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RESEARCH

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Impact of organic fertilization by the digestate from by-product on growth, yield and fruit quality of tomato (*Solanum lycopersicon*) and soil properties under greenhouse and field conditions

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Abstract

Background The application of organic fertilizer is a sustainable approach to maintain soil fertility in agricultural crop production. In contrast to other organic fertilizers, the digestate from by-products of anaerobic digestion has not been well characterized in terms of its agronomic properties. In this study, different fertilization treatments were investigated to evaluate their impacts on growth, yield and fruit quality of tomatoes and on soil properties under greenhouse and field conditions. The experiments comprised a control (unfertilized) and three treatments with the same nitrogen dose: chemical fertilizer, digestate from by-product (organic fertilizer) and digestate combined with chemical fertilizer.

Results The results showed that the application of digestate significantly increased the growth and fruit quality of tomato including height, stem diameter, leaf chlorophyll content index, and photosynthetic rate of tomato plant and sugar–acid ratio, protein content, and ascorbic acid content of the fruit. The nitrate contents in tomato fruit were lower in the digestate treatment and digestate combined with chemical fertilizer treatment than in the chemical fertilizer. The digestate combined with chemical fertilization resulted in the greatest increase in tomato yield, up to 26.29% and 10.78% higher than that in the chemical fertilizer treatment under field and greenhouse conditions, respectively. Moreover, fertilization with digestate treatment and digestate combined with chemical fertilizer treatment increased soil fertility, including soil nitrogen and carbon contents, and enhanced soil enzyme activities under both field and greenhouse conditions. In addition, the growth, yield, and fruit quality of tomato were significantly correlated with soil chemical characteristics and soil enzyme activities.

Conclusions The effects of digestate treatments to maintain a stable tomato yield and improve fruit quality may be due to the enhanced soil enzymatic activities and chemical properties. These results suggest that the use of digestate as a full or partial replacement for chemical fertilizer could improve the growth and fruit quality of tomato, maintain the yield, and reduce the use of inorganic fertilizers in tomato production.

Keywords Combined fertilization, Digestate, Fruit quality, Soil enzymes, Tomato, Yield

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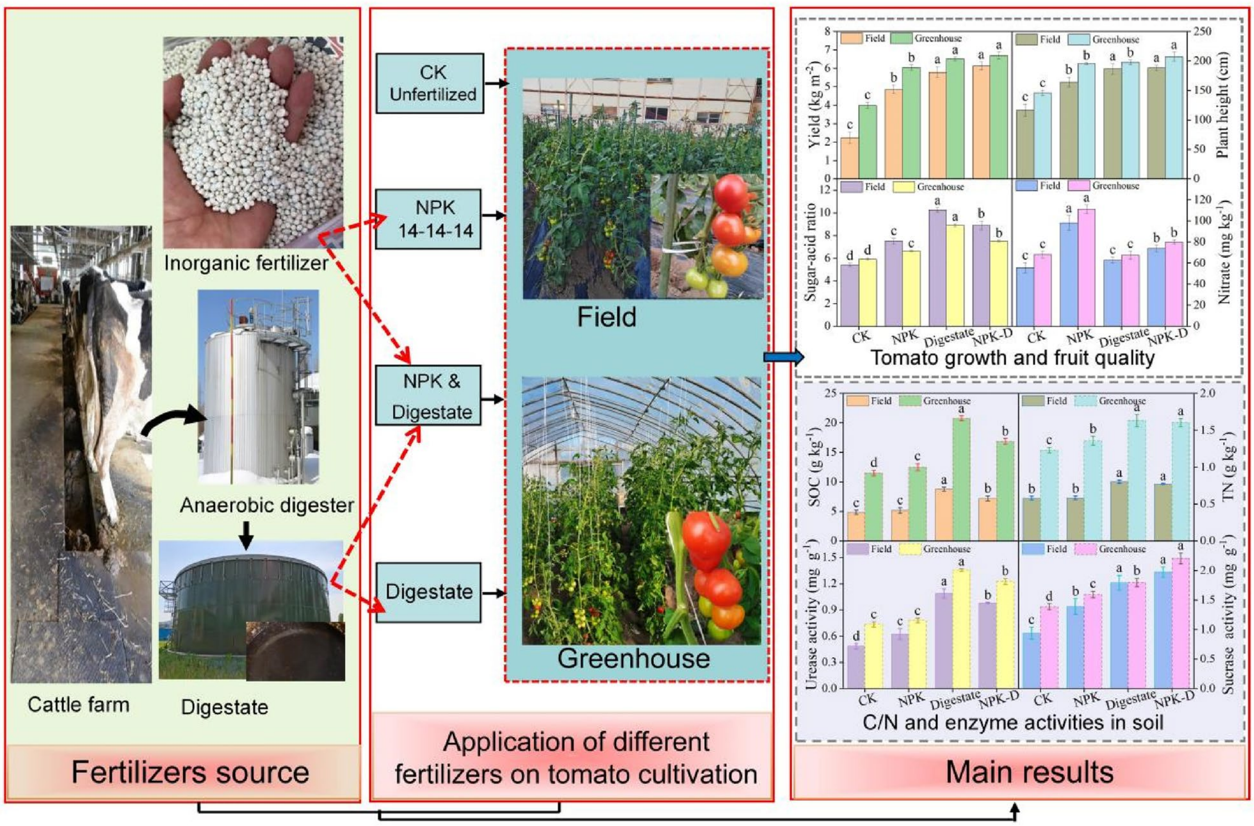
Graphical Abstract



Introduction

Chemical fertilization is one of the most widely used regimes in intensified agriculture [1, 2]. However, the long-term use of chemical fertilizers has many harmful effects, is a huge drain on mineral resources, and is not beneficial for sustainable agricultural development. Chemical fertilizers are the source of most of the nitrogen lost from farmlands, which is then released into the water or the atmosphere, leading to greenhouse gas emissions and soil salinization [2, 3]. In addition, excessive chemical fertilization results in decreases in food quality, such as increased nitrate accumulation and lower synthesis of ascorbic acid (AsA), and phenols in cultivated plants [4, 5]. Several studies have shown that organic fertilization could serve as a good substitute for chemical fertilizers and potentially minimize their adverse impacts [6, 7]. Organic fertilizers generally promote crop growth and increase the nutritional properties of plants [8, 9]. The integrated nutrient management method of fertilization management has been proposed as a solution to agro-environmental problems [10, 11]. The aim is not to remove chemical fertilizers completely, but to use a combination of organic and inorganic fertilizers, thus reducing the amount of chemical fertilizer applied in agricultural production. Many studies have confirmed that the use of organic fertilizer as an alternative or partial replacement for chemical fertilizers provides a reliable supply of nutrients during crop growth, increases crop yields, promotes soil health, and reduces farmland pollution [12–15].

Anaerobic digestion technology is one of the most important waste management strategies, and is extensively used for the commercial processing of agricultural and other wastes worldwide [16]. It not only helps to reduce greenhouse gas emissions in the agricultural production but also generates biogas, which is a biofuel that could be used for heat and electricity generation [17]. However, anaerobic digestion only partially addresses the issue of material and energy recovery, because a significant portion of organic matter and mineral elements still remain in the digestate [18, 19]. Thus, the true value of this waste product is not fully captured. In addition, due to the accumulation of biogas plants in certain regions with intensive livestock farming, an oversupply of digestate is expected to be generated [18]. If this excess digestate cannot be properly managed, new environmental issues will arise. Therefore, it is essential to devise some methods for the value-added utilization of digestate. From a circular economy, the utilization of digestate as organic fertilization is an interesting scenario. After anaerobic digestion, many nutrients from the feedstock, such as macroelements (N, P, K), and microelements (B, Cu, Mn, Zn) remain in the digestate [19, 20]. The utilization of digestate as fertilizer could therefore further enhance the sustainable development of agriculture. In addition to containing an abundance of mineral nutrients, digestate can hinder soil degradation due to salinity and enhance soil physical and chemical characteristics, such as soil water-holding capacity and soil enzyme activities [21]. However, the application of digestate is not widely acknowledged to increase crop yields and promote soil health.

Tomato (*Solanum Lycopersicon*) is among the most economically significant and nutritional vegetable crops cultivated worldwide [12]. Over 5 million hectares of land were used for tomato cultivation in 2019, with outputs of more than 180 million tons [22]. In Japan, tomato plays an important role in vegetable production, and the output value of tomatoes accounts for 10% of all vegetables [23]. In addition, tomato fruits contain various bioactive substances, such as organic acid, AsA, and phenols [24]. Regular consumption of tomatoes is thus very beneficial for human health. The yield and fruit quality of tomato are affected by the type of fertilization. For example, Bilalis et al. found that organic fertilization regime resulted in tomato fruits with a higher sugar–acid ratio (SAR) than that of those grown with conventional inorganic fertilizer [25]. Combined organic and inorganic fertilization has been shown to improve tomato yield and soil enzyme activities [26]. Hernández et al. reported that the amount of mineral nitrogen could be reduced by approximately 40% by using combined organic and inorganic fertilization while achieving similar tomato fruit yields [1]. In some studies, tomatoes grown in a nutrient system of organic fertilizer have shown improved quality characteristics. For example, Wang et al. found that, compared with chemical fertilization, organic fertilization decreased the nitrate content and enhanced the SAR of tomato fruit [27]. In another study, the levels of AsA and phenolic compounds in tomato fruits were enhanced by organic fertilization as compared with conventional fertilization [28]. To our knowledge, our study is the first experimental comparison of the effects of different fertilization treatments (digestate from a pilot-scale cattle farm waste recycling system, chemical fertilizer, and a combination of the two) on the growth, yield, and fruit quality of tomato and soil characteristics.

The objective of this study was to evaluate the effects of using digestate for tomato production as a full or partial replacement for chemical (NPK) fertilizers. We assumed that the application of digestate or digestate combined with chemical fertilizer would enhance the growth, yield, and fruit quality of tomato by altering soil chemical characteristics and enzyme activities. To this assumption, two experiments were therefore conducted under field and greenhouse conditions. Chemical fertilizer, digestate and digestate combined with chemical fertilizer and a control (unfertilized) were applied to soil and their effects on growth, yield, and fruit quality of tomato and chemical characteristics and enzyme activities in soil were investigated. In addition, we also explored the correlations between growth, yield, and fruit quality of tomato and various soil properties in different fertilization treatments.

Materials and methods

Fertilizer sources

The chemical fertilizer used in the current work, with 14% each of nitrogen, phosphorus, and potassium, was purchased from the Hokuren Fertilizer Co. (Sapporo, Japan). Digestate was collected from a pilot-scale cattle farm waste recycling system located on the campus of Hokkaido University, Hokkaido, Japan. This farm produces livestock manure (approximately 98% cattle manure). The livestock manure is digested into 80–120 m^3 biogas containing 60–65% methane, thereby producing digestate as a by-product of anaerobic digestion. The physicochemical properties of the digestate are shown in Table 1.

Experimental set-up

The amount of nitrogen applied in each fertilization treatment was approximately 180 kg N ha^{-1}. The

Table 1 Characterization of the digestate used in this study

	C	*N*	*P*	*K*	Ca	Mg
Unit	% dm	% dm	% dm	% dm	% dm	% dm
Digestate	40.452	2.133	1.463	4.469	2.306	0.963

dm dry matter

experiment consisted of a control and three fertilization treatments: (1) CK, no fertilizer; (2) NPK (fertilization with 180 kg N ha^{-1} of NPK fertilizer), fertilized with 514 kg ha^{-1} of 14–14–14 NPK fertilizer as the basic fertilizer, then fertigated with 386 kg ha^{-1} of 14–14–14 NPK fertilizer during the flowering, and fertigated with 386 kg ha^{-1} of 14–14–14 NPK fertilizer during the fruit swelling; (3) D (fertilization with 180 kg N ha^{-1} of digestate), fertilized with 66,667 L ha^{-1} of digestate as the basic fertilizer, then fertigated with 50,000 L ha^{-1} of digestate during the flowering, and fertigated with 50,000 L ha^{-1} of digestate during the fruit swelling; (4) NPK–D (fertilization with 90 kg N ha^{-1} of NPK fertilizer and 90 kg N ha^{-1} of digestate), fertilized with 257 kg ha^{-1} of 14–14–14 NPK fertilizer and 33,333 L ha^{-1} of digestate as the basic fertilizer, then fertigated with 193 kg ha^{-1} of 14–14–14 NPK fertilizer and 25,000 L ha^{-1} of digestate during the flowering, and fertigated with 193 kg ha^{-1} of 14–14–14 NPK fertilizer and 25,000 L ha^{-1} of digestate during the fruit swelling. At the same time, two cultivation experiments were conducted: one under a field condition and the other under a greenhouse condition (Fig. 1). Each experiment was performed using a randomized complete block design, with three plots per treatment, for a total of 12 plots for each experiment. Each plot was 2.2 m long and 1.3 m wide, comprising a total area of 2.86 m^2, and consisted of two rows. Plants were spaced 35 cm apart, with 50 cm between rows, for an average planting density of 10 plants plot^{-1}, amounting to about 35,000 plants per ha. The distance between each plot and the neighboring plots was 30 cm. Fertilizer rate, planting density, and crop management referred to the Medium-sized Tomato Cultivation Technical Guidelines by the Ministry of Agriculture, Forestry and Fisheries [23].

Experimental site and crop management

Experiments were conducted from June 20, 2021, to October 24, 2021, in the field and from June 29, 2021, to November 23, 2021, in the greenhouse on the campus of Hokkaido University (43°4′ N, 141°20′ E; 20 m above sea level), Hokkaido, Japan (Additional file 1: Fig. S1). Meteorological conditions from transplanting to harvest are listed in Additional file 1: Table S1. The determinate tomato variety cultivated in this experiment, Medium Matina, is popular with local growers and was purchased from Greenfield Project Corp. (Nagano, Japan). Prior to experiments, soil samples were characterized from a depth of 0 to 20 cm in the field and greenhouse as shown in Table 2. At the four-leaf stage, uniform healthy tomato seedlings were transplanted into the experimental plots. Agronomic management was the same for all treatments, including fertilization time, de-worming and de-leafing. The only difference was that the greenhouse was irrigated regularly every 3 days, whereas the field was irrigated less frequently during the rainy season, for a total of 24 times during the growing season. In addition, tomato plants were trellised using vertical strings in the greenhouse but were staked with canes and covered with bird-proof nets in the field (Additional file 1: Fig. S2).

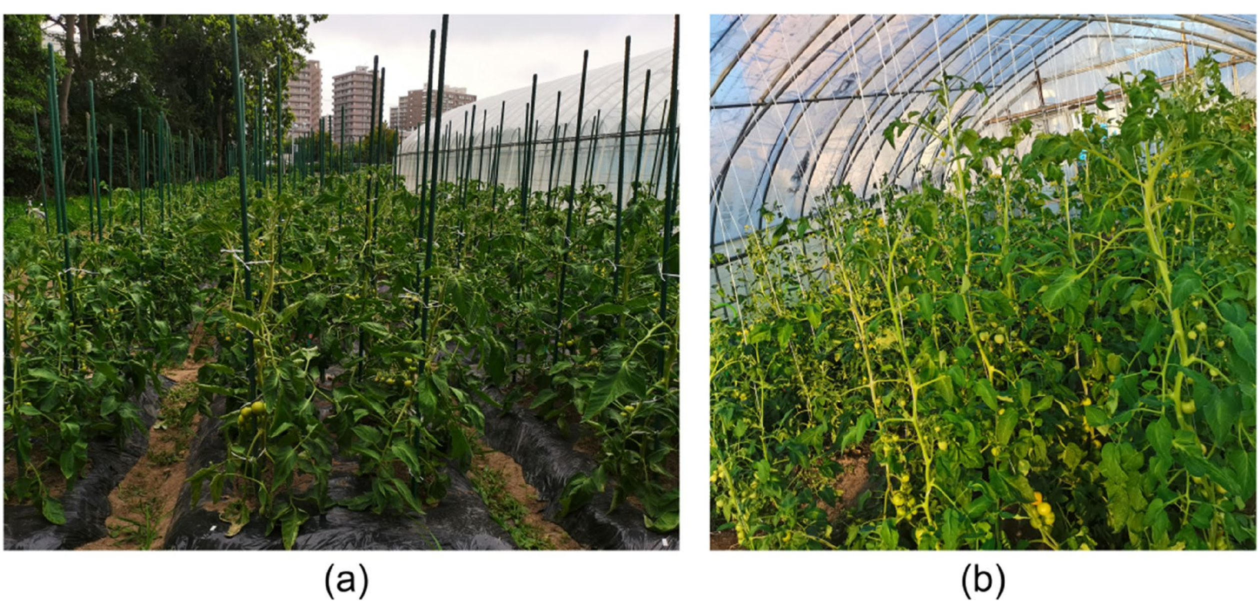


Fig. 1 Experimental sites used in the study. **a** Field; **b** greenhouse

Table 2 Characteristics of soil present on the two cultivation conditions before cultivation

Parameter	Unit	Field	Greenhouse
Attributes		Sandy soil	Loamy soil
P-absorption coefficient		480	1099
CEC	cmol kg^{-1}	0.97	2.93
N	g kg^{-1}	0.89	1.982
Olsen-P	mg 00 g^{-1}	6.4	38.1
K exchangeable	mg 100 g^{-1}	22	61.0
Ca exchangeable	mg 100 g^{-1}	157.8	401.1
Mg exchangeable	mg 100 g^{-1}	15.8	39.4
Cu	ppm	3.93	2.86
Zn	ppm	3.17	25.75
Mn	ppm	19.18	156.11
B	ppm	0.30	0.73

CEC cation exchange capacity

Sampling and analytical methods

Tomato plant growth traits

Plant growth was measured on September 10th, 2021, for plants in the field and on October 4th, 2021, for plants in the greenhouse. The height and stem diameter (cm) were measured and then the chlorophyll content indices were recorded by SPAD values which were measured by method described previously in 2020 [29] with a portable chlorophyll meter (SPAD-502, Minolta Camera Co. Ltd., Japan). The photosynthetic rate was measured as described in our previous study [20] with a plant photosynthesis meter (miniPPM-300, EARS, Delft, Netherlands) in the tomato plant.

Tomato fruit yield and quality

Red-ripened fruits were harvested until the end of the crop production. Tomato fruit yield was measured as the total weight of tomato fruits per m^2 of plants. During the tomato fruiting period, at least 30 fruits were collected from 10 plants per plot to generate a representative pooled fruit sample. Before further analysis, the tomato fruits were washed and sterilized. Tomato fruits were sliced and then homogenized in a blender for analysis of quality parameters. The soluble protein content, soluble sugar content, organic acid content and nitrate content of tomato fruits were determined using the described method of Wang et al. and SAR was defined as the ratio of soluble sugar to organic acid [27]. The AsA content in tomato fruits was measured using the molybdenum blue colorimetric method [20].

Soil chemical properties and enzyme activities

Soil samples (0–20 cm) were collected at 20 points around tomato roots in each plot and then mixed to obtain a composite sample. Soil samples were immediately stored at − 80 °C until analyses.

The soil pH was determined in a 1:2.5 (*w*/*v*) soil/water slurry. Soil organic carbon (SOC) was measured by the potassium dichromate–sulfate colorimetric method [14]. The total nitrogen (TN) and ammonium nitrogen (AN) contents in soil were determined in accordance with method of Lu [30]. Urease, sucrase, protease, and nitrate reductase (NR) activities in soil were measured according to Schinner et al. [31]. Control tests without soil or substrate were conducted to evaluate the abiotic transformation or spontaneity of all analyzed enzymes.

Statistical analysis

All values were represented as the mean ± SE of three replicates ($n = 3$). The data were subjected to one-way ANOVA followed by Duncan's post hoc test at $P < 0.05$ to assess the significance of differences among means [26]. A correlation matrix between growth traits and yield/quality of tomato and soil properties was constructed based on Spearman's correlation coefficients, and correlations were tested for significance ($P < 0.01$; $P < 0.05$).

Results

Growth of tomato plants

For all measured parameters the tomato plants that received chemical, organic and a combination of chemical and organic fertilization recorded significantly higher values as compared to the control (unfertilized).

The height, stem diameter, SPAD, and photosynthetic rate of tomato plants were affected by the fertilization treatments (Fig. 2). The NPK–D treatment resulted in the tallest plant height, with and increase 14.60% in the field and 6.14% in the greenhouse, both significantly higher compared to the NPK treatment. The stem diameters of the tomato plants in the NPK–D and D treatments were not significantly different but were significantly higher in both of these treatments than in NPK under both cultivation conditions ($P < 0.05$). There was no statistically significant difference in plant SPAD between the D and NPK–D treatments, both treatments had higher SPAD than the NPK treatment. The photosynthetic rate of tomato plants was significantly higher in the D and NPK–D treatments than in NPK, with that in D treatment being 34.48% (field) and 25.87% (greenhouse) higher than in NPK treatment.

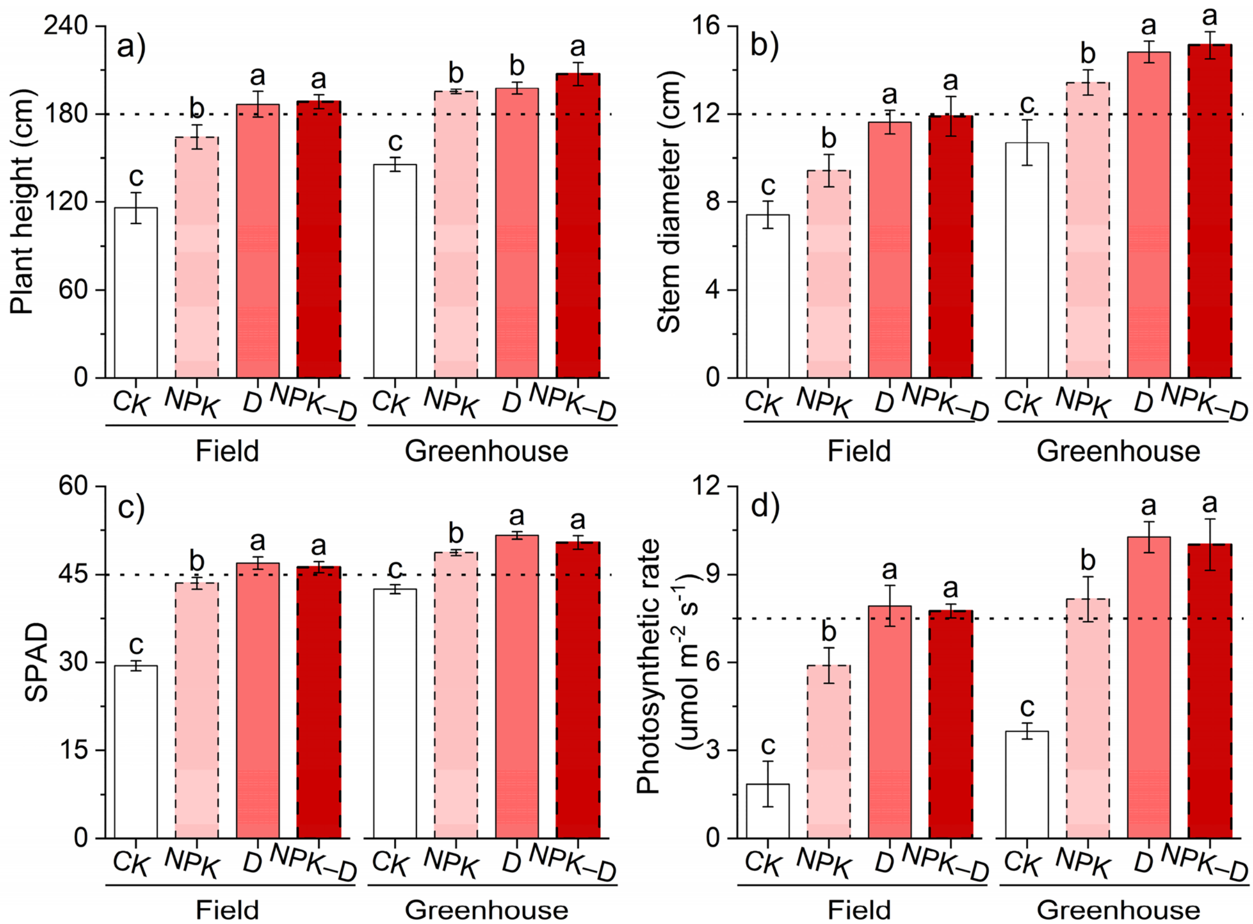


Fig. 2 Effects of fertilization types on growth of tomato plants in field and greenhouse conditions. **a**: Plant height; **b**: stem diameter; **c**: relative chlorophyll content (SPAD); **d**: photosynthetic rate. Means (± SE, $n=3$) with the same letter in the same cultivation condition are not significantly different from each other ($p<0.05$). CK represents the control treatment with no fertilizer; NPK represents the NPK (14:14:14) fertilizer treatment with 180 kg N ha^{-1}; D represents the digestate treatment with 180 kg N ha^{-1}; NPK–D represents the NPK (14:14:14) fertilizer with 90 kg N ha^{-1} and 90 kg N ha^{-1} of digestate

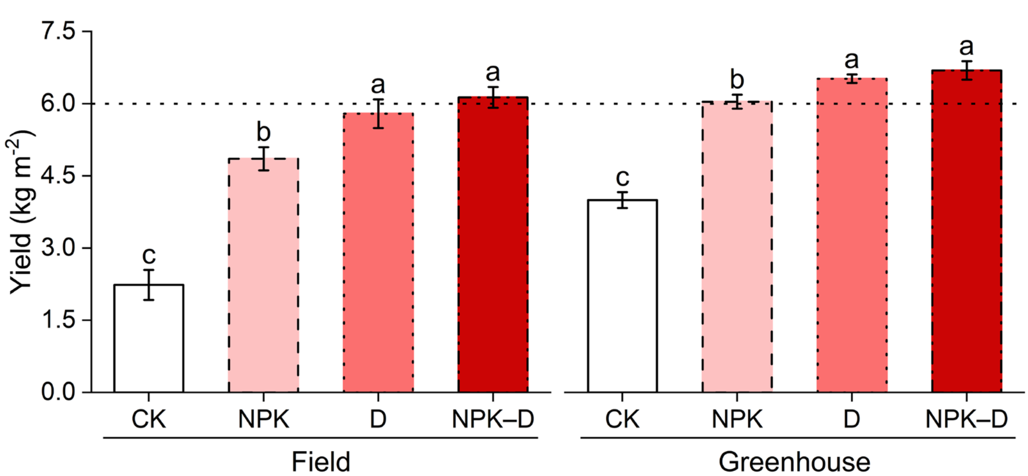


Fig. 3 Effects of fertilization types on tomato yield in field and greenhouse conditions. Means (± SE, $n=3$) with the same letter in the same cultivation condition are not significantly different from each other ($p<0.05$). CK represents the control treatment with no fertilizer; NPK represents the NPK (14:14:14) fertilizer treatment with 180 kg N ha^{-1}; D represents the digestate treatment with 180 kg N ha^{-1}; NPK–D represents the NPK (14:14:14) fertilizer with 90 kg N ha^{-1} and 90 kg N ha^{-1} of digestate

Yield of tomato fruits

The fruit yields of tomato plants were markedly higher ($P < 0.05$) in the D and NPK–D treatments than in NPK treatment under both cultivation environments (Fig. 3). Under field and greenhouse conditions, the highest fruit yield was in the NPK–D treatment. The fruit yield in NPK–D treatment was 26.29% higher than that in NPK treatment under the field condition and 10.78% higher than that in NPK treatment under the greenhouse condition. However, no significant difference in tomato fruit yield was observed between the D and NPK–D treatments under the field or the greenhouse conditions.

Quality of tomato fruits

The quality parameters of SAR, soluble protein content, AsA content, and nitrate content of tomato fruits are shown in Fig. 4. In both field and greenhouse conditions, the fruit SAR, soluble protein content, and AsA content were significantly higher in the D treatment than in the other fertilization treatments (Fig. 4a–c). The SAR of NPK–D treatment was 18.30% higher than those of NPK treatment under field conditions, and 13.29% higher than those of NPK treatment under greenhouse conditions. The soluble protein content of NPK–D was 19.81% higher than that of NPK under field conditions but was not significantly different ($P > 0.05$) from that of NPK under greenhouse conditions (Fig. 4b). The AsA content in tomato fruits was higher in NPK–D than in NPK under both cultivation conditions. Th nitrate contents in tomato fruit were higher in the NPK treatment than in the other treatments under both cultivation conditions (Fig. 4d). The nitrate contents in tomato fruit were significantly lower in D treatment than in NPK–D, by 17.84% under the field conditions and by 18.51% under the greenhouse conditions.

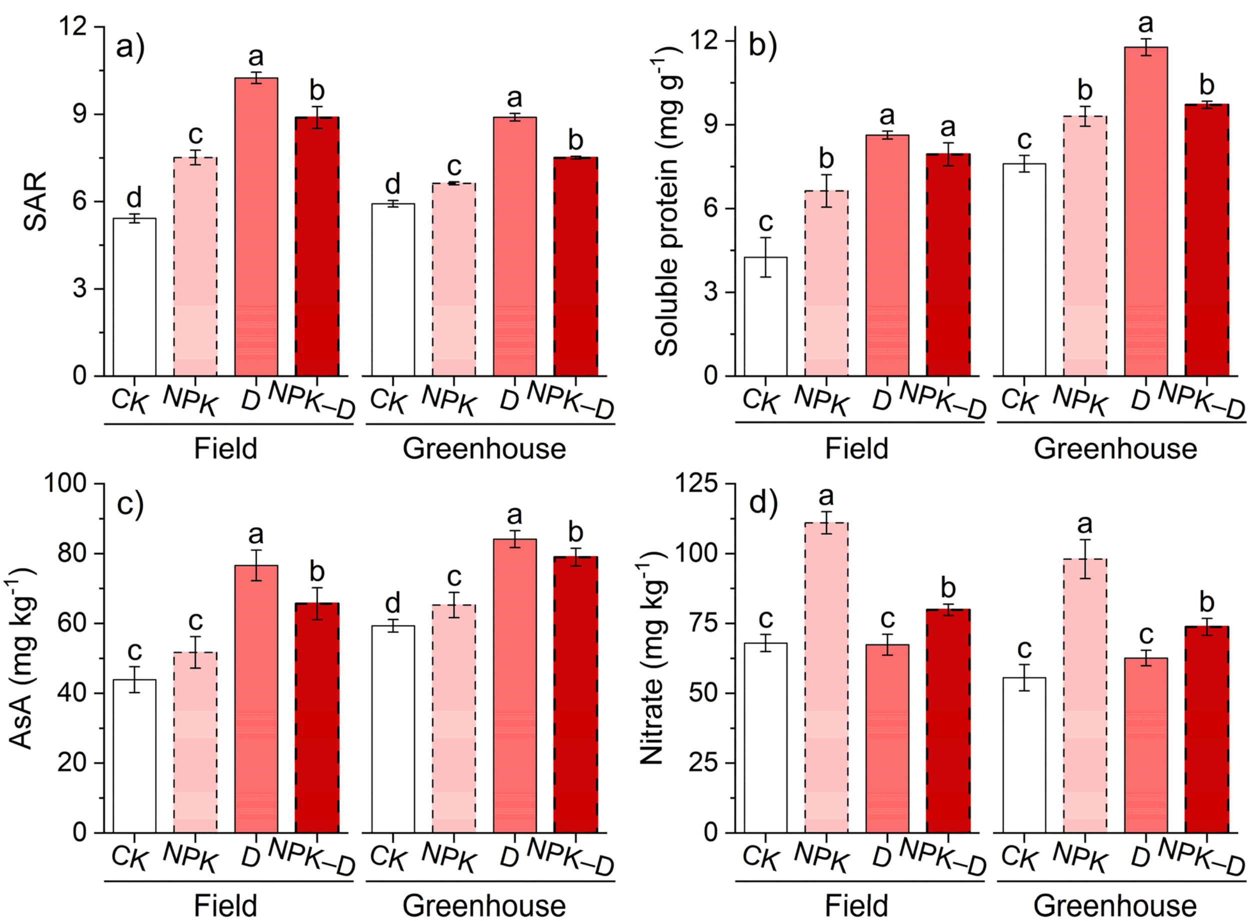


Fig. 4 Effects of fertilization types on tomato qualities in field and greenhouse conditions. **a**: Sugar–acid ratio (SAR), **b**: soluble protein, **c**: ascorbic acid (AsA); **d**: nitrate. Means (±SE, $n = 3$) with the same letter in the same cultivation condition are not significantly different from each other ($p < 0.05$). CK represents the control treatment with no fertilizer; NPK represents the NPK (14:14:14) fertilizer treatment with 180 kg N ha^{-1}; D represents the digestate treatment with 180 kg N ha^{-1}; NPK–D represents the NPK (14:14:14) fertilizer with 90 kg N ha^{-1} and 90 kg N ha^{-1} of digestate

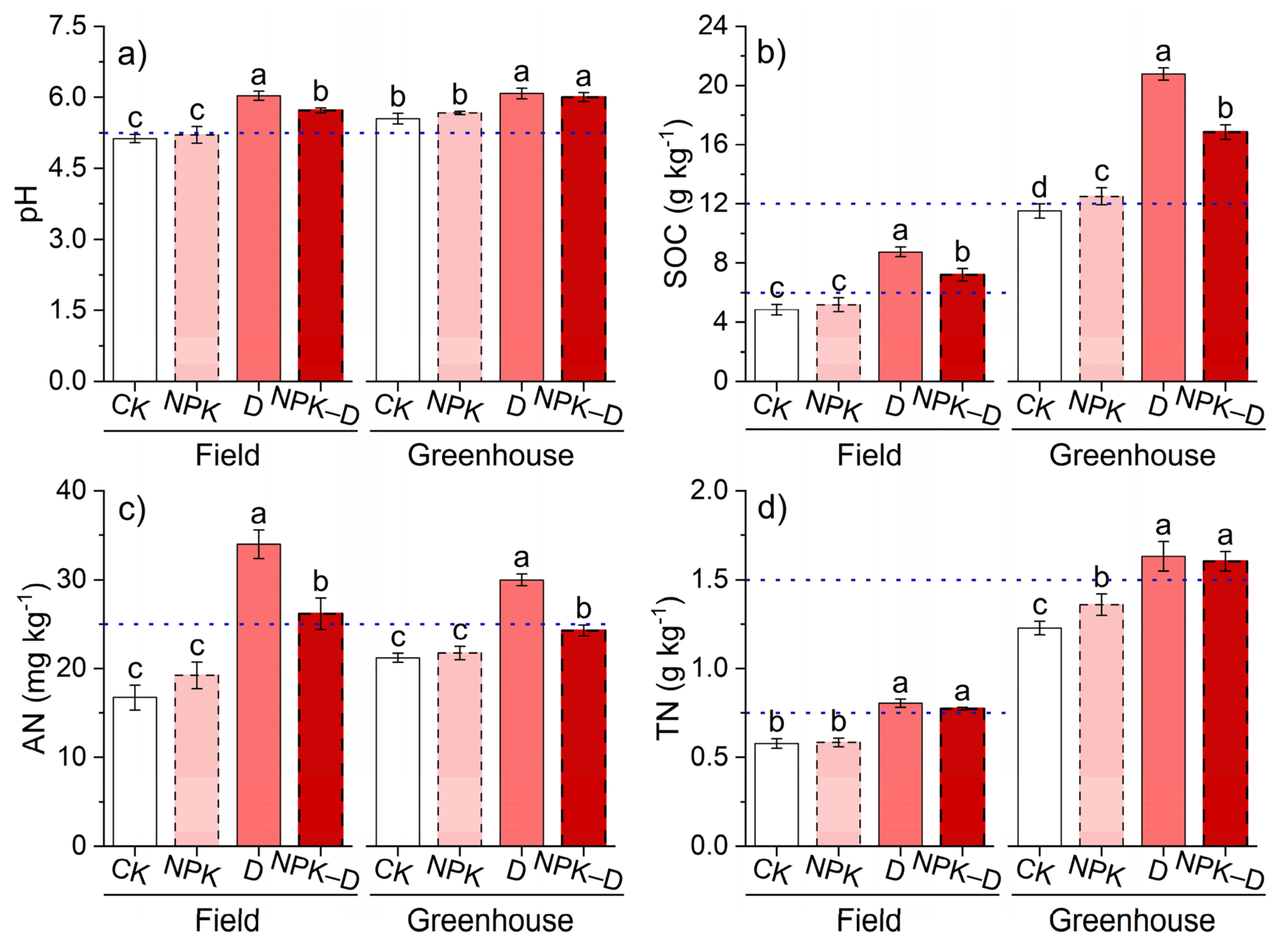


Fig. 5 Effects of fertilization types on soil chemical properties in field and greenhouse conditions. **a**: pH; **b**: soil organic carbon (SOC); **c**: ammonium nitrogen (AN); **d**: total nitrogen (TN). Means (± SE, $n=3$) with the same letter in the same cultivation condition are not significantly different from each other ($p<0.05$). CK represents the control treatment with no fertilizer; NPK represents the NPK (14:14:14) fertilizer treatment with 180 kg N ha^{-1}; D represents the digestate treatment with 180 kg N ha^{-1}; NPK–D represents the NPK (14:14:14) fertilizer with 90 kg N ha^{-1} and 90 kg N ha^{-1} of digestate

Soil chemical characteristics

The properties of soil from the field and greenhouse after harvest following the different fertilization treatments are summarized in Fig. 5. The soil pH values ranged from 5.13 to 6.03 under field conditions and from 5.55 to 6.08 under greenhouse conditions. The SOC in D treatment was 1.69-fold and 1.66-fold significantly higher ($P<0.05$) than in NPK treatment under the field and the greenhouse conditions, respectively. Under the field conditions, both digestate treatments were significant higher AN in soil than the NPK treatment, with D treatment displaying a 29.87% increase compared to NPK–D treatment. Similar trends in AN were observed under greenhouse conditions. The TN content in soil was lower in NPK treatment than in D treatment, by 37.41% under field conditions and by 20.03% under greenhouse conditions. There was no significant difference in TN content between the D and NPK–D treatments under both cultivation conditions.

Soil enzyme activities

Results of soil enzymatic activities analyses performed under both cultivation conditions are shown in Fig. 6. The lowest soil urease activities in all fertilization treatments were in NPK followed by NPK–D under both cultivation conditions, and the highest soil urease activity was in D treatment (Fig. 6a). Sucrase activity showed a different trend, being highest in the NPK–D treatment under greenhouse conditions, which is up to 22.78% significantly higher ($P<0.05$) than D treatment. However, no statistical difference in soil sucrase activity was found between the NPK–D and D treatments under field conditions. The soil protease activities differed significantly among all treatments under both field and greenhouse

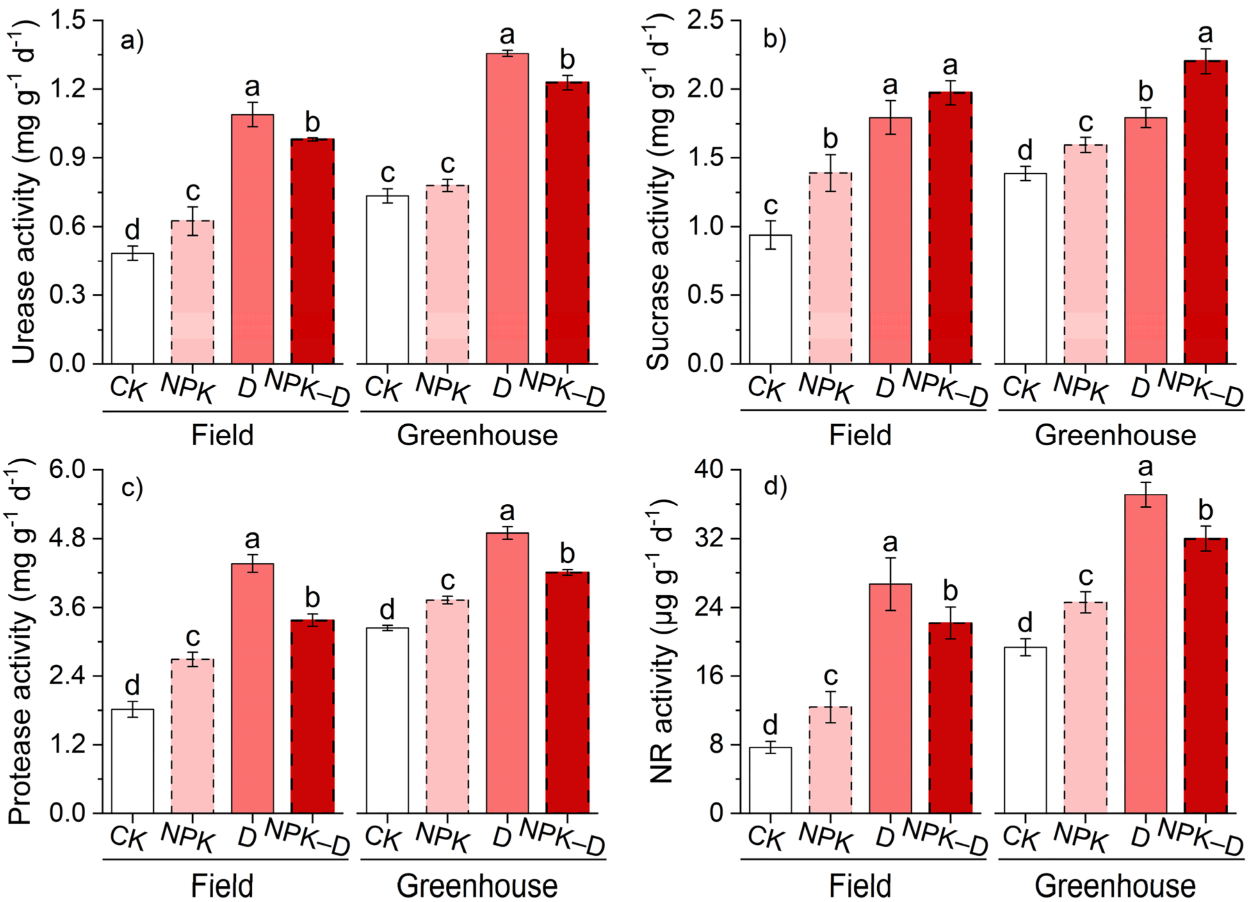


Fig. 6 Effects of fertilization types on soil enzyme activities in field and greenhouse conditions. **a**: Urease activity; **b**: protease activity; **c**: sucrase activity; **d**: nitrate reductase (NR) activity. Means (± SE, $n=3$) with the same letter in the same cultivation condition are not significantly different from each other ($p<0.05$). CK represents the control treatment with no fertilizer; NPK represents the NPK (14:14:14) fertilizer treatment with 180 kg N ha^{-1}; D represents the digestate treatment with 180 kg N ha^{-1}; NPK–D represents the NPK (14:14:14) fertilizer with 90 kg N ha^{-1} and 90 kg N ha^{-1} of digestate

conditions, and soil NR activity showed a similar to that of protease activity under both cultivation conditions.

Correlations of growth traits and yield/quality of tomato with soil properties

To further characterize the effect of fertilization treatments, we carried out a Spearman's correlation analysis to explore the relationships between the growth, yield, and fruit quality of tomato and soil chemical properties and enzyme activities (Fig. 7). A positive correlation was found between soil properties and growth, yield, and fruit quality indicators of tomato. Only the nitrate content of tomato fruit was negatively correlated with soil properties. Most growth indicators were significantly and positively correlated with soil properties. The maximum correlation coefficient (0.85) was between SPAD and TN ($P<0.01$). According to this analysis, tomato fruit yield was remarkably and positively related to soil properties except for AN in soil (SOC: $r=0.63$, $P<0.01$; TN: $r=0.66$, $P<0.01$). The SAR was significantly and positively correlated with soil pH and AN. Correspondingly, the AsA and soluble protein contents in tomato fruit were positively correlated with most soil properties. The nitrate content of tomato fruits was negatively correlated with pH, AN, and urease and protease activities in soil. Therefore, the growth, yield, and fruit quality of tomato were related to most soil properties affected by the fertilization treatments.

Discussion

Effect of fertilization on crop growth and yield

Organic fertilization as a full or partial replacement for inorganic fertilization is increasingly recommended for crop production [1, 10]. Previous studies have reported inconsistent results in terms of impacts of organic fertilizer on crop yield. Some researchers reported lower

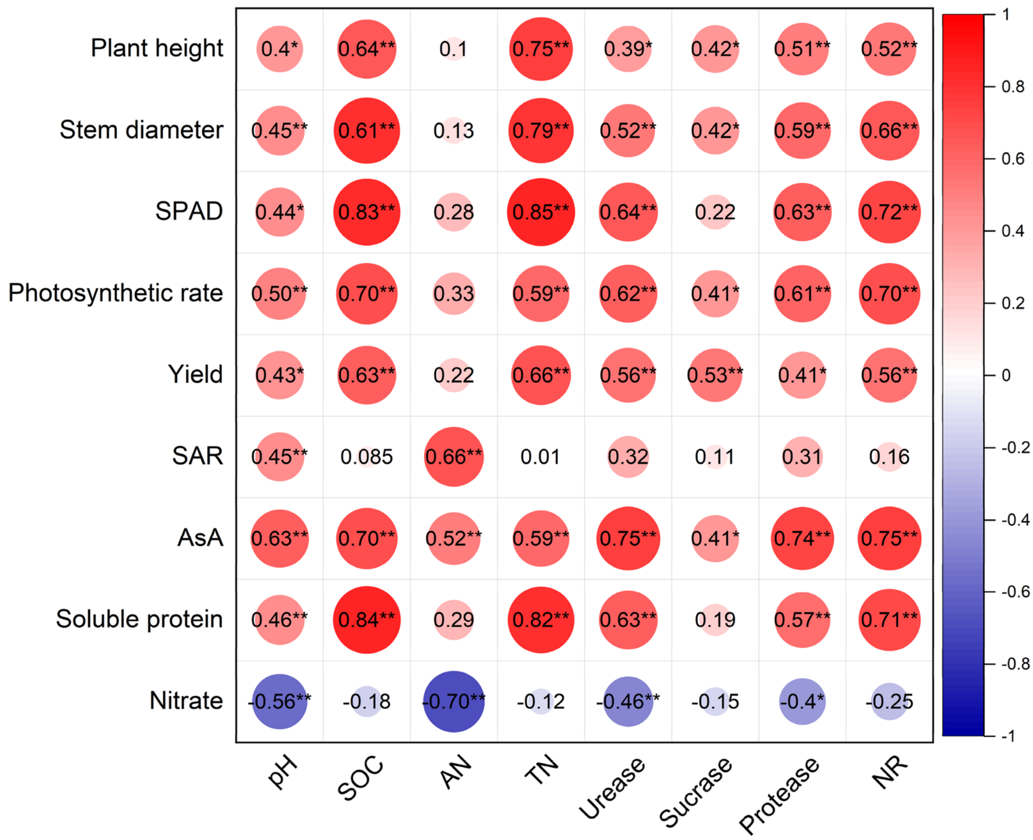


Fig. 7 Spearman correlation coefficients between soil indicators and tomato growth and yield/quality under different fertilization types. Red and blue circles represent positive and negative correlations, respectively. *, $p < 0.05$ and **, $p < 0.01$

yields under organic fertilization than under chemical fertilization [25, 27, 32]. It was proposed that this was due to the slow mineralization of organic nitrogen in organic fertilizers, leading to slower crop growth because of the relatively lower levels of available nitrogen in the early growth period [33]. In contrast, other studies reported that the application of organic fertilizer as a full or partial replacement for chemical fertilizer achieved similar or higher yields in agricultural production [15, 21, 26]. Consistent with those findings, in this study, the yields of tomato were comparable or even higher in the digestate treatments than in the chemical fertilizer treatment. Cristina et al. found that digestate had a potentially positive influence on tomato growth [29], and Wu et al. reported that the combined organic–inorganic fertilization improved tomato yield [26]. Further elucidation of the mechanisms underlying the effect of digestate as a full or partial replacement for NPK fertilization is therefore essential for improved tomato production.

Digestate is a good fertilizer as it is a source of macro- and micro-mineral elements and abundant organic matter [20]. Compared with chemical fertilizer, it has a stronger effect to improve soil fertility, thereby increasing crop production and promoting crop growth [34, 35]. The results of this study are in agreement with those of a previous work [29], in which the addition of digestate increased plant height and stem diameter. Interestingly, compared with chemical fertilizer, the digestate combined with chemical fertilizer had stronger growth-promoting effects on tomato plants in this study. Similar results were obtained in other studies [1, 9], where the combination of organic–inorganic fertilization led to a higher nitrogen level in the soil, thus promoting higher crop production. Brtnicky et al. suggested that the enhancements in crop growth may be partially due to the large increase in soil microbial biomass after use of digestate, resulting in more bioactive soil components in the digestate treatment [34]. In this study, SOC and soil TN were increased after application of digestate or digestate combined with chemical fertilizer. The high nutrient levels in soil with added digestate may have promoted tomato plant growth.

Fertilization can increase the photosynthesis in plants, thereby promoting the accumulation of organic matter. Higher photosynthetic rate has also been reported when organic fertilization was applied simultaneously with chemical fertilization [36]. Results of the present work confirmed the positive effects of digestate application on photosynthetic rate [35, 37]. Moreover, compared with CK and the chemical fertilizer treatment, the digestate fertilizer treatments resulted in increased SPAD values in tomato plants. Similar beneficial effects of organic fertilizer have been reported for in cucumber, kale, and lettuce [8, 38, 39]. Leaf chlorophyll content is directly related to indirect chlorophyll measurements, such as SPAD values [40]. Chlorophyll is the key pigment for photosynthesis, hence an increase in chlorophyll content will enhance photosynthesis, thereby increasing yield. Organic fertilization was shown to improve the status of soil TN and promote nitrogen uptake by plants, thus promoting chlorophyll synthesis [27]. Consistent with those results, we found that the application of digestate increased the soil TN, accompanied by an increase in plant leaf SPAD values. In contrast, another study found that application of digestate led to a decrease in leaf chlorophyll content in tomato plants [41]. This was probably because of excessive levels of heavy metals in the digestate used in that study [42]. The digestate used in our study was from a pilot-scale cattle farm and almost all of the input was cow manure, which has a lower heavy metal content than other digestate inputs (Additional file 1: Table S2) and less than the threshold value of heavy metals in organic fertilizers from the MAFF [21, 23]. Although the SPAD value was not decreased after the application of digestate in the current study, it is still possible that heavy metals could accumulate over long-term cultivation and suppress tomato growth and yield. Further research is required to explore the heavy metal contents in this and other digestates, and to monitor their fate in soil after the application of digestates as fertilizers.

Effect of fertilization on crop quality

The results of this study showed that fruit quality in tomato was significantly influenced by fertilizer treatments. The nitrate content in tomato fruits was lower in the digestate treatments than in the chemical fertilizer treatment, consistent with the results of a previous study [27]. Including mixed microelements such as magnesium, zinc, manganese, and boron in fertilization strategies can decrease the nitrate content of tomato fruits by 20% [43]. The lower nitrate contents in tomato fruit in the digestate treatments than in the chemical fertilizer treatment may be related to the supply of available micronutrients from digestate. The digestate used in our study was rich in potassium under the same amount of N dose, an element previously reported to enhance tomato fruit yield and quality [44]. Furthermore, the application of organic fertilizer increased the SOC. In another study, fruit quality parameters such as AsA and soluble sugar contents were significantly positively correlated with SOC [45], indicating that tomato fruit quality could be improved by adding digestate. In this study, addition of digestate increased the AsA content and SAR of tomato fruit, similar to the results reported by Wu et al. [26]. Tomato fruit quality is a complex character with multiple interactivities among the contributing factors. Our results confirmed the positive influence of digestate application on tomato fruit quality. In addition, Digestates contain some phytohormones (e.g., gibberellins, indoleacetic acid, and vitamins) [21, 38], and these bioactive compounds can significantly enhance crop quality. Another study found that the application of digestate increased SOC and soil fertility, resulting in a larger yield than that obtained using a balanced chemical fertilizer [26]. The correlation analysis in this study also revealed a significant positive correlation between fruit quality and soil parameters (SOC and TN). These results may explain why tomato plants treated with digestate produced higher-quality fruit. We also found that growth and fruit quality of tomato were clearly lower in field cultivation than in greenhouse cultivation under the same fertilization treatment. There are several possible explanations for this. First, frequent rain during the harvest period in the field resulted in a higher soil moisture content (Additional file 1: Table S3). The excess water decreased plant growth and metabolism, thereby reducing the synthesis of compounds related to fruit quality, such as AsA and proteins. Ultimately, such changes in metabolism resulted in a low yield, consistent with the results of other studies [46, 47]. Second, the soil in the field was sandy soil, whereas that in the greenhouse was loamy soil. Sandy soils lack nutrients, and this nutrient depletion limits plant growth and decreases the synthesis of proteins, AsA, and carbohydrates [29].

Effect of fertilization on soil chemical properties and enzyme activities

Fertilizers are reported to increase crop yields by changing soil chemical properties, such as soil pH, and the contents of TN and other nutrients [10, 14]. Organic fertilizers could neutralize the pH in soil, as found in this study and another study [19]. Organic fertilizers normally contain large amounts of organic matter, and their application provides many carbon sources for SOC improvement, thereby promoting soil humification [48]. SOC is one of the most relevant parameters to reflect soil quality and fertility [26]. In the current study, SOC was enhanced by the addition of digestate, consistent with previous findings [4, 14]. A higher SOC content could increase nutrient retention capacity of soil and facilitate nutrient availability to plant. Nitrogen is a key nutrient for plant growth in agricultural production. The application of digestate resulted in a significant increase in soil carbon and nitrogen contents, and these are key indicators of soil quality [49]. Another study reported that, compared with unfertilized, all fertilizer treatments increased the nitrogen content in soil [46]. We obtained similar results under greenhouse conditions, where the highest soil TN was in the digestate treatments. Thus, the addition of digestate resulted in satisfactory soil pH and soil carbon and TN for tomato plant growth, resulting in better yield and fruit quality. In addition, our study showed that the soil TN was not significantly different between the chemical fertilizer treatment and CK under field conditions, similar to the results of another study [26]. In this study, we detected differences between sandy soil and loamy soil with respect to the trends in soil TN among the various treatments, consistent with the findings of another study [29]. These differences are likely related to differences in the properties of sandy soil (field) and loamy soil (greenhouse).

Enzymes are important participants in soil nutrient cycling, and plant growth is closely related to soil enzyme activity [50]. We observed that digestate application resulted in increased values for soil chemical properties and soil enzyme activities. Chemical fertilizers have been reported to reduce the activity of hydrolases associated with carbon and nitrogen [51]. However, we observed the opposite trend in our study, namely, increased activities of urease, sucrase, protease, and nitrate reductase in all treatments. The fact that the highest soil urease activities were in the digestate treatments is consistent with the findings of other studies in which microbial urease production increased under high soil nitrogen status [48, 52, 53]. Similar to the results of another study [51], the highest sucrase activity and the second-highest protease activity were observed in plants in the organic fertilizer treatments. These results indicate that application of digestate could promote carbohydrate transformation and sucrose hydrolyzation, thus increasing crop yield [47]. An increase in the NR activity is correlated with improvement in the potential for nitrate reduction, which provides a stronger capacity for protein synthesis or nitrogen assimilation [54], leading to better nitrogen utilization by the plant.

Relationship between growth, yield, and fruit quality of tomato and soil properties

Many studies have focused on the ability of organic fertilizers to improve crop quality or yield without linking these changes to soil chemical properties and enzymatic activities [6, 9, 55]. Even less attention has been paid to the impact of digestate application on these parameters. However, soil properties reflect soil fertility and are essential indicators of crop growth and yield formation [56]. The growth, yield, and fruit quality of tomato were significantly correlated with most soil properties in the present study. Treatments consisting solely of digestate boosted fruit quality and resulted in the highest SOC but not the highest tomato yield, in agreement with previous studies [12, 27]. It has been reported that an increased carbon content in soil can improve tomato fruit quality [45]. In this study, parameters such as soluble protein and AsA contents in tomato fruits were significantly and positively correlated with SOC, indicating that fruit quality could be improved by the application of digestate. Compared with chemical fertilizers, organic fertilizers have been shown to enhance SOC and soil fertility, resulting in increased plant height, stem diameter, SPAD value, and yield [27]. In our study, we also detected significant positive relationship between most growth and fruit quality of tomato and soil nitrogen status. Our findings, which agree with those of Barzee et al. [57], confirm the superior performance of digestate compared with chemical fertilizer, possibly because of the higher soil TN after application of digestate. Other studies have shown that the massive increase in soil microbial biomass after the application of organic fertilizers can lead to improvements in crop growth, yield, and quality [12, 46, 51]. We did not detect a significant relationship between soil microbial biomass and tomato growth, yield, and fruit quality. However, we did observe that the growth, yield and fruit quality of tomato were positively associated with most of the soil enzyme activities determined in the current study. Therefore, we could conclude that digestate enhanced tomato growth, yield, and fruit quality by altering soil properties.

Although our findings suggest that digestate combined with chemical fertilizer enhances tomato growth and yield and improves the soil nutrient status. However, it was not significantly different from the digestate treatment, even the similar or lower fruit quality than in digestate treatment. Therefore, the optimum ratio of digestate to chemical fertilizer for tomato production remains to be determined. Future research should include a more in-depth analysis of the aspects addressed in the current study and determine the optimum ratio of organic to inorganic fertilizer.

Conclusion

In this study, tomato plants did obtain a similar or even higher growth potential under the same nitrogen dose following the application of digestate as a full or partial replacement for chemical fertilizer. Specifically, compared with chemical fertilizer, the partial or full substitution of digestate for chemical fertilizer promoted plant height, stem diameter, relative chlorophyll content, and photosynthetic rate in tomato plants, increased fruit yield, improved fruit sugar–acid ratio, soluble protein, ascorbic acid, and reduced the fruit nitrate levels. The application of digestate neutralized the pH of the soil and significantly increased the soil carbon and nitrogen, and improved soil enzyme activities, thereby promoting tomato growth and enhancing tomato yield and fruit quality. In short, our results suggested that the application of digestate as a full or partial replacement for chemical fertilizers has great potential to reduce the amount of chemical fertilizers and maintain soil fertility in tomato production. However, the optimal ratio of digestate to chemical fertilizer has not yet been determined. More favorable rates of combined application of digestate and chemical fertilizer in tomato production should be further evaluated to maximize yields and quality while reducing the use of chemical fertilizer and maintaining good-quality soil.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40538-023-00448-x.

Additional file 1: Fig. S1. Experimental sites at First Farm of Hokkaido University. **Fig. S2.** Cultivation environments used in the tomato plants. **Table S1.** Climatic conditions of experimental sites during production season. **Table S2.** Heavy metals in the dry matter of digestate used in this study and literatures. **Table S3.** Soil moisture content at harvest under different fertilization treatments.

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Author contributions
FL designed the experiment and wrote the manuscript; FL and YY determined the experimental indicators and analyzed the data; FL, JM and NS revised the manuscript; FL, YY, PG, and RN were involved in the field and greenhouse experiments; NS supervised and provided funding.

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Availability of data and materials
The data presented in this study are available in the article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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