Seaweed Extract and Microbial Biostimulants Show Synergistic Effects on Improving Organic Strawberry Production

Jianyu Li, Jeffrey K. Brecht, and Jeongim Kim
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611, USA

Laura S. Bailey, Manasi N. Kamat, and Kari B. Basso
Chemistry Department, University of Florida, Gainesville, FL 32611, USA

James C. Colee
Statistical Consulting Unit, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL 32611, USA

Xin Zhao
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611, USA

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Abstract. The application of seaweed extract and microbial biostimulants has been suggested as a promising approach to overcome yield-limiting factors in organic farming. Yet, information regarding their impact on organic strawberry production is limited. This 2-year field study evaluated the effect of seaweed extract and microbial biostimulants and their synergistic effects on strawberry plant growth, nutrient uptake, fruit yield, and quality under organic production. The biostimulant effects were compared on two strawberry cultivars: Sweet Sensation® Florida127 and Florida Brilliance. Over two seasons, the combination of seaweed extract plus microbial biostimulants applied biweekly consistently resulted in a significant increase of whole-season marketable and total strawberry yield by 23% and 20% on average, respectively, compared with the no-biostimulant control. Application of either biostimulant alone did not consistently show positive effects on strawberry productivity. Modified strawberry root system architecture, enhanced N uptake, increased number of crowns, and higher soil respiration were observed in the biostimulant combination treatment in contrast to the no-biostimulant control. The biostimulant impact was not influenced by strawberry cultivar, but genotypic difference in yield performance under organic production was observed. ‘Florida Brilliance’ produced significantly higher total fruit number and yield than ‘Florida127’ by 26% and 12%, respectively, in the first season, and by 34% and 11%, respectively, in the second season. Marketable fruit number (by 18%) and yield (by 9%) of ‘Florida Brilliance’ were also higher in the first season, along with greater marketable fruit number (by 31%) in the second season. In addition, ‘Florida Brilliance’ showed significantly higher values of SPAD index, photosynthetic rate (early harvest), and fruit mineral contents based on dry weight (late harvest) than ‘Florida127’ in both seasons. Although the biostimulant treatments exhibited little influence on the fruit quality attributes including soluble solids content (SSC), titratable acidity (TA), SSC/TA, and total anthocyanin content, varietal differences were observed with significantly higher levels of SSC and lower contents of total anthocyanins in ‘Florida127’ vs. ‘Florida Brilliance’ during each season. The benefits of combined application of seaweed extract and microbial biostimulants demonstrated in this study suggest the need to further elucidate their synergistic functions in promoting nutrient uptake and fruit yield in organic strawberry production systems under different soil and environmental conditions.

Organic strawberry (Fragaria ×ananassa Duch.) production has increasingly gained interest among growers worldwide. In the United States, the harvested organic strawberry acreage reached 2145 ha in 2021 with California as the top producing state followed by Florida (USDA-NASS 2022). Florida strawberry (Fig. 1A and C) and Sweet Sensation® Florida127 (Fig. 1B and C) are two strawberry cultivars that have dominated Florida strawberry production in recent years (The Packer 2019); however, little research-based information is available regarding their performance in organic cropping systems. Evaluating yield performance and fruit quality of these two leading cultivars in different organic management systems would aid further development of the organic strawberry industry. Compared with conventional production, the yield potential of organically grown strawberry can be 20% to 50% less (Conti et al. 2014; Lesur-Dumoulin et al. 2017; Macit et al. 2007). In addition to challenges associated with disease, pest, and weed management, nutrient supply and synchronizing nutrient availability with crop uptake also represent major constraints in organic strawberry production.

The beneficial effects of biostimulant application have been investigated on various horticultural crops, including improving vegetative growth (Polo and Mata 2018), enhancing nutrient uptake (Mutale-joan et al. 2020), promoting fruit yield (Drobek et al. 2019), and increasing tolerance to abiotic stresses (Van Oosten et al. 2017). In 2018, the US Farm Bill provided the first legal definition for “plant biostimulator” (US Congress 2018), which promoted interests from both researchers and producers in the use of different biostimulants in sustainable crop production. Depending on specific ingredients, biostimulants are generally classified into six main categories, including humic substances (e.g., humic and fulvic acids), seaweed extracts, beneficial microbes (bacteria and fungi), protein hydrolysates, chitosan, and inorganic compounds (e.g., silicon) (Yakhin et al. 2017).

Most commercially available seaweed extract biostimulants are derived from brown algae species (e.g., Ascophyllum nodosum, Ecklonia maxima, Macrocystis pyrifera, and Durvillaea potatorum) and may contain various components, such as mineral elements, amino acids, vitamins, betaines, cytokinins, sterols, and other organic compounds (Khan et al. 2009; Sivasankari et al. 2006; Zheng et al. 2016). Seaweed extract biostimulants have been reported to improve organic vegetable productivity, such as for leafy greens (i.e., lettuce, mustard, kale, Swiss chard, and collards; Sandhu et al. 2018) and okra (Zamana et al. 2021). However, few field studies using seaweed extract biostimulants have been conducted on organic strawberry systems, and the action mechanisms of seaweed extract biostimulants are still poorly understood due to their complex biochemical compositions and possibilities of multifaceted effects.

Microbial biostimulants mainly consist of plant growth-promoting microbes (PGPM), such as beneficial bacteria (e.g., Bacillus, Burkholderia, Pseudomonas), arbuscular mycorrhizal (AM) fungi (Glomeromyccota), and other beneficial fungi (e.g., Trichoderma). Previous studies showed that the application of PGPM increased plant growth and yield performance of crops like peanut (Dey et al. 2004), strawberry (Esikien et al. 2010; Sangiorgio et al. 2023), and raspberry (Orban et al. 2006). The proposed functions of PGPM include increasing plant access to nutrients; mediating soil nutrient cycling, such as symbiotic N₂ fixation (Sahin et al. 2004) and nitrogen (N) mineralization; enhancing pathogen resistance, such as production of siderophores (Gull and
atroviride
under lins (Guti
combined application of microbial biostimulant
nolates signi
Roussos et al. (2009), a mixture of a seaweed
According to another greenhouse study by
tract and silicon demonstrated synergistic effects
synergistically to enhance crop productivity.
many reports that biostimulants could work
significantly enhanced marketable straw-
Furthermore, the efficacy of commercial microbial biostimulants on organic strawberry production
field conditions has yet to be determined.
Interestingly, it has been indicated in
reports that biostimulators could work
synergistically to enhance crop productivity.
Weber et al. (2018) reported that seaweed ex-
and silicon demonstrated synergistic effects
for improving early-season marketable fruit
yield of greenhouse-grown organic strawberries.
According to another greenhouse study by
Ruboss et al. (2009), a mixture of a seaweed extract plus a commercial product of nitrophil-
ates significantly enhanced marketable straw-
berry fruit yield. In a greenhouse experiment of
lettuce, plant fresh weight was increased by the
combined application of microbial biostimulant
(Rhizophagus intraradices and Trichoderma atroviride) and plant-derived protein hydrolys-
sates (Rouphael et al. 2017). Combining sea-
weed extract biostimulant application and

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biofortification increased strawberry yield and fruit quality in conventional straw-
berry production under field conditions (Con-
sentino et al. 2023); however, little is known about the synergistic potential of combined
use of seaweed extract and microbial biosti-
mulants in organic strawberry production in
field cropping systems.

With a focus on seaweed extract and mi-
crobial biostimulants (Fig. 1D), this 2-year
organic strawberry production field study was conducted to determine the response of
short-day strawberry cultivars to single and
combined use of commercial biostimulants.
Specifically, the objectives of our study were
to examine the effects of seaweed extract and
microbial biostimulants on organic straw-
berry plant growth, nutrient uptake, and fruit
yield and quality of ‘Florida Brilliance’ and
Sweet Sensation® ‘Florida127’ in Florida’s
sandy soils.

Materials and Methods

Experimental design and field trial setup.
This 2-year study was conducted on certified
organic land at the University of Florida Plant
Science Research and Education Unit in
Citra, FL, during the 2018–19 and 2019–20
production seasons. The soil type at the re-
search site is Gainesville loamy sand (hyper-
thermic, coated Typic Quartzipsamments)
with 97.0% sand, 2.2% clay, and 0.8% silt,
and an average soil organic matter content at
0.8%. In both seasons, granular organic ferti-
ilizer Nature Safe 10N–0.9P–6.6K (Darling In-
ingredients Inc., Irving, TX, USA) was applied
preplant at an N rate of 84.1 kg ha
1. False
raised beds were formed first and then fol-
lowed by granular organic fertilizer application
on the bed top, and tillage was used to
mix organic fertilizer with soil at a depth of

15 cm on 3 Oct 2018 and 30 Sep 2019. On
the same day, the final raised beds were made
and covered with 0.03 mm black totally im-
permeable film plastic mulch (Intergro, Inc.,
Clearwater, FL, USA) and a single drip tape
(30.5 cm emitter spacing, 3.4 L h
1 m
flow rate; Jain Irrigation, Inc., Haines City,
FL, USA) was put on the soil surface in the
middle of each bed.

In both years, a split-plot design with four
replications of each biostimulant treatment
was used for the field trials. In the 2018–19
season, biostimulant treatments were arranged
in the whole plots following a randomized
complete block design. Three biostimulant
treatments were assessed along with a no-
bio 

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X.Z. is the corresponding author. E-mail: zxin@ufl.edu.
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Fig. 1. (A) Florida Brilliance strawberry cultivar during the harvest season of the organic strawberry produc-
tion field trial in Citra, FL. (B) Sweet Sensation® Florida127 strawberry cultivar during the harvest season
of the organic strawberry production field trial in Citra, FL. (C) Containerized transplants of Florida
Brilliance and Sweet Sensation® Florida127 strawberry cultivars before planting for the organic straw-
berry production field trial in Citra, FL. (D) Samples of the microbial biostimulant (left) and the seaweed
extract biostimulant (right) evaluated in the organic strawberry production field trial in Citra, FL.
transplanting (WAT) in both seasons and then increased to 7.85 kg ha\(^{-1}\) N and 6.28 kg ha\(^{-1}\) K for 4 to 29 WAT in the 2018–19 season and for 4 to 22 WAT in the 2019–20 season. Total organic fertilizer application rates were 302.3 and 247.4 kg ha\(^{-1}\) N, 2329 and 1890 kg ha\(^{-1}\) K, 250 and 206 kg ha\(^{-1}\) P in 2018–19 and 2019–20 seasons, respectively.

All strawberry plants were covered using the AgroFabric\textsuperscript{TM} System frost protection fabric (AgriFabrics LLC, Alpharetta, GA, USA) for 7 nights in the 2018–19 season and 14 nights in the 2019–20 season when the night air temperature was below 4 °C.

Biochemical analyses of seaweed extract biostimulant Stimplex\textsuperscript{®}. The presence and abundance of proteins, lipids, and metabolites in the seaweed extract were qualitatively analyzed using liquid chromatography–tandem mass spectrometry (LC-MS/MS). Biostimulant samples (100 μL each) were extracted for proteins, lipids, and metabolites. The proteins were extracted by acetone/methanol precipitation, lipids were extracted with a modified Folch method (Folch et al. 1957), and metabolites by ice-cold methanol. The details of the biochemical analysis protocols were described by Li et al. (2021).

Photosynthetic parameters and vegetative growth. Photosynthetic parameters including photosynthetic rate (A, μmol m\(^{-2}\) s\(^{-1}\) CO\(_2\)), transpiration rate (E, mmol m\(^{-2}\) s\(^{-1}\) H\(_2\)O), intercellular CO\(_2\) concentration (c\(_i\), μmol mol\(^{-1}\)), and stomatal conductance (g\(_{sw}\), mol m\(^{-2}\) s\(^{-1}\)) were measured twice (early harvest and peak harvest) in each season. Three representative plants were randomly chosen from each subplot and measurements were conducted on the most recent, fully developed, mature leaf from the top of the canopy of each plant with an LI-6800 portable photosynthesis system (Software Version 1.2.; LI-COR Inc., Lincoln, NE, USA). The light intensity and the CO\(_2\) reference concentration in the leaf chamber (6 cm\(^2\)) was 1000 μmol m\(^{-2}\) s\(^{-1}\). The drying procedure and N content analysis for determination of dry matter and N contents of the leafy biomass was then ground through a 1-mm sieve using a Wiley laboratory mill (Model 4; Thomas Scientific, Swedesboro, NJ, USA), before plant tissue N content analysis (by Waters Agricultural Laboratories, Inc., Camilla, GA, USA).

The total N accumulation (kg/ha) was then calculated for the harvest period (g/plant). The N accumulation in fruit included marketable and unmarketable fruit. Fresh marketable and unmarketable fruit were counted and weighed, and data were reported on a per-plant basis. Total fruit yield included marketable and unmarketable fruit yield.

N accumulation in aboveground biomass and fruit mineral content. After measuring growth parameters as aforementioned, samples of crown and leaf parts collected from destructive sampling at 200 DAT in the 2018–19 season and at 155 DAT during the 2019–20 season were dried at 65 °C for 7 d to determine dry weight. Dried plant biomass was then ground through a 1-mm sieve using a Wiley laboratory mill (Model 4; Thomas Scientific, Swedesboro, NJ, USA). The supernatant clear juice was placed in the ICAP-open vessel wet digestion Digi Block 3000 (by Waters Agricultural Laboratories, Inc., the N accumulation in crown and leaf parts was estimated by multiplying the plant tissue N content with the tissue dry weight per plant (g/plant). The N accumulation in fruit during early, peak, and late harvest seasons was estimated by multiplying the corresponding fruit N content of the fruit sample with the total fruit dry weight for the harvest period (g/plant). The total N accumulation (kg/ha) was then calculated by multiplying the amount of N accumulated in crown, leaf, and fruit tissues per plant by the plant population (43,056 plants/ha).

Root growth parameters. Root architecture was also compared between the water control and the biostimulant combination treatment. Two representative strawberry plants from each of the corresponding subplots were sampled for root assessment at 201 DAT on 23 Apr 2019 and at 155 DAT on 12 Mar 2020. The total root system was collected from the field using a shovel. The samples were submerged in plastic bags filled with deionized water for 1 h. The root system was carefully washed to remove the soil particles and then scanned using a root scanning apparatus (ESRON color image scanner LAI600+; EPSON, Toronto, ON, Canada). The determination of the root system characteristics, including total root length (cm/plant), average root diameter (mm), total root surface area (cm\(^2\)/plant), and numbers of tips, forks, and crossings was performed using the WinRhizo image analysis system (Version 2012B; Regent Instruments Inc., Quebec, QC, Canada). The strawberry roots were dried at 65 °C for 7 d to determine the dry weight.

Soil respiration. Soil respiration measurements were conducted at 60, 90, and 130 DAT during the 2019–20 strawberry growing season. One cylindrical PVC collar (20 cm in diameter and 10 cm in height) was inserted into the soil to a depth of 2 cm between the strawberry plants in each subplot. Soil collars were installed 1 week before the CO\(_2\) measurements to get stabilized CO\(_2\) flux inside collars. Soil CO\(_2\) efflux was measured using an LI-6800 portable photosynthesis system with an LI-6800 soil CO\(_2\) flux chamber (LI-COR Inc.). Measurements were consecutively replicated three times at each collar and the duration of each measurement was 160 s. All weeds inside the collar were removed immediately once the collar was placed in the field and the inside of the collars was kept weed free during the strawberry growing season. Soil moisture content and temperature as useful ancillary data were measured with a Stevens HydraProbe (Stevens Water Monitoring Systems, Inc., Portland, OR, USA) inserted into the soil in the vicinity of the collar. The soil respiration rate was expressed as μmol m\(^{-2}\) s\(^{-1}\) CO\(_2\).

Fruit quality attributes. Fruit quality attributes including titratable acidity (TA), soluble solids content (SSC), and total anthocyanin content (TAC) were measured during the early, peak, and late harvest periods in each production season. After removal of the calyxes, 20 fully ripe strawberries per biostimulant treatment replicate with marketable fruit quality were homogenized in a blender (Model: HBO998; Hamilton Beach Brands, Inc., Glen Allen, VA, USA). A portion (~45 g) of the homogenized mixture was centrifuged at 4 °C for 20 min at 19,319 g, using a Sorvall LYNX 4000 refrigerated centrifuge (Thermo Fisher Scientific, Waltham, MA, USA). The supernatant from the centrifuged sample was filtered through double-layer cheesecloth before further analysis. The filtered supernatant clear juice was analyzed to measure TA and SSC. The determination of TA was conducted using an automated titrator (905 Titrando; Metrohm, Riverview, FL, USA) by titrating 6 mL strawberry juice (filtered supernatant) with a solution of 0.1 M l–1 sodium hydroxide (NaOH) at an endpoint of pH 8.2. The TA was expressed as a percentage based on citric acid equivalents. The SSC was assessed using an automatic, temperature compensated refractometer (r°Brix; AMETEK Reichert Technology, Munich, Germany) and expressed as °Brix.
TAC was measured based on the pH difference method (Giusti and Wrolstad 2001). Briefly, anthocyanins were extracted using acidified methanol solution. A 2.0-g sample of the blended mixture was added into 5 mL of HCl (1%)-methanol solution and shaken by a vortex for 20 s. The samples covered with aluminum foil were equilibrated at 4°C for 15 min and then centrifuged at 4°C for 20 min at 19,319 g, using a Sorvall LYNX 4000 refrigerated centrifuge to collect the supernatant. The extractions were conducted in duplicate. Two dilutions of the same extract sample were prepared by adding 600 μL of extract to 2.4 mL of potassium chloride (0.025 M, pH = 1.0) and to 2.4 mL of sodium acetate (0.4 M, pH = 4.5), respectively. All samples were vortexed for 10 s and then equilibrated in the dark at room temperature for 15 min. Their absorbance was measured in triplicate (200 μL for each) at 515 nm and 700 nm for each solution mixture at pH = 1.0 and pH = 4.5, respectively, using a microplate reader (Epoch 2; BioTek Instruments, Inc., Winooski, VT, USA). Results were expressed as milligrams of pelargonidin 3-glucoside equivalents 100 g⁻¹ fresh strawberry. TAC was calculated as follows:

\[
TAC = \frac{(A \times MW \times DF \times 1000)}{(L \times c)}
\]

where \( A \) is the total absorbance calculated by \( (A_{515} - A_{300}) \) (PH = 1.0) – \( (A_{515} - A_{300}) \) (PH = 4.5); \( MW \) is the molecular weight (433.2 g mol⁻¹) of the reference anthocyanin compound (pelargonidin-3-glucoside); \( DF \) is the dilution factor; 1000 is the factor for conversion from g to mg; \( L \) is the pathlength (1 cm); and \( c \) is molar absorptivity coefficient (36,000 M cm⁻³⁻¹).

Statistical analyses. Data analyses were conducted separately for the two production seasons due to significant seasonal effects shown in a preliminary analysis (Linear Mixed Model). A linear mixed model with the GLIMMIX procedure in SAS (Version 9.4; SAS Institute, Cary, NC, USA) was used for data analysis. Data transformation was not needed after checking normality, homogeneity of variance, and linearity for each dataset. In both seasons, a two-way Linear Mixed Model was performed with strawberry cultivar, biostimulant, and their interactions as the fixed effects and block as the random effect in the model. Multiple comparisons of different measurements among treatments were performed using Tukey’s test at \( P \leq 0.05 \).

Results

Biochemical composition of the seaweed extract biostimulant. The seaweed extract biostimulant contained a minimal number of proteins based on the total spectral counts (less than 10) for each identified protein (Supplemental Fig. 1A); however, metabolomic identification was dominated by polyphenols (Supplemental Fig. 1B). Other categories of metabolites identified included amines, amides, organic acids, isoprenoids, steroids, and plasticizers. According to the manufacturer, cytokinin was an active ingredient with a 0.01% concentration (by volume) in this seaweed extract biostimulant product; however, it was not detected in our study using LC-MS/MS. The lipids identified were classified into four main categories including glycerolipids, glycerophospholipids, sphingolipids, and sterol lipids (Supplemental Fig. 1C). As the major lipid compounds detected, triglyceride, diglyceride, and phosphatidylcholine lipids accounted for 38.2%, 29.2%, and 15.0% of the lipids in the seaweed extract biostimulant, respectively (Supplemental Fig. 1D).

Photosynthetic parameters and vegetative growth. Biostimulants did not affect the photosynthetic parameters of strawberry leaves in either trial (data not shown). Photosynthetic rate (Fig. 2A), transpiration rate (Fig. 2B), and stomatal conductance (Fig. 2C) were significantly higher in ‘Florida Brilliance’ than ‘Florida127’ in the early season, by 10%, 12%, and 18%, respectively, in the 2018–19 trial and by 17%, 20%, and 27%, respectively, in the 2019–20 trial. SPAD values and crown diameter did not differ significantly among biostimulant treatments in either season (data not shown). Overall, ‘Florida Brilliance’ exhibited significantly higher SPAD values than ‘Florida127’, by 5% on average in both seasons (Fig. 3A and B). The crown diameter of strawberry plants increased dramatically between 1 and 90 DAT in the 2018 season and 60 DAT in the 2019–20 season until the end of each strawberry growing season (Fig. 3C and D).

Overall, the biostimulant treatments were similar to the no-biostimulant control in terms of crown and leaf numbers per plant, average individual leaf area, and total leaf area per plant in the early growing period (50 or 60 DAT) of both seasons (Fig. 4A–D). However, assessment at 200 DAT in the 2018–19 season and 155 DAT in the 2019–20 season indicated significantly greater numbers of crowns (by 35% and 27%, respectively) and leaves (by 42% and 27%, respectively) in plants treated with the biostimulant combination in contrast to the no-biostimulant control (Fig. 4A and B). Compared with the control, the microbial biostimulant alone significantly increased the crown number by 23% at 200 DAT in the first season, while the seaweed extract alone resulted in greater leaf numbers, by 30% at 200 DAT in the first season and by 17% at 155 DAT in the second season. The biostimulant combination treatment significantly increased the crown number compared with the seaweed extract alone and increased the plant leaf number compared with the microbial biostimulant alone by 29% and 25%, respectively, at 200 DAT in the first season, and by 18% and 13%, respectively, at 155 DAT in the second season. During the late growing period in both seasons, the combination treatment consistently maintained larger leaves than the control (Fig. 4C), and the leaf area per plant was significantly increased by all biostimulant treatments (Fig. 4D).

The two strawberry cultivars did not differ in crown number (Fig. 5A). Compared with ‘Florida Brilliance’, ‘Florida127’ had significantly greater total leaf number per plant by 12% and 20% at 50 and 200 DAT, respectively, in the first season, and by 18% and...
Fig. 3. Effects of strawberry cultivars on leaf relative chlorophyll content (expressed as SPAD value) and crown diameter during 2018–19 (A and C) and 2019–20 (B and D) production seasons in Citra, FL. DAT = days after strawberry transplanting. Treatment values with the same letter at each sampling date do not differ significantly at $P \leq 0.05$ according to Tukey’s test.

13% at 60 and 155 DAT, respectively, in the second season (Fig. 5B). The average individual leaf area of ‘Florida Brilliance’ was significantly larger than ‘Florida127’, by 10% at 50 DAT in the first season and by 5% at 60 DAT in the second season, but ‘Florida Brilliance’ leaf area was 8% lower than ‘Florida127’ at 200 DAT in the first season (Fig. 5C). In contrast to average individual leaf area, total leaf area per plant was significantly higher for ‘Florida127’ than ‘Florida Brilliance’, by 31% at 200 DAT in the first season and by 14% at 155 DAT in the second season (Fig. 5D).

Organic strawberry fruit yield components. For the whole-season fruit yield in the 2018–19 season, the biostimulant combination treatment led to significantly higher marketable and total fruit yields per plant (Tables 1 and 2) than that of the seaweed extract (by 23% on average) or the microbial biostimulant (by 17% on average) alone, and the no-biostimulant control (by 25% on average). The marketable and total fruit numbers per plant were also significantly increased by the combined biostimulant application, compared with applying the microbial biostimulant alone (by 21% and 19%, respectively) and the without biostimulant control (by 27% and 32%, respectively). For the 2019–20 whole-season fruit yield, the biostimulant combination treatment showed significantly higher marketable (by 22%) and total (14%) fruit yields relative to the no-biostimulant control; however, no-biostimulant effect was observed in fruit number.

For the 2018–19 season monthly fruit yield, the combined biostimulant application significantly increased marketable fruit number in December compared with the seaweed extract treatment alone (by 25%) and the no-biostimulant control (by 15%), whereas the increases in marketable fruit number and yield in April reached 162% and 165%, respectively, compared with the control (Table 1). In addition, the combined biostimulant application significantly increased total fruit number (by 44%) and yield (by 94%) in April than microbial biostimulant alone treatment, and the increase rose to 122% and 143%, respectively, when compared with the no-biostimulant control. In the 2019–20 season, the combination treatment led to increases of 21% and 22% in December marketable fruit number and yield, respectively, compared with the control (Table 1). It also significantly increased the number and yield in January compared with the microbial biostimulant alone (by 35%), the seaweed extract alone (by 23%), and the no-biostimulant control (by 59%). In addition, it produced 23% and 27% more berries in December with respect to total fruit number and yield, respectively, compared with the control (Table 2). It also led to significantly higher fruit yield in January than the microbial biostimulant alone (by 22%) and the control (by 26%).

Strawberry yield responses to biostimulant treatments did not vary with cultivars; however, fruit yield differed significantly between the two cultivars (Tables 1 and 2). In both seasons, ‘Florida Brilliance’ yielded significantly higher than ‘Florida127’ in total fruit number (by 26% during 2018–19 and 34% during 2019–20) and yield (by 12% during 2018–19 and 11% during 2019–20) as well as marketable fruit number (by 18% during 2018–19 and 31% during 2019–20). Although ‘Florida Brilliance’ showed higher marketable fruit yield than ‘Florida127’ by 9% in the 2018–19 season, no varietal difference was found in the second season.

The monthly fruit yield comparison between cultivars showed that in the first season, ‘Florida Brilliance’ produced significantly higher marketable fruit number than ‘Florida127’ for the December (by 26%), January (by 69%), and March (by 32%) harvests, along with higher marketable fruit yield in December (by 14%) and January (by 60%), whereas ‘Florida127’...
produced more marketable fruit number (by 59%) and yield (by 81%) in April (Table 1). Compared with ‘Florida127’, ‘Florida Brilliance’ also exhibited significant increases in monthly total fruit number (23% to 67%) and yield (13% to 50%) for the December, January, and March harvests (Table 2). In contrast, ‘Florida127’ yielded more than ‘Florida Brilliance’ in total fruit number (by 63%) and yield (by 85%) in April. In the second season, marketable fruit numbers were significantly greater for ‘Florida Brilliance’ vs. ‘Florida127’ in December (by 17%) and January (by 128%) (Table 1). The January yield advantage for ‘Florida Brilliance’ reached 70% for marketable fruit yield. The total fruit numbers in December, January, and March were also significantly higher for ‘Florida Brilliance’ vs. ‘Florida127’, by 14%, 93%, and 71%, respectively (Table 2). The January total fruit yield favored ‘Florida Brilliance’ over ‘Florida127’ by 61%.

Nitrogen accumulation in aboveground biomass and fruit mineral content. In the 2018–19 season, the biostimulant combination significantly increased N accumulation in leaves, fruit, and total aboveground tissue (including crown, leaves, and fruit), by 63%, 16%, and 29%, respectively, compared with the microbial biostimulant alone, and by 69%, 26%, and 38%, respectively, compared with the no-biostimulant control (Fig. 6). In the 2019–20 season, the combined application also resulted in greater levels of N accumulation in leaves (by 56%), fruit (by 16%), and total aboveground tissue (by 22%), relative to the control (Fig. 6). Moreover, the seaweed extract alone treatment significantly increased N accumulation in leaves (by 25%) and total aboveground tissue (by 14%) compared with the control.

The N accumulation in crowns and leaves was significantly higher in ‘Florida127’ vs. ‘Florida Brilliance’, by 26% and 38%, respectively, in the first season, and by 14% and 17%, respectively, in the second season. Compared with ‘Florida127’, ‘Florida Brilliance’ showed greater fruit N accumulation, by 15% in the first season and by 12% in the second season. However, the two cultivars did not differ significantly in total aboveground plant N accumulation in either season (Fig. 6).

Soil respiration. Soil respiration rate was only measured at 60, 90, and 130 DAT in the second season (Fig. 7). During the soil respiration measurements, the average soil temperature and moisture (volumetric water content) were 21°C and 12% at 60 DAT, 15°C and 10% at 90 DAT, and 22°C and 11% at 130 DAT, respectively. Compared with the control, the seaweed extract alone and biostimulant combination treatments significantly increased soil respiration rate, by 52% and 28% at 60 DAT, 93% and 60% at 90 DAT, and 33% and 44% at 130 DAT, respectively. The microbial biostimulant alone also led to significant increases at 60 DAT (by 24%) and 130 DAT (by 22%) relative to the control. In addition, soil respiration rate was significantly higher in the seaweed extract alone treatment than that of the microbial biostimulant alone (by 23%) and the combined application (by 19%) at 60 DAT as well as the microbial biostimulant alone (by 59%) at 90 DAT. Compared with the microbial biostimulant alone, the combination treatment significantly increased soil respiration rate by 32% and 18% at 90 DAT and 130 DAT, respectively.

Fruit quality attributes of organic strawberry. In both seasons, ‘Florida127’ had a significantly higher level of fruit SSC than ‘Florida Brilliance’ regardless of the sampling date (Table 5). In the first season, ‘Florida127’ also showed significantly higher fruit TA compared with ‘Florida Brilliance’, by 12% at 75 DAT (early harvest stage) and by 7% at 180 DAT (late harvest stage). The SSC/TA ratio of ‘Florida127’ was also significantly higher than that of ‘Florida Brilliance’, by 15% at 140 DAT (peak harvest stage) in the first season and by 16% at 140 DAT (peak harvest stage) and by 24% at 160 DAT (late harvest stage) in the second season. ‘Florida Brilliance’ consistently exhibited significantly higher TACs than ‘Florida127’, by 35% in the first season and 18% in the second season on average (Table 5). The fruit from the seaweed extract alone treatment had a significantly lower SSC/TA ratio compared with the combination (by 13%) and microbial alone (by 8%) treatments and the no-biostimulant control (by 7%) at 180 DAT in the first season. In contrast, the combination and seaweed alone treatments significantly increased the SSC/TA ratio of strawberry fruit by 20% and 28%, respectively, compared with the microbial biostimulant alone, and by 13% and 20%, respectively, compared with the control, at 140 DAT in the second season (Table 5). The biostimulant treatments did not demonstrate any significant effect on total anthocyanin content.
Table 1. Marketable fruit yield components of organic strawberry as affected by biostimulant and strawberry cultivar treatments during the 2018–19 and 2019–20 production seasons in Citra, FL.

<table>
<thead>
<tr>
<th>Treatment(^i)</th>
<th>Marketable fruit number (no./plant)</th>
<th>Marketable fruit yield (g/plant)</th>
<th>Marketable fruit number (no./plant)</th>
<th>Marketable fruit yield (g/plant)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dec Jan Feb Mar Apr WS(^i)</td>
<td>Dec Jan Feb Mar Apr WS(^i)</td>
<td>Dec Jan Feb Mar WS</td>
<td>Dec Jan Feb Mar WS</td>
</tr>
<tr>
<td>Biostimulant (B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STTE</td>
<td>4.5 a 4.1 10.2 6.7 3.4 a 28.9 a</td>
<td>101.2 123.5 238.1 93.4 54.4 a 611.1 a</td>
<td>4.1 a 3.3 7.6 1.6 16.5</td>
<td>96.3 a 90.5 a 1652.1 16.1 368.1 a</td>
</tr>
<tr>
<td>ST</td>
<td>3.6 b 3.3 9.2 5.6 2.2 ab 23.9 b</td>
<td>82.0 93.5 212.5 76.4 34.4 ab 498.7 b</td>
<td>3.8 ab 3.0 6.9 1.6 15.3</td>
<td>85.8 ab 73.8 b 1449.1 15.8 320.2 b</td>
</tr>
<tr>
<td>TE</td>
<td>4.0 ab 3.2 9.9 5.0 1.8 ab 23.9 b</td>
<td>94.0 94.7 237.8 65.8 29.6 ab 521.8 b</td>
<td>3.9 ab 3.3 7.1 1.7 16.0</td>
<td>89.5 ab 66.9 bc 1547.1 21.1 322.2 ab</td>
</tr>
<tr>
<td>CK</td>
<td>3.9 b 3.4 9.7 4.4 1.3 b 22.7 b</td>
<td>92.0 102.2 223.0 58.2 20.5 b 495.8 b</td>
<td>3.4 b 2.2 6.6 1.4 13.6</td>
<td>79.0 b 57.0 c 1463.1 18.9 301.2 b</td>
</tr>
<tr>
<td>Cultivar (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florida Brilliance</td>
<td>4.4 a 4.4 a 10.2 6.2 a 1.7 b 26.9 a</td>
<td>98.4 a 127.2 a 226.7 78.5 24.7 b 555.5 a</td>
<td>4.1 a 4.1 a 7.4 1.8 17.4 a</td>
<td>88.0 a 90.8 a 1471.1 19.6 345.5</td>
</tr>
<tr>
<td>Florida127</td>
<td>3.5 b 2.6 b 9.3 4.7 b 2.7 a 22.8 b</td>
<td>86.4 b 79.7 b 229.0 68.4 44.7 a 508.2 b</td>
<td>3.5 b 1.8 b 6.7 1.3 13.3 b</td>
<td>87.3 b 53.3 b 1585.1 16.4 315.4</td>
</tr>
<tr>
<td>P value</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.005 0.18 0.55 0.08 0.02 0.003</td>
<td>0.06 0.07 0.35 0.13 0.02 0.004</td>
<td>0.03 0.25 0.41 0.85 0.12 0.005</td>
<td>0.03 &lt;0.001 0.41 0.19 0.005</td>
</tr>
<tr>
<td>C &lt;0.001</td>
<td>0.09 0.01 0.03 0.001</td>
<td>0.02 &lt;0.001 0.89 0.16 0.009 0.04</td>
<td>0.01 &lt;0.001 0.48 0.21 0.02 0.86</td>
<td>&lt;0.001 0.52 0.31 0.26 0.26</td>
</tr>
<tr>
<td>B×C</td>
<td>0.07 0.21 0.39 0.36 0.51 0.32</td>
<td>0.10 0.33 0.58 0.45 0.52 0.57</td>
<td>0.12 0.35 0.32 0.17 0.74 0.24</td>
<td>0.24 0.15 0.18 0.15 0.39</td>
</tr>
</tbody>
</table>

\(^i\) STTE = combined application of Stimplex\(^5\) plus TerraGrow\(^5\); ST = Stimplex\(^5\); TE = TerraGrow\(^5\); CK = water control.

Means followed by the same letter within a column are not significantly different at \(P ≤ 0.05\) according to Tukey's test.
Table 2. Total fruit yield components of organic strawberry as affected by biostimulant and strawberry cultivar treatments during the 2018–19 and 2019–20 production seasons in Citra, FL.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total fruit number (fruit/plant)</th>
<th>Total fruit yield (g/plant)</th>
<th>Total fruit yield (g/tree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dec Jan Feb Mar Apr</td>
<td>Dec Jan Feb Mar Apr</td>
<td>Dec Jan Feb Mar Apr</td>
</tr>
<tr>
<td>STTE</td>
<td>4.9 a 13.4 27.2 108.4 34.5 b</td>
<td>91.8 b 92.5 b 276.5 115.1 b</td>
<td>63.7 b 69.5 b 214.5 135.2 b</td>
</tr>
<tr>
<td>CK</td>
<td>4.9 a 13.1 18.0 a 3.0 b 4.9 a</td>
<td>34.8 b 34.5 b 91.8 a</td>
<td>91.8 b 92.5 b 276.5 115.1 b</td>
</tr>
</tbody>
</table>

**Means** followed by the same letter within a column are not significantly different at *P* < 0.05 according to Tukey’s test.

**Table notes:**
- **STTE** = combined application of Stimplex plus TerraGrow; **CK** = water control.
- **Cultivar** (C): Florida Brilliance, Florida 127.
- **Biostimulant** (B): STTE = Stimplex plus TerraGrow; CK = water control.

The synergistic effects of the biostimulants on crop yield performance in this study could be attributed to several plant physiological and morphological factors including enhanced total root length and surface area, improved nutrient uptake (e.g., N), enlarged total and single leaf area, and increased numbers of crowns and leaves during the production season. Because all flower stalks of strawberry plants originate in crowns, strawberry plants with increased crown numbers tend to produce more fruit (Cocco et al. 2011). Furthermore, the resulting increased leaf number and enlarged leaf area could have produced and supplied more carbohydrate assimilates to the strawberry fruit (Weraduwage et al. 2015). Negi et al. (2021) also reported that an increase in number of leaves resulted in enhancement of strawberry fruit yield. Similarly, Sani et al. (2020) reported the synergistic effect of a combination of seaweed extract (Ascophyllum nodosum) and Trichoderma-based biostimulants on increasing total fruit number and yield and average fruit weight of organic tomato, which was ascribed to improved N and K uptake and plant growth attributes including root dry weight and numbers of leaves and branches. Meanwhile, it is important to note that the efficacy of biostimulant products may also depend on their formulations, extraction methods, and other intrinsic factors (Cristofano et al. 2021). Given the nature of Florida’s sandy soils, keeping the seaweed extract biostimulant in the rhizosphere might be a practical challenge. Moreover, strawberry roots with fibrous and shallow architecture may respond poorly to the liquid seaweed extract biostimulant in deep sandy soils (Dong et al. 2020). In this case, the beneficial microorganisms from the microbial biostimulant may have assisted the strawberry plant roots in absorbing the seaweed extract biostimulant more effectively and efficiently by stimulating root growth and improving root system architecture as indicated by the increased total root length and surface area (Dias et al. 2009; Roushauf et al. 2017). On the other hand, the complex ingredients contained in seaweed extract (e.g., polyphenols and organic acids) as identified in our study could potentially promote the activity of extraneous microbes from the microbial biostimulant as well as the indigenous communities of soil organisms by providing carbon (C) and N sources (Alam et al. 2014; Renaud et al. 2019). For example, Schmidt et al. (2013) reported an increase in soil respiration rate in response to application of exogenous polyphenols based on a laboratory incubation study. A similar laboratory experiment by Qu and Wang (2008) also showed that soil amended with different types of phenolic acids had higher soil microbial activities as indicated by increased soil respiration rates. The enhancement of organic strawberry yield observed in the combined seaweed extract plus microbial biostimulants treatment may also stem from the multifunctional network of root-
Fig. 6. Effects of biostimulant treatments (left) and strawberry cultivars (right) on N accumulation in fruit, leaf, and crown tissues during 2018–19 and 2019–20 production seasons in Citra, FL. STTE = combined application of Stimplex® plus TerraGrow®, ST = Stimplex®, TE = TerraGrow®, CK = water control. Bars with the same uppercase letter for total accumulation of N in all above-ground tissues and bars with the same lowercase letters for N accumulation in a given type of tissue do not differ significantly at $P \leq 0.05$ according to Tukey’s test.

To fully understand the synergistic benefits of seaweed extract and microbial biostimulants, more studies are needed to explore their effects on soil chemical and physical properties, soil microbial communities, soilborne pathogens, root-soil-microbe interactions in the rhizosphere, and plant tolerance to abiotic stresses such as drought and temperature extremes. As pointed out by a recent meta-analysis by Li et al. (2022), yield improvement by different biostimulants can be more pronounced with soil treatment vs. foliar application, while greater yield benefits have been observed in less humid environments and sandy soils with low organic matter content and insufficient nutrient conditions.

The biostimulant effects on fruit yield did not differ between the two strawberry cultivars and our results suggested that Florida Brilliance generally outperformed Florida127 under organic production. In particular, ‘Florida Brilliance’ showed better yield performance in the early harvest season (December and January) when the strawberry market is more profitable. We did not observe any major cultivar differences in terms of disease and pest problems except that ‘Florida Brilliance’ plants were less affected by angular leaf spot (caused by Xanthomonas fragariae) than ‘Florida127’ in the 2018–19 season (data not shown). Both cultivars were developed for conventional strawberry production in Florida, and this study provided research-based evidence for differential adaptation of these strawberry cultivars to organic production systems. More studies are warranted to further understand specific traits that help promote strawberry productivity in organic growing conditions.

### Table 3. Nutrient contents of strawberry fruit (dry weight basis) as affected by biostimulant and strawberry cultivar treatments at the late harvest season of the 2018–19 and 2019–20 trials in Citra, FL.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>N (g kg$^{-1}$)</th>
<th>P (g kg$^{-1}$)</th>
<th>K (g kg$^{-1}$)</th>
<th>Mg (g kg$^{-1}$)</th>
<th>S (g kg$^{-1}$)</th>
<th>Ca (g kg$^{-1}$)</th>
<th>B (mg kg$^{-1}$)</th>
<th>Zn (mg kg$^{-1}$)</th>
<th>Mn (mg kg$^{-1}$)</th>
<th>Fe (mg kg$^{-1}$)</th>
</tr>
</thead>
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<tr>
<td><strong>2018–19 season</strong></td>
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<tr>
<td>Biostimulant (B)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STTE</td>
<td>11.19</td>
<td>2.86</td>
<td>16.97 a</td>
<td>1.48</td>
<td>0.93 a</td>
<td>2.01</td>
<td>10.3</td>
<td>23.5</td>
<td>26.6</td>
<td>1.9</td>
</tr>
<tr>
<td>ST</td>
<td>10.98</td>
<td>2.74</td>
<td>16.30 a</td>
<td>1.45</td>
<td>0.91 a</td>
<td>1.94</td>
<td>10.5</td>
<td>26.8</td>
<td>27.1</td>
<td>2.6</td>
</tr>
<tr>
<td>TE</td>
<td>10.84</td>
<td>2.77</td>
<td>15.91 ab</td>
<td>1.41</td>
<td>0.89 ab</td>
<td>1.91</td>
<td>9.8</td>
<td>21.5</td>
<td>26.2</td>
<td>1.9</td>
</tr>
<tr>
<td>CK</td>
<td>10.39</td>
<td>2.61</td>
<td>14.69 b</td>
<td>1.36</td>
<td>0.81 b</td>
<td>1.83</td>
<td>10.5</td>
<td>21.9</td>
<td>25.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Cultivar (C)</td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Florida Brilliance</td>
<td>12.22 a</td>
<td>3.04 a</td>
<td>17.49 a</td>
<td>1.56 a</td>
<td>0.95 a</td>
<td>2.02 a</td>
<td>10.4</td>
<td>24.0</td>
<td>27.9 a</td>
<td>2.5</td>
</tr>
<tr>
<td>Florida127</td>
<td>94.84 b</td>
<td>2.44 b</td>
<td>14.45 b</td>
<td>1.29 b</td>
<td>0.82 b</td>
<td>1.83 b</td>
<td>10.2</td>
<td>22.8</td>
<td>24.5 b</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>2019–20 season</strong></td>
<td></td>
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<tr>
<td>Biostimulant (B)</td>
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<td></td>
</tr>
<tr>
<td>STTE</td>
<td>12.01</td>
<td>3.32</td>
<td>16.34 a</td>
<td>1.45</td>
<td>0.94 a</td>
<td>2.12</td>
<td>13.1</td>
<td>24.7</td>
<td>27.2</td>
<td>3.4</td>
</tr>
<tr>
<td>ST</td>
<td>11.53</td>
<td>3.21</td>
<td>15.90 a</td>
<td>1.41</td>
<td>0.92 a</td>
<td>2.01</td>
<td>13.0</td>
<td>26.5</td>
<td>28.7</td>
<td>3.2</td>
</tr>
<tr>
<td>TE</td>
<td>11.50</td>
<td>3.12</td>
<td>15.76 ab</td>
<td>1.37</td>
<td>0.83 b</td>
<td>1.97</td>
<td>12.0</td>
<td>24.4</td>
<td>26.1</td>
<td>3.6</td>
</tr>
<tr>
<td>CK</td>
<td>11.01</td>
<td>3.21</td>
<td>14.99 b</td>
<td>1.32</td>
<td>0.82 b</td>
<td>1.91</td>
<td>12.8</td>
<td>25.7</td>
<td>26.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Cultivar (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Florida Brilliance</td>
<td>12.98 a</td>
<td>3.42 a</td>
<td>16.59 a</td>
<td>1.50 a</td>
<td>0.93 a</td>
<td>2.02 a</td>
<td>12.6</td>
<td>25.1</td>
<td>28.6 a</td>
<td>3.7</td>
</tr>
<tr>
<td>Florida127</td>
<td>10.05 b</td>
<td>3.01 b</td>
<td>14.91 b</td>
<td>1.20 b</td>
<td>0.83 b</td>
<td>1.83 b</td>
<td>12.5</td>
<td>23.8</td>
<td>25.7 b</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>P value</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.27</td>
<td>0.18</td>
<td>0.04</td>
<td>0.12</td>
<td>0.04</td>
<td>0.26</td>
<td>0.88</td>
<td>0.37</td>
<td>0.43</td>
<td>0.39</td>
</tr>
<tr>
<td>C</td>
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<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.81</td>
<td>0.60</td>
<td>0.001</td>
<td>0.19</td>
</tr>
<tr>
<td>B+C</td>
<td>0.31</td>
<td>0.12</td>
<td>0.56</td>
<td>0.43</td>
<td>0.23</td>
<td>0.29</td>
<td>0.56</td>
<td>0.43</td>
<td>0.61</td>
<td>0.12</td>
</tr>
</tbody>
</table>

STTE = combined application of Stimplex® plus TerraGrow®, ST = Stimplex®, TE = TerraGrow®, CK = water control. The fruit were sampled on 4 Apr 2019 and 2 Mar 2020. Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey’s test.
microbial biostimulants throughout the season. The increase in soil respiration rate was likely
due to various compounds identified in the sea-
weed extract biostimulant, such as polyphenols,
organic acids, proteins, fatty acids, and steroids
(Supplemental Fig. 1). Those organic compounds
can affect soil microbial communities by providing substrates (C and N sources) to
stimulate metabolism activities of soil mi-
crobio (Cleveland et al. 2007). The increased
soil respiration suggested a possible enhance-
ment of nutrient availability through increased
decomposition of organic matter mediated by
soil microbes (bacteria and fungi) and soil
fauna (e.g., microarthropods and nematodes)
(Reynolds and Hunter 2001). Our results are in
agreement with the conventional strawberry
study by Alam et al. (2013), which also reported
increased soil respiration rates in the field as a
result of the application of seaweed extracts de-
erived from Ascophyllum nodosum. However,
more research is warranted to elucidate the di-
rect linkage of increased soil microbial activities
to improvement of strawberry growth and yield
performance.

Effects of strawberry cultivar and seaweed
extract and microbial biostimulants on N accu-
mulation in aboveground biomass and fruit min-
eral content. The increase in plant aboveground
N accumulation by the combined application of
seaweed extract and microbial biostimulants
was largely related to the greater level of
biomass contributed by leaves and fruit. The to-
tal N accumulation in the aboveground biomass
was similar in the two strawberry cultivars.
However, 'Florida127' accumulated more N in
crowns (26% of total aboveground N accumu-
lation) and leaves (22% of total aboveground N
accumulation) and less N in fruit (52% of total
aboveground N accumulation) than 'Florida
Brilliance', which showed 22%, 18%, and 60% of
accumulated N in crowns, leaves, and fruit,
respectively. This implies that these two
strawberry cultivars grown under the same
organic management conditions in the pre-
sent study had similar overall N uptake ca-
pacities, but how the N was allocated differed
between the two cultivars. The higher yielding
potential of 'Florida Brilliance' compared with
'Florida127' could be at least partly attribut-
able to its greater N allocation and assimilation
into fruit, making 'Florida Brilliance' more ad-
vantageous for organic production systems.

Our study showed that both the seaweed
extract application and the combination of
seaweed extract and microbial biostimulants
increased the contents of K and S in straw-
berry fruit in the late harvest season. Seaweed
extracts have been reported to increase nu-
trient uptake by plants, possibly due to the
improved root system architecture (Mattner
et al. 2018). Our results provided further
evidence that the combined use of seaweed
extract and microbial biostimulants could
promote strawberry uptake of some nu-
trients (N, K, and S) by increasing total
root length and surface area. The fruit con-
tents of N, P, K, S, Ca, Mg, and Mn were
consistently higher in 'Florida Brilliance'
vs. 'Florida127' in both seasons, which is in ac-
cordance with previous studies that the levels of
macro- and micronutrients in strawberry fruit

Fig. 7. Effects of biostimulant treatments on soil respiration rate in organic strawberry field during
2019–20 in Citra, FL. STTE = combined application of Stimplex® plus TerraGrow®; ST = Stimplex®; TE = TerraGrow®; CK = water control. Bars with the same letter at each sampling date do
not differ significantly at $P \leq 0.05$ according to Tukey’s test.

**Table 4.** Root dry weight, total root length, average root diameter, total root surface area, and numbers of root tips, forks, and crossings of strawberry plants in the 2018–19 and 2019–20 trials in Citra, FL.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Root dry wt (g)</th>
<th>Total root length (cm/plant)</th>
<th>Avg root diam (mm)</th>
<th>Total root surface area (cm²/plant)</th>
<th>Tips (no.)</th>
<th>Forks (no.)</th>
<th>Crossings (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018–19 season</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biostimulant (B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STTE</td>
<td>10.22 a</td>
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<td>1.06</td>
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<td>0.12</td>
</tr>
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</table>

1 STTE = combined application of Stimplex® plus TerraGrow®; CK = water control.

The plant roots were sampled on 23 Apr 2019 and 12 Mar 2020.

Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ according to Tukey’s test.
Table 5. Soluble solids content (SSC), titratable acidity (TA), SSC/TA ratio, and total anthocyanin content (TAC) of organic strawberry fruit as affected by biostimulant and strawberry cultivar treatments during the 2018–19 and 2019–20 production seasons in Citra, FL.

<table>
<thead>
<tr>
<th>SSC (°Brix)</th>
<th>TA (%)</th>
<th>SSC/TA</th>
<th>TAC (mg/100 g FW)</th>
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<td>2019–20 season</td>
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<td>140 DAT</td>
<td>180 DAT</td>
</tr>
<tr>
<td></td>
<td>75 DAT</td>
<td>140 DAT</td>
<td>180 DAT</td>
</tr>
<tr>
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<td>140 DAT</td>
<td>180 DAT</td>
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<td>7.1</td>
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<td>7.2</td>
<td>6.9</td>
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</tr>
<tr>
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<td>6.5 b</td>
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<td>2019–20 season</td>
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<td>B+C</td>
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<td>0.18</td>
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</table>

¹ STTE = combined application of Stimplex⁷ plus TerraGrow⁶; ST = Stimplex⁷; TE = TerraGrow⁶; CK = water control.

Means followed by the same letter within a column are not significantly different at P ≤ 0.05 according to Tukey’s test.

are cultivar dependent (Celiktopuz et al. 2021; Jurgil-Małecka et al. 2017). Strawberry culti-
vvar adaptation to organic systems with respect
to nutrient uptake, assimilation, and allocation
deserves more studies for identifying and develop-
opping genotypes suitable for organic production.

In our study, ‘Florida Brilliance’ fruit ex-
hibited greater levels of TAC throughout the
harvest season during both trials. As the an-
thocyanin content in strawberry fruit is closely
related to red fruit color intensity, the lower TAC
found in ‘Florida127’ reflected its lighter red
color as reported previously (Kelly et al. 2016).

The higher TAC level in ‘Florida Brilliance’ also
suggests improved nutritional quality and
benefits for human health, particularly due to
the antioxidant capacities associated with an-
thocyanins (Giampieri et al. 2012). The fruit an-
thocyanin levels measured in our study fall
within the range of 23 to 45 mg of pelargonidin
3-glucoside per 100 g of fresh weight for differ-
ent strawberry cultivars reported previously
(Wang and Zheng 2001). Balancing yield and
fruit quality is another area of interest in future
research for improving organic strawberry
production systems. Overall, our study sug-
ests that compared with ‘Florida127’, ‘Florida
Brilliance’ was better adapted to organic pro-
duction systems in Florida as reflected by the
improved photosynthetic ability, increased
N accumulation in fruit, and enhanced early-
season fruit yield performance along with
acceptable fruit quality with higher levels of
total anthocyanins.

Conclusions

Our findings indicate that overall ‘Florida
Brilliance’ outperformed ‘Florida127’ for fruit
yield under organic production and produced
strawberries with higher anthocyanin contents,
whereas ‘Florida127’ might have better flavor
as reflected by higher values of fruit SSC and
SSC/TA. The seaweed extract and microbial
biostimulants exhibited synergistic effects in
improving strawberry fruit yield, suggesting their
integrative potential as a promising measure to
enhance strawberry productivity in organic sys-
tems. The combined application of seaweed ex-
tract plus microbial biostimulants also resulted in
greater numbers of crowns and leaves, enlarged
leaf area, modification of root morphology with
increased total root length and surface area, en-
hanced N accumulation in aboveground tissue,
and increased soil respiration rates. Further re-
search is warranted to investigate the synergistic
effects of different types of biostimulants on
crop productivity improvement in addition to
their individual impacts and the underly-
ing mechanisms.

References Cited

Ahmed A, Hasnain S. 2014. Auxins as one of the
factors of plant growth improvement by plant
growth promoting rhizobacteria. Pol J Micro-
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2014-035.

Ascosphillum extract application can promote
plant growth and root yield in carrot associated
with increased root-zone soil microbial activity.

Effect of Ascosphillum extract application on
plant growth, fruit yield and soil microbial

1124

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