consecutive years improved tuber quality by increasing the contents of pectin, soluble sugar, carotenoid, and crude protein. Meeting the needs of nutrients in different growth periods was important for improving the root quality of sweet potato. Chemical fertilizers enhance the crop growth, leaf nutrient content and quality of the final product[72]. Yolcu[73] reported that organic and chemical fertilizer applications have significant effects on the crude protein content of common vetch. However, no effect was recorded on tuber N, P, or starch content in organic potato[74]. Soil amended with BF improves banana quality by increasing the total soluble sugars and sugar/acid ratio[75,76]. Akca and Ercisli[77] demonstrated that BF imparts positive effects on sweet cherry quality. *Trichoderma pseudokoningii* inoculations could prevent cucumber fusarium wilt and improve quality[67]. In the present study, the BF showed no significant effect on tuber quality except for increased contents of soluble sugar and carotenoid. This phenomenon may be related to the different crops and climate conditions. The combination of BF and split fertigation could improve sweet potato root yield without degrading its quality in a continuous cropping system under plastic film-mulched drip-fertigated field conditions.

Akhtar et al.[78] reporeted that soil URE and ALP had positive correlations with soil organic carbon (SOC). Moreover, the soil URE had a positive correlation with soil AP and the crop yield was positively correlated with the soil AN and AP. Borase et al.[79] showed that wheat yield was positively correlated with SOC and the SOC showed a significant positive correlation with all soil enzymes. Yang et al.[80] also showed that SOC, soil URE and SUC had positive correlations with the wheat yield. Under a rice-wheat rotation in Chengdu Plain, China, there was positive correlation with SOC, soil URE, AP and AK[81]. However, there was no positive correlation between AP, AK, URE, and DHA under a maize–wheat rotation in a rainfed Indian soil[82]. For rice, there was correlation among the rice yield, AP and AK[81]. For potato, soil AN had a significant influence on SOC, soil AP and AK. The soil URE had a significant influence on soil SUC and ALP[83]. For tomato, there was no correlation between the tomato fruit yield and SOM, AP and AK. However, there was positive correlation with soil AP, AK, and SOM[84] (Ye et al., 2020). In the present study, for sweet potato, significant correlations were observed among AN, AP, AK, SOM and URE, SUC, DHA, and ALP, indicating that the higher the activity of these soil enzymes, the higher contents of soil fertility. Similar correlations were observed among DMAT, AN, AP, AK, SOM, and all soil enzymes, suggesting that the improved soil nutrient status is beneficial for increasing DMAT, therefore, the final RT was increased. The improved soil nutrient status caused by the combination of BF with split fertigation was the main reason for increasing the final RT in this study.

Conclusions

The combination of BF with split fertigation for two consecutive years significantly increased the activities of soil SUC, DHA, and ALP and positively affected the soil AP, AK and SOM, thereby promoting plant nutrient absorption and resulting in high plant DM accumulation. This cultivation method ultimately resulted in a relatively high RT and improved root quality by maintaining relatively high contents of pectin, soluble sugar, and carotenoid, which can effectively alleviate the problems associated with the consecutive monoculture of sweet potato. The combined basic application of 60 L ha^{-1} BF and split application of 450 kg ha^{-1} WS fertilizer was the most promising treatment for farming sweet potato, and it could alleviate problems associated with the consecutive monoculture of sweet potato.

Data availability

All data generated and/or analyzed during the current study are included in this article.

Received: 8 February 2024; Accepted: 4 November 2024

References

1. Srinivasarao, C. et al. Continuous cropping under elevated CO_2: Differential effects on C_4 and C_3 crops, soil properties and carbon dynamics in vsemi-arid alfisols. *Agr Ecosyst. Environ.* **218**, 73–86 (2016).
2. Jie, W. G., Liu, X. R. & Cai, B. Y. Diversity of rhizosphere soil arbuscular mycorrhizal fungi in various soybean cultivars under different continuous cropping regimes. *PLoS One*. **8**, e72898 (2013).
3. Qin, W., Wang, D. Z., Guo, X. S., Yang, T. M. & Oenema, O. Productivity and sustainability of rainfed wheat-soybean system in the North China Plain: Results from a long-term experiment and crop modelling. *Sci. Rep.* **5**, 17514 (2015).
4. Han, G. M. et al. Biochar effects on bacterial community and metabolic pathways in continuously cotton-cropped soil. *J. Soil Sci. Plant. Nutr*. **19**, 249–261 (2019).
5. Li, Y. et al. Humic acid fertilizer improved soil properties and soil microbial diversity of continuous cropping peanut: A three-year experiment. *Sci. Rep.* **9**, 12014 (2019).
6. Gao, Z. M. et al. Effects of continuous cropping of sweet potato on the fungal community structure in Rhizospheric soil. *Front. Microbiol.* **10**, 2269 (2019).
7. Lee, H. U., Chung, M. N., Han, S. K., Ahn, S. H. & Choi, I. H. Effect of subsoiling on growth and yield of sweetpotato in continuous sweetpotato cropping field. *Kor J. Crop Sci.* **60**, 47–53 (2015).
8. Dong, Z. Q. et al. Effect of different NPK fertilization timing sequences management on soil-petiole system nutrient uptake and fertilizer utilization efficiency of drip irrigation cotton. *Sci. Rep.* **13**, 14287 (2023).
9. Liu, M. J. et al. Enhancement growth, water use efficiency and economic benefit for maize by drip irrigation in Northwest China. *Sci. Rep.* **13**, 8392 (2023).
10. Önder, D., Onder, S., Cahskan, M. E. & Cahskan, S. Influence of different irrigation methods and irrigation levles on water use efficiency, yield, and yield attributes of sweet potato. *Fresen Environ. Bull.* **24**, 3398–3403 (2015).
11. Huang, F. Y. et al. Impact of farmland mulching practices on the soil bacterial community structure in the semiarid area of the loess plateau in China. *Eur. J. Soil. Biol.* **92**, 8–15 (2019).
12. Saudy, H. S., El-Bially, M. A., Ramadan, K. A. & El-Nasr, A. H. & Abd El-Samad, G.A. Potentiality of soil mulch and sorghum extract to reduce the biotic stress of weeds with enhancing yield and nutrient uptake of maize crop. *Gesunde Pflanzen*. **73**, 555–564 (2021).
13. Wees, D., Seguin, P. & Boisclair, J. Sweet potato production in a short-season area utilizing black plastic mulch: Effects of cultivar, in-row plant spacing, and harvest date on yield parameters. *Can. J. Plant. Sci.* **96**, 139–147 (2016).
14. Hou, F. Y. et al. Mulching with plastic film improved the root quality of summer-sown sweet potato (*Ipomoea batatas* (L). Lam.) In northern China. *J. Integr. Agr*. **18**, 982–991 (2019).
15. Varughese, A. & Habeeburrahman, P. V. Fertigation and plastic mulching in tomato and brinjal-A review. *Agric. Rev.* **36**, 246–249 (2015).
16. Ma, Z. W. et al. Urea fertigation sources affect nitrous oxide emission from a drip-fertigated cotton field in northwestern China. *Agr Ecosyst. Environ.* **265**, 22–30 (2018).
17. Wu, D. L. et al. Effect of different drip fertigation methods on maize yield, nutrient and water productivity in two-soils in Northeast China. *Agr Water Manage.* **213**, 200–211 (2019).
18. Sun, B. et al. Application of biofertilizer containing *Bacillus subtilis* reduced the nitrogen loss in agricultural soil. *Soil. Biol. Bioch.* **148**, 107911 (2020).
19. Basu, S., Rabara, R. & Negi, S. Towards a better greener future-an alternative strategy using biofertilizers. I: Plant growth promoting bacteria. *Plant. Gene*. **12**, 43–49 (2017).
20. Xiong, W. et al. Bio-fertilizer application induces soil suppressiveness against Fusarium wilt disease by reshaping the soil microbiome. *Soil. Biol. Bioch*. **114**, 238–247 (2017).
21. Du, T. Y. et al. Long-term organic fertilizer and biofertilizer application strengthens the associations between soil quality index, network complexity, and walnut yield. *Eur. J. Soil. Biol.* **116**, 103492 (2023).
22. Amirnia, R. et al. Nitrogen-fixing soil bacteria plus mycorrhizal fungi improve seed yield and quality traits of Lentil (*Lens culinaris* Medik). *J. Soil. Sci. Plant. Nutr.* **19**, 592–602 (2019).
23. Chen, W. et al. Mechanisms by which organic fertilizer and effective microbes mitigate peanut continuous cropping yield constraints in a red soil of south China. *Appl. Soil. Ecol.* **128**, 23–34 (2018).
24. Bonanomi, G. et al. Combined application of photo-selective mulching films and beneficial microbes affects crop yield and irrigation water productivity in intensive farming systems. *Agric. Water Manage.* **184**, 104–113 (2017).
25. Htwe, A. Z., Moh, S. M., Soe, K. M., Moe, K. & Yamakawa, T. Effects of biofertilizer produced from Bradyrhizobium and Streptomyces griseoflavus on plant growth, nodulation, nitrogen fixation, nutrient uptake, and seed yield of mung bean, cowpea, and soybean. *Agronomy*. **9**, 77 (2019).
26. El Amerany, F., Rhazi, M., Wahbi, S., Taourirte, M. & Meddich, A. The effect of Chitosan, arbuscular mycorrhizal fungi, and compost applied individually or in combination on growth, nutrient uptake, and stem anatomy of tomato. *Sci. Hortic.* **261**, 109015 (2020).
27. Wu, J. J. et al. Taxonomic response of bacterial and fungal populations to biofertilizers applied to soil or substrate in greenhouse-grown cucumber. *Sci. Rep.* **12**, 18522 (2022).
28. Wen, Z. H., Chen, Y. X., Liu, Z. Q. & Meng, J. Biochar and arbuscular mycorrhizal fungi stimulate rice root growth strategy and soil nutrient availability. *Eur. J. Soil. Biol.* **113**, 103448 (2022).
29. IUSS Working Group WRB. World Reference Base for Soil Resources. Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome (2015). (2014).
30. Jiang, Y. M. et al. Effect of herbicide used with years (8 + 1) on soil enzymic activity and microbial population diversity. *J. Soil. Sediment.* **17**, 2490–2499 (2017).
31. Zhang, Z., Yu, Z. W., Zhang, Y. L. & Shi, Y. Split nitrogen fertilizer application improved grain yield in winter wheat (*Triticum aestivum* L.) via modulating antioxidant capacity and ^{13}C photosynthate mobilization under water-saving irrigation conditions. *Ecol. Process.* **10**, 21 (2021).
32. López-Bellido, L., López-Bellido, R. J. & Redondo, R. Nitrogen efficiency in wheat under rainfed mediterranean conditions as affected by split nitrogen application. *Field Crop Res.* **94**, 86–97 (2005).

33. Chen, X. G., Kou, M., Tang, Z. H., Zhang, A. J. & Li, H. M. The use of humic acid urea fertilizer for increasing yield and utilization of nitrogen in sweet potato. *Plant. Soil. Environ.* **63**, 201–206 (2017).
34. Kotroczó, Z. et al. Soil enzyme activity in response to long-term organic matter manipulation. *Soil. Biol. Biochem.* **70**, 237–243 (2014).
35. Liu, Y. M., Yang, H. Y., Li, X. R. & Xing, Z. S. Effects of biological soil crusts on soil enzyme activities in revegetated areas of the Tengger Desert, China. *Appl. Soil. Ecol.* **80**, 6–14 (2014).
36. Singh, D., Sharma, P., Kumar, U., Daverey, A. & Arunachalam, K. Effect of forest fire on soil microbial biomass and enzymatic activity in oak and pine forests of Uttarakhand Himalaya, India. *Ecol. Process.* **10**, 29 (2021).
37. Li, Z. G. et al. Woody organic amendments for retaining soil water, improving soil properties and enhancing plant growth in desertified soils of Ningxia. *China Geoderma*. **310**, 143–152 (2018).
38. Wang, H. et al. 1-Methylcyclopropene containing-papers suppress the disassembly of cell wall polysaccharides in Anxi Persimmon fruit during storage. *Int. J. Biol. Macromol.* **151**, 723–729 (2020).
39. Liu, H. J. et al. Switch from apoplasmic to symplasmic phloem unloading during storage roots formation and bulking of sweetpotato. *Crop Sci.* **59**, 675–683 (2019).
40. Sumanta, N., Haque, C. I., Nishika, J. & Suprakash, R. Spectrophotometric analysis of chlorophylls and carotenoids from commonly grown fern species by using various extracting solvents. *Res. J. Chem. Sci.* **4**, 63–69 (2014).
41. Uzun, A., Gücer, S. & Acikgoz, E. Common vetch (*Vicia sativa* L.) germplasm: correlations of crude protein and mineral content to seed traits. *Plant. Foods Hum. Nutr.* **66**, 254–260 (2011).
42. Li, Q. L., Huang, C. G., Qi, Y. J. & Yang, Z. J. Effects of base-topdressing ratio and number of topdressing on soil nutrient content in tobacco field. *Grain Oil Sci. Tech.* **44**, 93–94 (2019).
43. Mujuru, L., Rusinamhodzi, L., Nyamangara, J. & Hoosbeek, M. R. Effects of nitrogen fertilizer and manure application on storage of carbon and nitrogen under continuous maize cropping in Arenosols and Luvisols of Zimbabwe. *J. Agric. Sci.* **154**, 1–16 (2016).
44. Abd-Elrahman, S. H., Saudy, H. S., El-Fattah, A., Hashem, F. A. & D.A. & Effect of irrigation water and organic fertilizer on reducing nitrate accumulation and boosting lettuce productivity. *J. Soil. Sci. Plant. Nutr.* **22**, 2144–2155 (2022).
45. Agbede, T. M. Tillage and fertilizer effects on some soil properties, leaf nutrient concentrations, growth and sweet potato yield on an Alfisol in southwestern Nigeria. *Soil. Till Res.* **110**, 25–32 (2010).
46. Dębska, B., Ugosz, D., Piotrowska, D. J., Ugosz, A. & Banach-Szott, M. The impact of a bio-fertilizer on the soil organic matter status and carbon sequestration-results from a field-scale study. *J. Soil. Sediment.* **16**, 2335–2343 (2016).
47. Li, R., Tao, R., Ling, N. & Chu, G. X. Chemical, organic and bio-fertilizer management practices effect on soil physicochemical property and antagonistic bacteria abundance of a cotton field: implications for soil biological quality. *Soil. Till Res.* **167**, 30–38 (2017).
48. Saudy, H. S., Hamed, M. F., El-Metwally, I. M., Ramadan, K. A. & Aisa, K. H. Assessing the effect of biochar or compost application as a spot placement on broomrape control in two cultivars of faba bean. *J. Soil. Sci. Plant. Nutr.* **21**, 1856–1866 (2021).
49. Hu, C. et al. Effect of biological organic manure on soil enzyme activity and crop yields. *Acta Agric. Boreali-Sin*. **32**, 308–312 (2017).
50. Huang, N. et al. The influence of different concentrations of bio-organic fertilizer on cucumber *fusarium* wilt and soil microflora alterations. *PLoS One*. **12**, e0171490 (2017).
51. Rezig, F. A. M., Mubarak, A. R. & Ehadi, E. A. Impact of organic residues and mineral fertilizer application on soil-crop system: II soil attributes. *Arch. Agron. Soil. Sci.* **59**, 1245–1261 (2013).
52. Tarkalson, D. D. & Payero, J. O. Comparison of nitrogen fertilization methods and rates for subsurface drip irrigated corn in the semi-arid Great Plains. *T ASABE*. **51**, 1633–1643 (2008).
53. Liu, Y., Li, J. S. & Li, Y. K. Effects of split fertigation rates on the dynamics of nitrate in soil and the yield of mulched drip-irrigated maize in the sub-humid region. *Appl. Eng. Agric.* **31**, 103–117 (2015).
54. Yin, X. H., Bai, J. H. & Seavert, C. F. Pear responses to split fertigation and band placement of nitrogen and phosphorus. *Horttechnology*. **19**, 586–592 (2008).
55. Wang, F., Wang, Z. H., Kou, C. L., Ma, Z. H. & Zhao, D. Responses of wheat yield, macro- and micro-nutrients, and heavy metals in soil and wheat following the application of manure compost on the north China plain. *PLoS One*. **11**, e0146453 (2016).
56. Rezaienia, M., Ramroudi, M., Galavi, M. & Fofouzandeh, M. Effects of bio-fertilizers on physiological traits and absorption of some nutrients of chicory (Cichoriumintybus L.) in response to drought stress. *Pizhūhishhā-yiulum-i dāmī-i Īrān*. **15**, 925–938 (2018).
57. Yobo, K. S., Laing, M. D. & Hunter, C. H. Effects of single and dual applications of selected *Trichoderma* and *Bacillus* isolates on performance of dry bean seedlings grown in composted pine bark growth medium under shadehouse conditions. *J. Plant. Nutr.* **32**, 1271–1289 (2009).
58. Covarrubias-Ramírez, J. M. et al. Phosphorus uptake and use efficiency by potato cultivar alpha using ^{32}P. *Agrociencia*. **39**, 127–136 (2005).
59. García-López, A. M., Recena, R., Avilés, M. & Delgado, A. Effect of *Bacillus subtilis* QST713 and *Trichoderma asperellum* T34 on P uptake by wheat and how it is modulated by soil properties. *J. Soil. Sediment.* **18**, 727–738 (2018).
60. Shen, Z. Z. et al. Soil pre-fumigation could effectively improve the disease suppressiveness of biofertilizer to banana Fusarium wilt disease by reshaping the soil microbiome. *Biol. Fert Soils*. **54**, 793–806 (2018).
61. Wu, Y., Zhao, C. Y., Farmer, J. & Sun, J. Effects of bio-organic fertilizer on pepper growth and Fusarium wilt Biocontrol. *Sci. Hortic.* **193**, 114–120 (2015).
62. Makhlouf, B. S. I., Khalil, S. R. A. & Saudy, H. S. Efficacy of humic acids and chitosan for enhancing yield and sugar quality of sugar beet under moderate and severe drought. *J. Soil. Sci. Plant. Nutr.* **22**, 1676–1691 (2022).
63. Chen, X. G., Kou, M., Tang, Z. H., Zhang, A. J. & Wei, M. Responses of root physiological characteristics and yield of sweet potato to humic acid urea fertilizer. *PLoS One*. **12**, e0189715 (2017).
64. Kelling, K. A., Arriaga, F. J., Lowery, B., Jordan, M. O. & Speth, P. E. Use of hill shape with various nitrogen timing splits to improve fertilizer use efficiency. *Am. J. Potato Res.* **92**, 71–78 (2015).
65. Zebarth, B. J., Snowdon, E., Burton, D. L., Goyer, C. & Dowbenko, R. Controlled release fertilizer product effects on potato crop response and nitrous oxide emissions under rain-fed production on a medium-textured soil. *Can. J. Soil. Sci.* **92**, 759–769 (2012).
66. Choudhary, M. et al. Long-term effects of organic manure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean-wheat cropping system in the Indian Mid-himalayas. *Agr Ecosyst. Environ.* **257**, 38–46 (2018).
67. Mei, L. I. et al. The effects of Trichoderma on preventing cucumber fusarium wilt and regulating cucumber physiology. *J. Integr. Agr*. **18**, 607–617 (2019).
68. Ding, C. Y., Shen, Q. R., Zhang, R. F. & Chen, W. Evaluation of rhizosphere bacteria and derived bio-organic fertilizers as potential biocontrol agents against bacterial wilt (*Ralstonia solanacearum*) of potato. *Plant. Soil.* **366**, 453–466 (2013).
69. Teixeira, L. A. J., Spironello, A., Furlani, P. R. & Sigrist, J. M. M. Split application of NPK fertilizers on pineapple. *Revista Brasileira De Fruticultura*. **24**, 219–224 (2002).
70. Garrido-Lestache, E., López-Bellido, R. J. & López-Bellido, L. Effect of N rate, timing and splitting and N type on bread-making quality in hard red spring wheat under rainfed Mediterranean conditions. *Field Crop Res.* **85**, 213–236 (2004).
71. Groenbaek, M. & Kristensen, H. L. Split dose fertilization with urea increases glucosinolate contents in white cabbage (*Brassica oleracea* L. var. *capitata*) under experimental pot conditions. *Sci. Hortic.* **168**, 64–72 (2014).
72. Abou El-Enin, M. M. et al. Foliage-sprayed nano-chitosan-loaded nitrogen boosts yield potentials, competitive ability, and profitability of intercropped maize-soybean. *Int. J. Plant. Prod.* **17**, 517–542 (2023).

73. Yolcu, H. The effects of some organic and chemical fertilizer applications on yield, morphology, quality and mineral content of common vetch (*Vicia sativa* L). *Tur J. Field Crops*. **16**, 197–202 (2011).
74. El-Sayed, S. F., Hassan, H. A. & El-Mogy, M. M. Impact of bio- and organic fertilizers on potato yield, quality and tuber weight loss after harvest. *Potato Res.* **58**, 67–81 (2015).
75. El-Moniem, E. A. A., Abd-Allah, A. & Ahmed, M. The combined effect of some organic manures, mineral N fertilizers and algal cells extract on yield and fruit quality of Williams banana plants, american-eurasian. *J. Environ. Sci.* **4**, 417–426 (2008).
76. Shen, Z. Z. et al. Induced soil microbial suppression of banana fusarium wilt disease using compost and biofertilizers to improve yield and quality. *Eur. J. Soil. Biol.* **57**, 1–8 (2013).
77. Akca, Y. & Ercisli, S. Effect of plant growth promoting rhizobacteria (PGPR) inoculation on fruit quality in sweet cherry (*Prunus avium* L.) cv. 0900 Ziraat. *J. Food Agric. Environ.* **8**, 769–771 (2010).
78. Akhtar, K. et al. Straw mulching with fertilizer nitrogen: an approach for improving crop yield, soil nutrients and enzyme activities. *Soil. Use Manage.* **35**, 526–535 (2019).
79. Borase, D. N. et al. Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. *Ecol. Indic.* **114**, 106322 (2020).
80. Yang, Y. H. et al. Impact of combining long-term subsoiling and organic fertilizer on soil microbial biomass carbon and nitrogen, soil enzyme activity, and water use of winter wheat. *Front. Plant. Sci.* **12**, 788651 (2022).
81. Huang, C. et al. Effects of fungal residues return on soil enzymatic activities and fertility dynamics in a paddy soil under a rice-wheat rotation in Chengdu Plain. *Soil. Till Res.* **108**, 16–23 (2010).
82. Saha, S., Gopinath, K. A., Mina, B. L. & Gupta, H. S. Influence of continuous application of inorganic nutrients to a maize–wheat rotation on soil enzyme activity and grain quality in a rainfed Indian soil. *Eur. J. Soil. Biol.* **44**, 521–531 (2008).
83. Zhang, F. et al. Effects of drip irrigation on yield, soil fertility and soil enzyme activity of different potato varieties in Northwest China. *Front. Plant. Sci.* **14**, 1240196 (2023).
84. Ye, L. et al. Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality. *Sci. Rep.* **10**, 177 (2020).

Author contributions

Wenxue Duan, Haiyan Zhang and Liming Zhang conceived and designed the study. Wenxue Duan, Haiyan Zhang, Beitao Xie performed the experiments. Wenxue Duan, Haiyan Zhang and Fuyun Hou analyzed the data. Wenxue Duan wrote the paper. Liming Zhang and Qingmei Wang reviewed and edited the manuscript. The final version was read and approved by all authors.

Funding

The research program was sponsored by the Natural Science Foundation of Shandong Province, China (ZR2021MC092), the China Agriculture Research System of MOF and MARA (CARS-10-GW09), the Modern Agricultural Technology System of Tubers and Root Crops in Shandong Province, China (SDAIT-16-09), and and the Key Research and Development Program of Shandong Province, China (2022TZXD0028, 2023TZXD001).

Declarations

Competing interests

The authors declare no competing interests.

Ethics approval

Experimental research and field studies on plants, including the collection of plant material, was carried out in accordance with relevant institutional, national, and international guidelines and legislation.

Additional information

Correspondence and requests for materials should be addressed to H.Z. or L.Z.

Reprints and permissions information is available at www.nature.com/reprints.