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Effect of rock dust-amended compost on the soil properties, soil microbial activity, and fruit production in an apple orchard from the Jiangsu province of China

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ABSTRACT

This study examined the effect of compost fortified with rock dust on the soil properties, soil microbial activity, and yield and fruit quality in a mature apple orchard from the Jiangsu province of China. The incorporation of rock dust significantly improved the microelement contents of Ca, Mg, Fe, Mn, Zn, B, and Al, but without increasing phytotoxicity of the compost. The fortified compost had higher metabolic activity and functional diversity of microorganisms as determined by the community-level physiological profiling with Biolog EcoPlates. The two-year incorporation of the rock dust compost into a poor-quality soil led to a significant increase in the yield with the increase of 120% and 187% compared to untreated control in 2013 and 2014, respectively. Application of rock dust compost obviously promoted superoxide dismutase (SOD) activity and concentration of vitamin C in mature apple trees. The beneficial effects coincided with higher microbial activity and shifts in the composition of the soil microbiome. Our results demonstrate that the practice of combining the rock dust-fortified compost with NPK fertilizers provides a cost-effective way of supplying crops with macro-and micronutrients ensuring better vegetative growth and higher yields.

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Introduction

Composting is a controlled decomposition of organic matter into mineralized products (CO_2, H_2O, NH_4^+) and stable humic substances performed by communities of aerobic thermophilic and mesophilic microorganisms (Bernal et al. 2009; de Guardia et al. 2010; Das et al. 2011). Although not a new technology, composting represents and environmentally-friendly way of recycling food, yard, and farm wastes into a value-added product that has multiple uses in agriculture. The process of composting is also employed by livestock industry for the disposal of manure and reduction of its negative impact (odor and gaseous emissions, soil and water pollution, etc.) on the environment (Burton and Turner 2003). Composting significantly reduces or eliminates the risk of spreading pathogens, parasites, and weeds associated with the direct land application of manure and leads to a final stabilized product, which can be used to improve and maintain the quality and fertility of the soil (Larney and Hao 2007).

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Supplemental data for this article can be accessed here.

Plants require a range of essential macro- and micronutrients for optimum growth and productivity. To improve yields, farmers often use large amounts of chemical fertilizers containing nitrogen, phosphorus, and potassium, which over time adversely affects soil quality, increases the emission of greenhouse gases, contaminates groundwater and causes eutrophication of surface water bodies (Foley et al. 2011). Organic fertilizers, including those produced via the process of composting, are less damaging to the environment and capable of supplying crop plants with necessary macro-and trace elements. In contrast to chemical fertilizers, the plant nutrients are typically present in composts in a slow-release form and at lower concentrations (Claassen and Carey 2007). Hence, it is essential to carefully control the composting ingredients to create a nutrient – balanced product capable of improving the growth, yield, and quality of crops (Proietti et al. 2016).

Rock dust is a mineral-rich byproduct of mining and quarry industry, which can be used to improve the fertility of soil, stimulate plant growth, enhance the activity of beneficial microflora, increase resistance to pests and diseases, and increase the quality of fruits and vegetables (Li and Dong 2013; Beerling et al. 2018). The rock dust lacks significant amounts of nitrogen, phosphorus, and potassium, but contains calcium and trace elements like Fe, Al, and Mg, which are difficult to replace once they have been removed from the soil through the process of natural weathering or intensive use (Nunes et al. 2014). Fortifying soils with ground rock has been practiced locally as a way of rejuvenating lateritic soils and promoting tree establishment in Europe (Albert 1940) and improving crop yields in highly weathered soils of some parts of Turkey, Africa, Brazil, Malaysia, and Mauritius (de Villiers 1961; Leonardos et al. 1987; Polat et al. 2004; Van Straaten 2006; Anda et al. 2013). For example, sugarcane trials with crushed basalt applications over 20 t ha^{-1} in combination with conventional NPK fertilizers increased yields by up to 30% over five successive harvests on the highly weathered soils of Mauritius compared with plots receiving fertilizer and no basalt addition (de Villiers 1961). However, in contrast to plants, the effect of rock dust amendments on the composition and activity of soil microbial communities remains unexplored.

Apples are the most popular fruit in China, and the country is a global leader in the production and world’s largest exporter of this commodity (Wang et al. 2016). Apple trees grow best in well-drained, deep and fertile soils, and the availability of nutrients greatly influences the yield and overall quality of fruit produced in commercial orchards (Milošević and Milošević 2015). On the other hand, the agriculture industry focuses almost exclusively on the use of macronutrient (NPK) fertilizers while neglecting micronutrients and organic matter, a practice that ultimately affects soil properties and apple productivity.

In a previous greenhouse study, we demonstrated that the application of rock dust increased soil enzymatic activity, promoted plant growth, and reduced the severity of bacterial wilt of tomato (Li and Dong 2013). Since the best results were achieved by combining the rock dust with commercial organic fertilizer, we hypothesized that this material could be used during composting as a source of plant micronutrients. To test this hypothesis, we combined goat manure, wheat straw, and rock dust to produce a compost fertilizer rich in plant micronutrients and beneficial elements. The compost was combined with the conventional NPK fertilizer to amend the soil in a mature apple orchard in the Jiangsu province of China. We pursued the following specific objectives: 1) to assess the effectiveness of the goat manure/rock dust compost amendment on the soil microbial activity as well as yield and fruit quality of apple trees, and 2) to examine the impact of rock dust on the composting process.

Materials and methods

Composting process

The material for composting was procured from a local farmer and included a mixture of goat dung and wheat straw shredded into 3-cm long fragments. The total nitrogen (N), total phosphorus (P), total potassium (K), and organic matter (OM) contents of the wheat straw were 0.8%, 0.5%, 3.3%, and 58.2%, respectively. In contrast, the goat dung contained 1.4%, 0.5%, 1.2%, and 25.0%, respectively, of N, P, K, and OM. Two different types of compost were prepared and used throughout the study. The first type, referred to as composted manure (CM), was produced by mixing seven parts of dung with three parts of wheat straw (w/w), which resulted in a C/N ratio of ca. 26. The second type, referred to as composted manure with rock dust (CMRD), was prepared identically except for the addition of 0.4 part of the byproduct of quarry industry, which serves as a source of different trace mineral nutrients. The chemical composition of the rock dust used in this study was described earlier by Li and Dong (2013).

All composting ingredients were combined in desired ratios, thoroughly mixed, equilibrated to the moisture content of ca. 80%, and arranged in 5 m (length) × 1 m (width) × 1 m (height) piles on a flat, concrete surface. The heaps were manually turned for aeration every 3 d and watered to maintain the moisture content of 50–60%, which helped to control temperature and sustain an optimal level of microbial activity (Bernal et al. 2009). The composting was carried out for a total of 30 d, after which the material was sampled for chemical property analysis. The tested properties included the temperature during the composting process, pH, electrical conductivity (EC), macronutrients (total and available N, total and available P, total and available K, Na, Ca, Mg), and micronutrients (Fe, Al, Mn, B, Zn), which were assayed as described by Li and Dong (2013).

Seed germination trials

The phytotoxicity of composts was assessed by measuring the seed germination rate of wheat (*Triticum aestivum*), oilseed rape (*Brassica napus*), tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), corn (*Zea mays*), and rice (*Oryza sativa*) (Gilbert et al. 2001; Li et al. 2014). Briefly, ten grams of compost were mixed with 100 mL of distilled water, and the resultant suspension was incubated for 24 h at room temperature and clarified by passing through filter paper. Twenty-milliliter aliquots of the filtrate were then dispensed into Petri dishes containing batches of different seeds (100 seeds per batch) spread on a double layer of filter paper. The treated seeds were incubated at 25°C ± 1°C under cool white fluorescent light (30 μmol m^{-2} s^{-1} with 16 h light/8 h dark photoperiod) and examined daily to count the number of germinated seeds, which were judged by the appearance of a visible radicle. The germination rates were determined on the seventh day by using the following formula: Germination rate (%) = (number of germinated seeds/ total number of seeds) ×100%. Treatments were replicated three times, and the entire experiment was repeated.

Community-level physiological profiling

The effect of rock dust on the metabolic activity and diversity of compost microorganisms was evaluated by the community-level physiological profiling (CLPP) with Biolog EcoPlates (Biolog, Hayward, CA, USA). This method was also used to compare the metabolic activity of microorganisms in the unamended orchard soil with that in soils fertilized with CM and CMRD composts. Samples of soil for the CLPP analysis were collected around tree roots at the time of harvest. To generate the carbon substrate utilization profiles, one gram of fresh soil or compost was mixed for 20 min with 99 mL of 10 mM phosphate buffer (pH 7.0), and 100 μL aliquots of the resultant suspension were inoculated into wells of a Biolog EcoPlate containing 31 different carbon sources. The inoculated plates were incubated for a week at 25°C in the dark, and the absorbance at 590 nm was measured every 12 h using a MicroStation microplate reader (Biolog). For each sample, the capacity of microbial communities to catabolize different carbon sources was expressed by calculating the average well-color development (AWCD) value. Also, Shannon-Wiener diversity (H′), Shannon evenness (E), and Simpson diversity (D) indices were calculated based on OD_{590} absorbance values recorded after 120 h of incubation following the method of Ge et al. (2018).

Field trials

The studies were conducted in a mature apple orchard near the town of Songlou, Feng county, Jiangsu province (116°29′ E, 34°36′ N). The area receives 800–930 mm of precipitation annually and has the annual average temperature around 14°C (Tu et al. 2012). The orchard soil was a sandy loam with pH 7.5 and 0.3% nitrogen, 0.1% phosphorus, 1.3% potassium, and 0.6% soil organic carbon. The orchard occupied and area of 0.5 ha and has 30 rows of apple trees with seven trees per row (*Malus domestica* Borkh cv. Red Fuji). All trees were approximately 15 years old, and due to age and poor management practices displayed signs of physiological stress and/or disease. The disease symptoms manifested in the form of leaf scorch (browning of leaves from the edge inwards) and some dying of upper branches.

The compost application trials were conducted in the autumn of 2012 and 2013 with fruit harvested in the following year. Three treatments were established and designated as M (soil amended with the CM compost), MRD (soil amended with the CMRD compost), and CK (no-compost control soil). Each treatment included a total of 35 trees arranged in five replicates with seven trees per replicate. The fertilizer and composts were first applied in November 2012. All treatments received the same chemical fertilizer (15% N, 15% P_2O_5, and 15% K_2O), which was applied at the rate of 2,600 kg ha^{-1}. In addition, the M and CM treatments received, respectively, the MRD or CMRD compost at a rate of 26,000 kg ha^{-1}. The composts and chemical fertilizers were thoroughly mixed with soil and backfilled into 15 to 40 cm deep fertilization ditches dug at the tree dripline. The fertilization and compost application were repeated in November 2013, and the fruits were hand-picked in October 2013 and 2014. The yield was expressed as the average weight of per tree and was calculated by sampling one randomly selected tree each replicate with a total of five trees evaluated per treatment.

Fruit quality testing

The fruit quality tests were performed in 2014 immediately after harvest. Three fruits of uniform size and color were randomly selected from each replicate tree with five replicates in every treatment. The fruits were peeled with a potato knife, and thin pieces of pulp were immediately frozen in liquid nitrogen and stored at −80°C until analyses. To assay the superoxide dismutase (SOD, EC 1.15.1.1) activity, 100 mg of apple tissue were finely ground in liquid nitrogen and homogenized in 500 μL of 50 mM potassium phosphate buffer (pH 7.8) supplemented with 0.1 mM EDTA, 1.0% (w/v) soluble polyvinylpyrrolidone (PVP-10), and 0.1% (v/v) Triton X-100. The SOD activity was assayed by measuring the absorbance of reduced ferricytochrome c at 550 nm with a spectrophotometer (Fernández-Trujillo et al. 2007). The ascorbic acid content was measured by the titrimetric method with potassium bromate-bromide solution following the method of Koog et al. (1998). The total acidity was determined by the AOAC method via titration against a standard 0.1 M solution of NaOH (Herlich 1990), and the total sugar content was measured by the anthrone method (Khairul et al. 2013). The hardness of apples was determined using an HFH 80 Fruit Hardness Tester (Omega Engineering, Norwalk, CT, USA).

Leaf chlorophyll content assays

In September 2014, three trees from each replicate were randomly selected to determine the concentration of chlorophyll in leaf tissue. For each tree, 12 healthy five-month-old leaves were sampled from branches growing in four directions, placed on ice and transported to the laboratory for processing. The content of leaf chlorophyll was assayed according to Porra et al. (1989). Briefly, a 0.20-cm^2 disc of leaf tissue was excised with a 0.5-cm cork borer and immediately weighed. Chlorophyll pigments were extracted by submerging the leaf disk in 1.0 mL of ice-cold 80% (v/v) acetone containing 2.5 mM sodium phosphate buffer (pH 7.8). The extracts were clarified by centrifugation at 4°C for 20 min at 16,000 × g, and the amount of chlorophyll was determined by measuring the absorbance at 663.6 nm, 646.6 nm and 750.0 nm with a DU 800 spectrophotometer (Beckman-Coulter, Brea, CA, USA).

Statistical analyses

All values were expressed as mean ± standard error (SE) of the mean. The differences in chemical properties, germination rate, and microbial activity between CM and CMRD treatments were analyzed by two-sample *t*-test ($\alpha = 0.05$). Other data were analyzed by the one-way analysis of variance (ANOVA) and Duncan's multiple range test ($\alpha = 0.05$) using SPSS version 20.0 (IBM, Armonk, NY, USA). The hierarchical clustering and heatmap visualization of Biolog data were performed with the vegan R package (Oksanen et al. 2019).

Results

Phytotoxicity and chemical properties of composts used in the study

The phytotoxicity of mature composts was assessed after 30 d of composting by evaluating the seed germination rate of wheat, oilseed rape, tomato, cucumber, maize, and rice. The treatment of seed with compost extracts resulted in the germination rate of 84% to 98%, with exact values varying depending on the plant species (Table 1). Overall, oilseed rape, tomato, and maize exhibited the lowest rate of germination close to 90%. Although not statistically significant, the application of CMRD compost resulted in slightly better seed germination compared to the treatment with CM compost.

The chemical property analysis of the finished CM and CMRD composts revealed that they were slightly alkaline with pH 8.0. The electrical conductivity (EC) measurements demonstrated that the rock dust-fortified (CMRD) compost contained a substantially higher amount of soluble salts compared to the CM compost. The macronutrient analysis revealed no differences between the CMRD and CM composts in the amount of N, P, and K (Table 2). On the other hand, the compost amended with rock dust had significantly higher levels of microelements, such as Ca ($p = 0.005$), Mg ($p = 0.042$), Fe ($p = 0.001$), Mn ($p = 0.041$), Zn ($p = 0.047$), B ($p = 0.004$), and Al ($p = 0.002$). In particular, the concentration of aluminum and iron in the CMRD compost was 2–3 times higher than in the CM compost (Table 2). Taken collectively, these results demonstrate that the inclusion of rock dust in the process of composting fortifies the final product with plant micronutrients without increasing its phytotoxicity.

Table 1. Germination rates of different composts.

	Seed germination (%)					
Treatment[a]	Wheat	Oilseed rape	Tomato	Cucumber	maize	Rice
CM	95 ± 6[b]	85 ± 3	85 ± 2	90 ± 4	85 ± 2	92 ± 4
CMRD	98 ± 6	84 ± 3	84 ± 2	92 ± 3	89 ± 2	87 ± 5

[a] CM, composted manure; CMRD, composted manure with rock dust. [b] Values are means ± standard error of three independent experiments.

Table 2. Chemical properties of composts used in the study.

		EC[b]*	TN[c]	TP[d]	TK[e]	Ca*	Mg*	Fe*	Mn*	Zn*	B*	Co	Ni	Al*	Na
Treatment [a]	pH	dS m^{-1}	%			mg kg^{-1}									
CM	8.0	6.9	1.1	0. 9	3.1	23.8	15.5	3.3	0.4	1.1	0.2	0.005	0.1	13.5	76.3
CMRD	8.0	7.3	1.3	1.0	3.5	35.4	20.0	10.5	0.6	1.4	0.3	0.008	0.1	27.8	80.5

[a]CM, composted manure; CMRD, composted manure with rock dust. [b] EC, electrical conductivity. [c] TN, total N. [d] TP, total P. [e] TK, total K. * Values in the column are significantly different at $\alpha = 0.05$ (one sample *t*-test).

The effect of rock dust on the microbial metabolic activity in compost

During composting, the temperature of CM and CMRD composts increased in the initial phase reaching a maximum of around 65 °C and then decreased to ambient temperature. However, due to the difference in starting materials, the temperature in the CMRD treatment was about 2 °C higher than in CM during the first 12 d of the composting process (Figure 1(a)). The physiological activity of microbial communities from CM and CMRD composts were qualitatively and quantitatively compared using Biolog EcoPlates. The AWCD profiles of the two composts exhibited a similar pattern that included a 24-h lag phase followed by a rapid rise in the OD$_{590}$ absorbance until 120 h, after which the rate of increase tapered off (Figure 1(b)). Interestingly, the peak mean AWCD value observed with samples of the CM compost was at 1.3, while the CMRD compost reached a significantly higher AWCD value of 1.6 (Figure 1). The culturable counts exhibited a similar trend, with the levels of bacteria, fungi, and Actinomycetes trending higher in CMRD relative to CM (Figure S1). Further analyses also revealed that microbial communities from the CMRD compost had significantly higher functional diversity and evenness, as estimated by Shannon diversity (H′,p = 0.019), Shannon evenness (E, p = 0.030), and Simpson (D, p = 0.039) indices (Table 3). Together, these data suggest that the addition of rock dust promotes metabolic activity and increases the functional diversity within compost microbial communities.

The capacity of microorganisms to catabolize 31 substrates present in the Biolog EcoPlate was visualized by subjecting the OD$_{590}$ absorbance values to hierarchical clustering and presenting

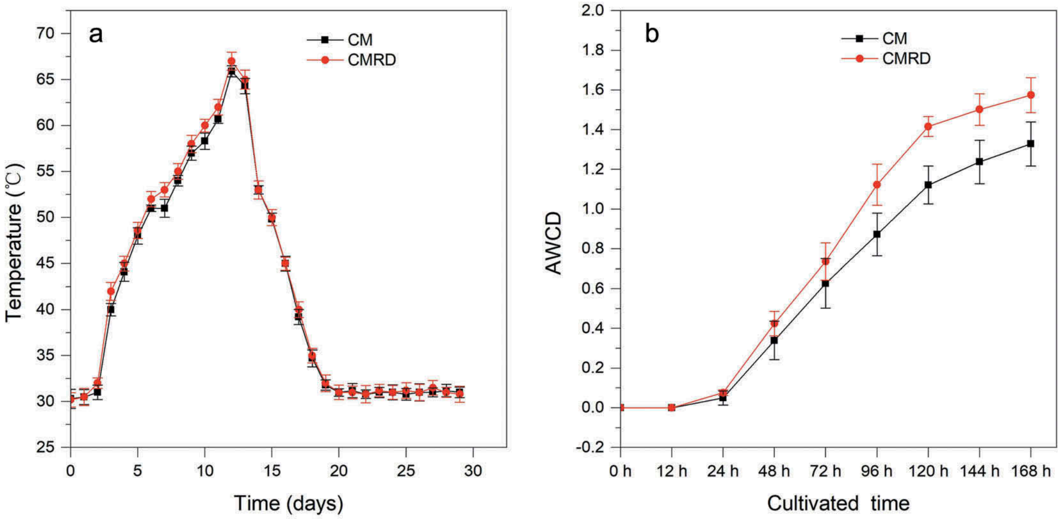

Figure 1. Variation in temperature during composting (A) and average well color development (AWCD) in Biolog EcoPlates inoculated with samples of CM and CMRD composts (B). The inoculated Ecoplates were incubated at 25°C for 168 h, and the OD$_{590}$ readings were taken every 12 h.

Table 3. Microbial diversity indices in composts estimated by the community-level physiological profiling with Biolog EcoPlates.

Treatment [a]	Shannon diversity (H′) *	Shannon evenness (E) *	Simpson diversity (D) *
CM	2.91 ± 0.08 [b]	0.93 ± 0.07	0.93 ± 0.01
CMRD	3.10 ± 0.03	0.95 ± 0.01	0.95 ± 0.01

[a]CM, composted manure; CMRD, composted manure with rock dust. [b] Values are means ± standard error. * Values in the column are significantly different at α = 0.05 (one sample *t*-test).

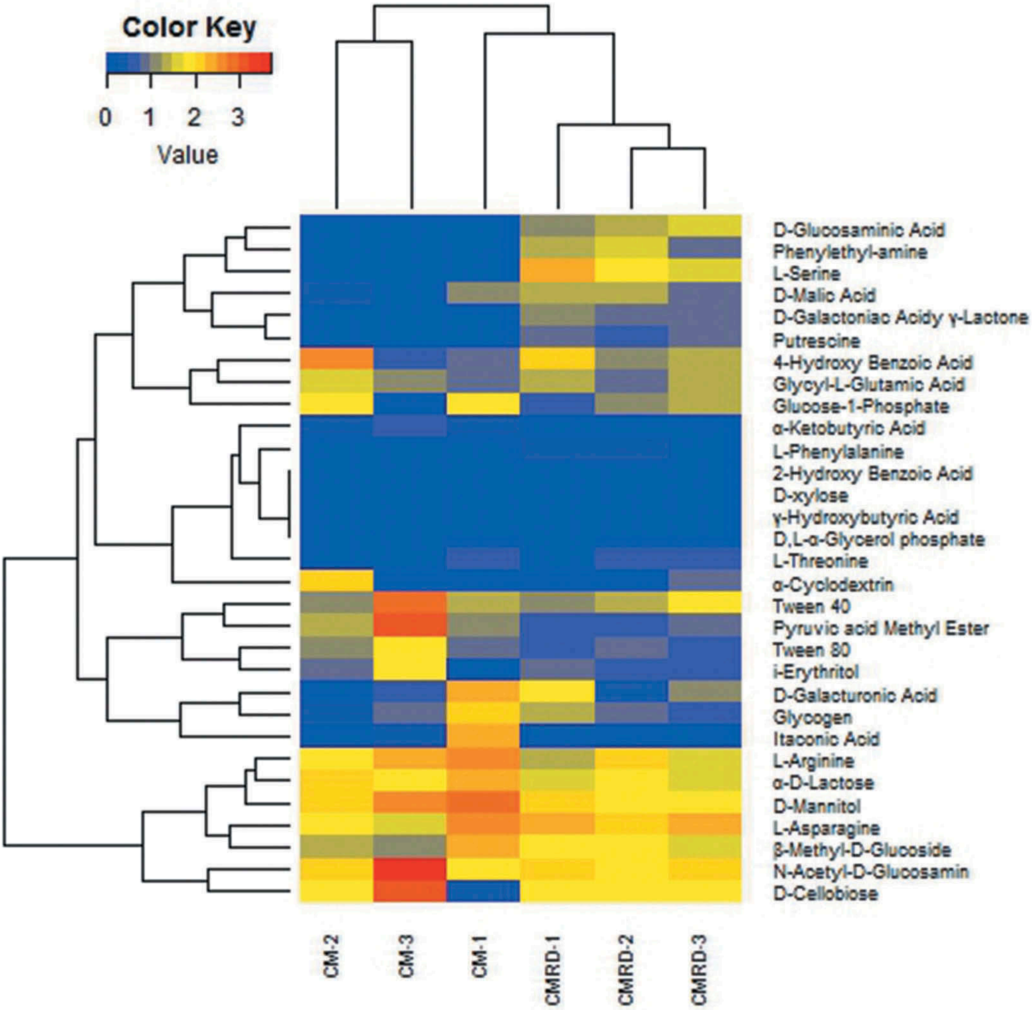

Figure 2. Hierarchical clustering of metabolic profiles of microbial communities from the CM and CMRD composts. The color scale of the heatmap reflects the utilization of the 31 carbon substrates present in the Biolog EcoPlate after 120 h of incubation. Individual replicates within each treatment are numbered.

results of the analysis in a form of the heat map (Figure 2). A detailed comparison revealed the utilization of 25 different carbon sources in the microplates inoculated with samples of the CMRD compost. In contrast, only 21 substrates were metabolized in the EcoPlates inoculated with CM compost. Microorganisms from both composts actively utilized most carbohydrates (glucose-1-phosphate, α-D-lactose, D-mannitol, β-methyl-D-glucoside, N-acetyl-D-glucosamine, D-cellobiose), some amino acids (glycyl-L-glutamic acid, L-arginine, L-asparagine), 4-hydroxybenzoic acids, and Tween 40. Both groups of microorganisms were unable to catabolize 2-hydroxybenzoic acid, D-xylose, γ-hydroxybutyric acid, and D, L-α-glycerol phosphate. In contrast, the two microbial communities differed in the ability to utilize D-glucosaminic acid, phenylethyl-amine, L-serine, D-galactonic acid γ-lactone, and putrescine, all of which were better catabolized by microbes from the CMRD compost thus indicating a broader range of microbial metabolic activity (Figure 2). The result suggest that the addition of rock dust provides microelements stimulate the activity of microorganisms, which results in the accelerated breakdown (mineralization) of organic matter and increased nutrient content of the fortified compost (Table 2).

The community-level physiological profiling of soils amended by different composts

The estimation of soil metabolic potential has been used as a sensitive means of assessing soil quality. We employed the community-level physiological profiling (CLPP) to evaluate the impact of compost amendments of the activity and diversity of microorganisms in the orchard soil. The AWCD curves of the control soil and soils amended with CM and CMRD composts had a similar sigmoidal profile and contained a 24 h lag phase followed by a rapid increase in AWCD values, which continued to rise till the end of the incubation (Figure 3). The CLPP profiling also revealed that the highest AWCD values were associated with the soil treated with the CMRD compost, followed by the soil amended with the CM compost and the untreated control. We used principal component analysis (PCA) to correlate the application of the two different composts with changes in the carbon source utilization patterns of soil microorganisms. The PC1 and PC2 principal components explained, respectively, 62.6% and 9.9% of the total variance and identified the three treatments that had been distinguished by their AWCD activity (Figure 4). The control soil and the soil amended with the CM compost were relatively close but statistically separated, whereas the MRD treatment appeared more distinct across the first principal component. The results indicated that the addition of rock dust to compost led to the increased microbial activity and shifts in the microbiome composition of the orchard soil.

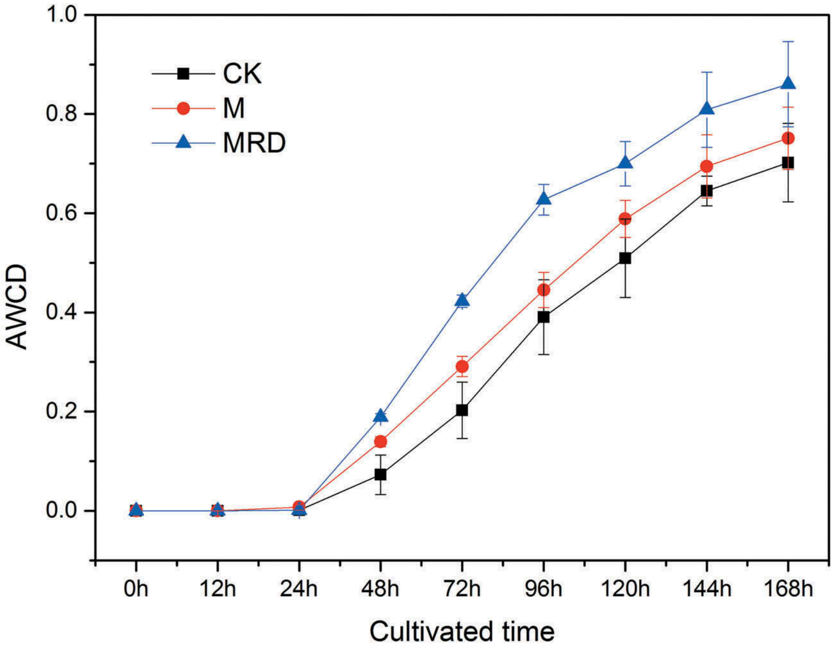

Figure 3. Average well color development (AWCD) in Biolog EcoPlates inoculated with the control apple orchard soil and soils amended with CM and CMRD composts. The inoculated plates were incubated at 25°C for 168 h, and the OD_{590} readings were taken every 12 h. The soil treatments are designated as follows: M, soil amended with the CM compost; MRD, soil amended with the CMRD compost; CK, the control soil without compost.

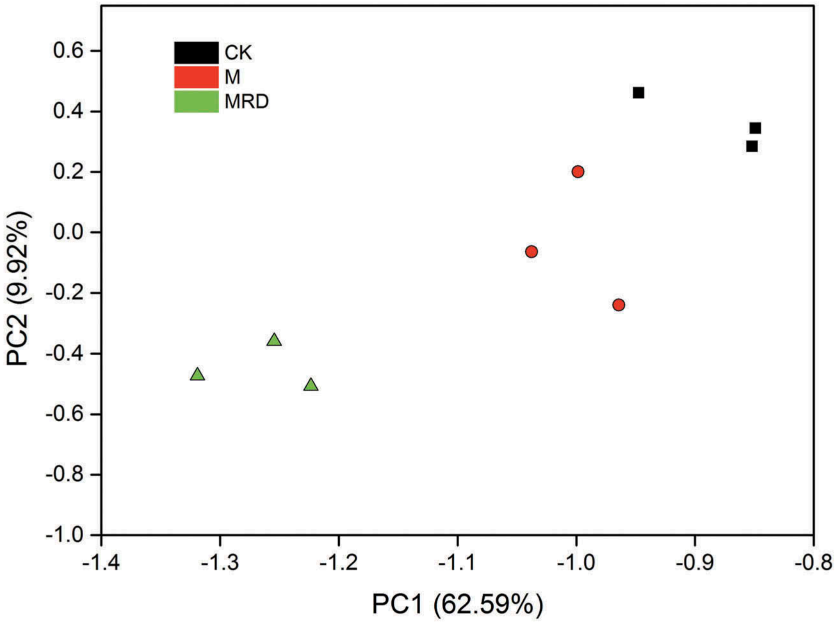

Figure 4. Principal component analysis (PCA) of microbial communities in the apple orchard soil amended with CM and CMRD composts. The soil treatments are designated as follows: M, soil amended with the CM compost; MRD, soil amended with the CMRD compost; CK, the control soil without compost.

Table 4. Per tree yield treated by different composts in the year of 2013 and 2014.

	2013				2014			
Treatment[a]	Chlorophyll content (mg/g)	Weight (g/fruit)	Yield[c] (kg/tree)	Yield increase (%)	Chlorophyll content (mg/g)	Weight (g/fruit)	Yield (kg/tree)	Yield increase (%)
CK	1.64 ± 0.07a[b]	159 ± 26a	55 (30–114)	/	1.66 ± 0.03a	149 ± 19a	49 25–100	/
M	1.90 ± 0.06b	209 ± 53b	103 (50–140)	89	1.91 ± 0.04b	212 ± 38b	110 50–150	127
MRD	2.01 ± 0.05b	247 ± 29 c	120 (60–154)	120	2.21 ± 0.06 c	252 ± 31 c	139 76–148	187

[a]CK, untreated control soil; M, soil amended with composted manure; MRD, soil amended with composted manure with rock dust. [b] Values are means ± standard error; means in the same column followed by the same letter are not significantly different at α = 0.05. [c] Yield is expressed as a mean per tree (*n* = 5) followed by the range calculated for five trees from a treatment.

Apple yield in compost-amended soils

Crop performance is linked to specific chemical, physical, and biological soil properties, and healthier soil enhances crop productivity. In 2013, the amendment of orchard soil with both types of compost resulted in higher fruit yield compared to the untreated control (Table 4). In 2013, the average yield per tree for the CK, M, and MRD treatments was 55 kg, 103 kg, and 120 kg, respectively. These numbers correspond to 89% and 120% yield increase, respectively, for the M and MRD treatments compared to the unamended control. The per tree yield within the same treatment varied significantly, which likely reflects the non-uniform growth of trees across the orchard. The application of both composts also significantly increased fruit weight, which was 209 g and 247 g for the M (p = 0.004) and MRD (p = 0.001) treatments compared to 159 g for the unamended soil (CK). In addition to better yield, trees from the M and MRD treatments also had higher leaf chlorophyll content (Table 4). In the following year (2014),

Table 5. Apple fruit quality in different treatments.

Treatment [a]	*SOD*[b] *(U/mg)*	*Vitamin* C (mg/100 g)	Total sugar (%)	Acidity (%)	Hardness ($\times 10^5$ Pa)
CK	13.82 ± 0.23a[c]	43.34 ± 4.15a	7.97 ± 1.62a	0.21 ± 0.04a	5.90 ± 0.62a
M	16.12 ± 0.35b	57.26 ± 12.11b	8.58 ± 0.15a	0.21 ± 0.06a	6.60 ± 0.78ab
MRD	24.47 ± 0.12 c	66.83 ± 4.39 c	10.23 ± 0.89b	0.18 ± 0.01b	7.42 ± 1.03b

[a] CK, untreated control soil; M, soil amended with composted manure; MRD, soil amended with the composted manure fortified with rock dust. [b] SOD, *superoxide dismutase.* [c] Values are means ± standard error; means in the same column followed by the same letter are not significantly different at α = 0.05.

similar positive results were observed with the per tree yield, fruit weight, and chlorophyll content, all of which were significantly higher in compost treatments relative to the untreated control. The average yield was even higher than in 2013, with M and MRD treatments providing, respectively, a 127% and 187% increase compared to the untreated control (Table 4). Finally, the application of the rock dust-fortified compost improved the overall appearance of trees in the MRD treatment, which exhibited fewer disease symptoms and had fewer dropped fruits (Figure. S2).

Effect of compost amendments on the fruit quality

In addition to crop productivity, the uptake and partitioning of macro- and micronutrients affect the morphological, physical, chemical, and organoleptic properties of fruits. Therefore, we investigated the effect of different compost amendments on fruit quality by measuring and comparing several key parameters linked to the nutrition value, taste, and price of the apples. Results of the analysis revealed that the application of CM and CMRD composts correlated with the significant increase in the SOD activity (CM: $p = 0.011$; CMRD: $p = 0.001$) and concentration of vitamin C (CM: $p = 0.015$; CMRD: $p = 0.009$) in the apple pulp (Table 5). The promoting effect was higher in fruits from the MRD treatment compared to the M treatment. The amount of total sugar and acid, and fruit hardness were similar in apples collected from the M treatment and control plants. In contrast, apples collected from the MRD treatment had significantly higher amount of the total sugar ($p = 0.031$), increased hardness ($p = 0.034$) and reduced the acidity ($p = 0.045$) (Table 5).

Discussion

The conventional and fortified composts produced in this study had similar amounts of N, P, and K, but differed in the levels of plant micronutrients, such as Ca, Mg, Fe, Mn, Zn, B, and Al, which were higher in the rock dust-containing product (Table 2). The two-year application of the conventional compost positively influenced the vegetative growth and productivity of apple trees, which is consistent with similar studies conducted in other crop systems (Proietti et al. 2015). The rock dust-fortified compost (MRD treatment) compost significantly outperformed the conventional counterpart, and its application markedly increased the number of fruits, chlorophyll content, and resulted in fewer dead branches and fallen fruits throughout summer (Table 4; Figure S2). These findings agree with previous studies that demonstrated the efficacy of organic fertilizers and rock dust amendments in poor soils (Szmidt 1998; Leonardos et al. 2000; Sikora 2004; Curtis and Claassen 2005; Claassen and Carey 2007), and contradict reports on the neutral effects of treating agricultural soils with volcanic rock or granite dusts (Bolland and Baker 2000; Ramezanian et al. 2013). Rocks can contain dozens of chemical elements in different concentrations and forms, and it is likely that the varying effects on plant productivity reflect differences in soil properties and the mineralogical composition of soil amendments (Dorrzapf 1973; O'Brien et al. 1999; Wilson 2004).

Our results further suggest that the amendment of soil with composted manure and rock dust provides an effective management practice for improving fruit quality in mature orchards. We observed a significant increase in the weight and hardness of fruit (Tables 4 and 5). These changes were accompanied by higher levels of SOD, vitamin C, total sugars, and lower titratable acidity in apples collected from trees treated with the rock dust-fortified compost (Table 5). The total sugar content and titratable acidity are important quality parameters that strongly influence the taste of fruits, while vitamin C and superoxide dismutase are valuable nutritional quality attributes (Ruiz and Egea 2008; Milošević et al. 2013). We speculate that these positive changes in the fruit quality are linked to the higher micronutrient content of the MRD treatment. Interestingly, similar results have been reported in other crops, where an increase in the supply of B, Fe, or Zn resulted in higher sugar levels and reduced acid content (Khayyat et al. 2007; Li et al. 2017; Yu et al. 2019). In general, increasing sugar content, reduction of acidity and firmness is on attainment of fruit maturity and ripening. However, apples in MRD treatment exhibited significantly higher amount of the total sugar, increased hardness and reduced acidity (Table 5). The hardness increase happened in CMRD treated apples possibly due to their dissimilarities in fruit density. Higher density leads to higher dry matter content that in turn makes apples firm, which was strongly supported by the findings that per apple weight was higher in MRD treatment (Table 4).

Our study also revealed the stimulatory effect exerted by the rock dust on indigenous microorganisms present in the compost and orchard soil. The addition of rock dust to the compost feedstocks resulted in the measurable increase of the functional metabolic diversity and changes in the richness and evenness of the compost microbiota (Table 3). Furthermore, the C source utilization analysis revealed that microbial communities from the rock dust-fortified compost had higher EcoPlate AWCD values and catabolized more carbon sources compared to their counterparts from the conventional compost (Figures 1(b) and 2). Albeit not statistically significant, the fortified compost also had higher NPK content (Table 2) suggesting that the addition of rock dust may affect dynamics of the composting process by modulating the levels of energy and/or heat in the composting heap (Figure 1(a)). These findings are similar to the results of Garcia-Gomez et al. (2002), who demonstrated that the use of rock dust in composting resulted in higher microbial activity during the start-up and mesophilic phases, elevated temperature and protein, and increased oxygen consumption. Finally, the application of the fortified compost also had a stronger impact on the soil microbial community compared to its conventional counterpart. This agrees with the report that the addition of mica, basalt, and rock phosphate to soil microcosms altered the balance of nutrients and induced substantial changes in the composition of bacterial and fungal communities (Carson et al. 2007).

Microorganisms were implicated in the accelerated weathering of minerals, and the dissolution rates of feldspar, biotite, quartz, and other minerals grow with increased microbial populations (Banfield et al. 1999). Soil microorganisms promote the disaggregation and dissolution of minerals by excreting organic acids and carbon dioxide that interacts with water to form carbonic acid, which slowly dissolves calcium-containing containing rocks (Uroz et al. 2009). Other mechanisms involve the catalysis of redox reactions and secretion of biological polymers that increase the retention of water time on the mineral surface and interact with ions by complexing them and lowering their solution saturation state (Welch and Vandevivere 1994). Finally, microorganisms produce biogenic chelators, such as siderophores that scavenge iron from the environment and make it available for microbial growth (Wilson et al. 2016). It is plausible that similar mineral weathering mechanisms operate in the compost and soils fortified with rock dust and make micronutrients more bioavailable to both the indigenous microorganisms and plants. However, the exact mechanism behind this phenomenon remains poorly understood. Given the critical importance of microbial processes for the production of high-quality composts and the vital contribution of microorganisms to plant health, our findings warrant further studies into effects of mineral-rich rock dust on the soil microbiota.

Conclusions

Our study showed that the incorporation of rock dust into goat manure significantly improved the microelement content, microbiological activity and diversity of the compost. We further demonstrated that the amendment of apple orchard soil with the rock dust-fortified compost in combination with NPK fertilizers stimulated soil microflora, improved yields and fruit quality in mature apple trees, and reduced the time-consuming and labor-intensive work. Collectively, our results suggest that this practice provides a cost-effective way of supplying crops with macro- and micronutrients and may be particularly beneficial in poor-quality soils depleted by intensive use and inadequate management practices. However, more work is required to extend this conclusion to other types of soil and optimize the compost quality and rates of use.

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