Received: 1 July 2022 | Accepted: 4 February 2023
DOI: 10.1002/jpln.202200232

RESEARCH ARTICLE

Grape pomace's potential on semi-arid soil health enhances performance of maize, wheat, and grape crops

Isaac K. Mpanga[1,2] | Günter Neumann[3] | Judith K. Brown[4] | Joseph Blankinship[5] | Russell Tronstad[6] | Omololu Idowu[7]

[1]Circular Planet Institute LLC, Austin, Texas, USA

[2]Cooperative Extension, The University of Arizona, Camp Verde, Arizona, USA

[3]Institute of Crop Science (340h), Universität Hohenheim, Stuttgart, Germany

[4]School of Plant Sciences, The University of Arizona, Tucson, Arizona, USA

[5]Department of Environmental Science, The University of Arizona, Tucson, Arizona, USA

[6]Department of Agricultural and Resource Economics & Cooperative Extension, College of Agriculture and Life Sciences, The University of Arizona, Tucson, Arizona, USA

[7]Extension Plant Sciences/Plant & Environmental Sciences, New Mexico State University, Las Cruces, New Mexico, USA

Correspondence
Isaac Kwadwo Mpanga, Circular Planet Institute LLC, 5900 Bacons Drive, Suite 100, Austin, TX 78731, USA.
Email: mpangaisaac75@gmail.com

This article has been edited by Daniele Antichi.

Funding information
USDA; NIFA

Abstract

Background: Grape pomace (GP) is a by-product of wineries after filtering the grape juice for wine production. GP contains seeds, pulp, skin, and stalks with acidic properties, and it is normally composted before using as a soil amendment. However, composting GP requires more time, labor, and equipment; furthermore, composting loses some of the desirable organic acids for arid soils. The acidic properties of these organic acids and the plant nutrients in GP make it a desirable amendment for arid soils in both non-composted and composted forms.

Aim: This study investigates the potential of directly applying GP as a soil amendment and its impact on arid soil health and plant performance.

Methods: To test the potential of non-composted GP as a soil amendment, greenhouse and field studies were conducted by combining GP with existing management practices (manure application for soil used in the greenhouse study and fertigation for the field study) to assess the effects of GP on soil health and crop (maize, wheat, and grape) performance.

Results: Adding 5% GP to an alkaline soil significantly increased maize and wheat growth and shoot nutrient concentrations in the greenhouse and grapes in the field (48% yield increase). The significance of GP on maize, wheat, and grapes was associated with soil nutrient enhancements (i.e., nutrients supplied, increase in organic matter and microbial biomass increase, reduction in pH, and better nutrient mobilization).

Conclusion: GP has the potential for direct use as a soil amendment for soil and crop health improvement, especially in arid soils with high pH and limited soil organic matter.

KEYWORDS
grape pomace (GP), soil health, soil pH, sustainable agriculture, waste

1 | INTRODUCTION

Worldwide grapes are the largest fruit crop produced by tonnage (Trinklein, 2013). According to the International Organization of Vine and Wine Statistical Report on World Vitiviniculture, 39% of world grape production is in Europe, 34% in Asia, 18% in America, 2% in Australia, and 1.7% in South Africa. Annual grape production stands at almost 70 million tons worldwide. Grape pomace (GP) is a by-product obtained from wineries after crushing the grape and filtering the juice immediately (white wine) and after fermentation (red wine) (Kalli et al., 2018). Estimates show that the production of 6 L of wine produces 1 kg of GP (Mendes et al., 2013), and 80% of the grape's weight is extracted for wine production with the remaining 20% being GP (Kalli et al., 2018).

The challenge for wineries worldwide is how to upscale a cleaner and simpler waste management plan for their GP with potential economic gains for them and the environment. For example, in Europe, a disposal fee of 230 euros month^{-1} m^{-3} h^{-1} is charged, along with a variable fee depending on the type and quantity of alcohol produced by a winery industry. Depending on the location and court in Europe, a fine of unauthorized discharge of winery waste increase exponentially from less than 10,000 to between 30,000 and 40,000 euros with a possible imposed prison sentence (Devesa-Rey et al., 2011). Disposing GP into landfills adds to environmental waste issues with potential contaminations to water bodies and excessive costs to the wineries; hence, a cost-effective alternative to managing it sustainably by identifying practical uses in a circular economic approach is needed.

Management of GP fits perfectly into the growing trend of circular economic concepts. Circular economic ideas include waste recycling and other environmentally friendly production systems in agriculture and industries toward a "zero waste" agricultural system (Lucarini et al., 2019; Tuck et al., 2012; Zuin & Ramin, 2018). The food industry, cosmetics, pharmaceuticals, energy recovery systems, and agriculture, such as livestock feeds and composting, already uses GP (Beres et al., 2017; Kalli et al., 2018). Composting GP is one of the options that has been investigated with extensive research using different approaches (Ferrer et al., 2001; Salgado et al., 2019) for applications as soil amendments. The challenge with composting GP is a delay in compost maturation (Westover, 2006), which is labor-intensive due to the periodic turning of the compost piles. However, GP is acidic due to high organic acid contents and contains both macro- and micro-nutrients (García-Lomillo et al., 2017). The moisture content of GP ranges from 50% to 72% depending on the variety and degree of grape ripeness at harvest. The lignin content ranges from 16.8% to 24.2%, and the protein content is 4% or less of total GP compounds (Teixeira et al., 2014). GP has a pH of 3.5–3.9 (Bernardi et al., 2010; Ferrer et al., 2001), an acidity of 6.4 g of citric acid kg^{-1}, and an ash content of 46.5 g kg^{-1} dry matter (Castro et al., 2014) with complex substrates such as neutral polysaccharides, pectic substances, structural proteins, fatty acids, insoluble proanthocyanidins, and other phenolic compounds (Lucarini et al., 2019; Spinei & Oroian, 2021). Therefore, GP is a potentially beneficial amendment for alkaline soil management when applied as a raw material without composting. In recent reviews, it has been shown that GP controls pathogens while promoting beneficial bacterial species in the animal gut that leads to alleviating antibacterial resistance (Hassan et al., 2019). The findings that GP is beneficial to animal production may outweigh the phytosanitary concerns associated with the direct GP application to soils; hence, more investigations are needed as in this study.

There is little information on how the direct use of GP as a soil amendment impacts soil pH, plant-available nutrients, soil microbial activities, plant growth, and nutrient uptake. Soil pH is a measure of soil acidity or alkalinity. It is an important indicator of soil health and is a critical factor for soil nutrient transformations, plant availability of nutrients, and soil microbial activity. Organic amendments improve soil's physical, chemical, and biological attributes (Kalembasa & Kalembasa, 2016). In alkaline soils, phosphorus (P) solubility may be limited due to precipitation by abundant calcium ions, thus reducing P availability for plant uptake. Application of different forms of nitrogen fertilizers triggering changes in rhizosphere pH or addition of sulfur could manage imbalanced soil pH (Brady & Weil, 1999; Neina, 2019). A soil pH of 5.5–7.5 is suitable for crop nutrient uptake for most crops, while lower or higher soil pH beyond this range often leads to soil nutrient imbalances that create nutrient deficiencies or toxicities, which limit plant growth (USDA, n.d.). Reducing alkaline soil pH remains a challenging task, especially for certified organic production systems that are not allowed to use synthetic chemicals in their fields. To date, the most prominent methods for reducing the pH in alkaline soils for immediate effects include the application of urea and ammonium-based nitrogen fertilizers frequently stabilized with urease or nitrification inhibitors (Fageria et al., 2010; Malhi et al., 1995; Mpanga, Nkebiwe, et al., 2019; Mpanga, Gomez-Genao, et al., 2019; Mpanga et al., 2020; Mpanga, 2020) and the use of elemental sulfur (Horneck et al., 2007; Obreza et al., 2015; USDA, 2018). These approaches are not always desirable due to their cost and potentially negative environmental effects such as greenhouse gas emissions from their productions and transportation; hence, alternative local materials such as GP that are inexpensive and environmentally friendly may be the solution for many areas.

Organic carbon is an essential feed source for soil microbiota (Breulmann et al. 2014; Fanin et al. 2019; Fanin et al. 2014; Fierer et al. 2003). Soil organic matter is frequently deficient in semi-arid soils due to higher temperatures, insufficient moisture, and low availability of organic feedstock, limiting the diversity and functions of the soil microbiota. High pH soils particularly limit the availability of phosphate and micronutrients to most plants, and the practice of using synthetic nitrogen fertilizers and plant growth-promoting microorganisms as well as foliar application of micronutrients has been used to mitigate these problems (Brady & Weil, 1999; Mpanga et al., 2018; Mpanga, Gomez-Genao, et al., 2019; Mpanga, 2020; Mpanga et al., 2020; Mpanga, Nkebiwe, et al., 2019; Neina, 2019; Nkebiwe et al., 2016; USDA, 2018). There is an ongoing search for alternative organic amendments for alkaline soil pH management, with additional benefits such as soil health, and GP may be suitable for addressing these issues.

Therefore, the main aim of this study is to assess the effects of GP on (1) plant performance (maize [*Zea mays* L.] and wheat [*Triticum aestivum* L.]) under controlled greenhouse conditions; (2) wine grape (*Vitis vinifera* L.) performance in the field; and (3) soil organic matter, nutrient availability, pH, and microbial composition. The reason for selecting maize and wheat for the greenhouse work was related to seasonality and resources. The greenhouse had no heating, limiting our plan to repeat the maize experiment in the fall/winter since maize is a summer annual crop. We, therefore, used winter wheat as the test crop during the fall/winter season since it is cool-season species. This gave us the opportunity to study the nutrient availability of two plant species at different times of the year. The grape for the field trial was aimed at closing the nutrients loop in the production circle and the grower's interest in the concept of utilizing the GP from their winery in their grape field on the same farm.

Research questions for adding GP as a soil amendment to a farmer's practice (FP) were as follows:

1. Does GP amendment increase soil nutrient content, reduce soil pH, and increase soil microbial diversity and biomass? The prediction was that adding GP to FP would reduce soil pH and increase soil nutrient content and microbial diversity and biomass.
2. Does GP affect the growth and shoot nutrient of maize and wheat during greenhouse production? We predicted that in the greenhouse trial, applying GP to soil that received annual manure application (farmer's practice [FP]) would improve the growth performance and nutrient uptake of maize and winter.
3. How does GP affect vine performance (mineral uptake, yield, and quality) under field production? We predicted that adding GP to FP (fertigation) would improve the performance of the vines.

2 | MATERIALS AND METHODS

2.1 | Soils and GP properties

The chemical properties of the study soils are given in Table S1. The greenhouse study soil (Table S1a) came from the University of Arizona Cracchiolo DK Experiment Station, and the field study soil (Table S1b) from Javelina Leap Vineyard & Winery, both sites are in Cornville, AZ, USA. Cornville has an elevation of 997 m at 34.73°N and 111.97°W with Swisshelm soil taxonomic classification, average annual rainfall of 355 mm, snowfall of 38 mm, 52 precipitation days, 274 sunny days, and 14°C yearly average temperature. The GP properties are given in Table S1c.

2.2 | Greenhouse study

Soil for the greenhouse study (Table S1a) was sampled at a depth of 0–15 cm from the University of Arizona Experiment Station at Cornville, Arizona pasture field 2 weeks after annual manure application. The field had annual poultry manure applications as the standard FP at 2239.5 kg ha^{-1} year^{-1}, which was split-applied (1:1) in March and September (Table S1a; Mpanga et al., 2021). The soil was air-dried in the greenhouse and passed through a 2-mm sieve to remove stones and large plant materials and mixed uniformly. The GP (Table S1c) was a by-product of red wine obtained from Alcantara Vineyards and Wineries (Camp Verde, Arizona) immediately after fermentation (1 week at 21–25°C) and filtration of grape juice during red wine processing. The material was solarized by air drying for 4 days and finely ground to 1–2 mm using a kitchen blender.

Two separate experiments were conducted in the greenhouse at the Verde Valley Senior Center in Cottonwood, Arizona, with maize (Native American hybrid from Hopi greasy hair called the "ceremonial pink" or the "martin Prechtel's blue Pueblo heirloom") and winter wheat (Gore soft red), respectively, using the University of Arizona Cracchiolo DK Experiment Station soil (Table S1a) and GP (Table 1c). This soil was selected for the experiment because of its high pH (8.1). Each experiment (maize and wheat) had two treatments (standard farmer's practice with only poultry manure application at 2239.5 kg ha^{-1} year^{-1} (FP) and FP+ 5% GP dry biomass) with a total substrate weight of 2.5 kg dry weight per plastic pots (18 cm × 17 cm × 16 cm) in three replicates with a randomized complete design. Substrates were thoroughly mixed and incubated in the greenhouse for 2 weeks before sowing. The greenhouse had no heating and lighting systems.

2.2.1 | Planting

The maize experiment was planted on 4 October, 2020, with three seeds per pot and thinned to one seedling on day 7 and allowed to grow for 30 days. The winter wheat experiment was planted on 13 October, 2020, with 15 seeds per pot and allowed to grow for 40 days. The plants were irrigated at 70% water holding capacity and continually watered by weight once a day for the first two weeks and twice a day from week 3 until harvest.

2.2.2 | Shoot harvest and nutrient analysis

The shoot of the maize experiment was harvested at 30 days, while the winter wheat was harvested at 40 days after sowing by using scissors to cut at the base of the plants just above the soil. The fresh weight of the shoots was instantly determined by weighing them with HRB 10001 electronic precision balance (LW Measurements LLC, Rohnert Park, CA, USA). Samples were then oven-dried for 72 h at 65°C to obtain dry shoot biomass. After drying, samples were sent for elemental analysis at the Texas A & M Soil and Forage Testing Laboratory in College Station, TX, USA. Plant nitrogen (N) levels were determined by combustion (Havlin & Soltanpour, 1980) using an elemental analyzer (Elementar, Hesse, Germany), whereas P, potassium (K), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were determined by an ICP spectrometer (Spectro Analytical Instruments GmbH, Kleve, Germany) after nitric acid digestion (Nelson & Sommers, 1973).

2.3 | Field study

2.3.1 | Location

Our field location is the Javelina Leap Vineyard in Cornville, AZ, USA.

2.3.2 | Planting density

The grape vineyard (Zinfandel with roots stock 1103P) has a planting distance of 1.5 m within rows and 2 m between rows, and a stand density of 6667 plants ha^{-1}.

2.3.3 | Fertigation

The vineyard has received standard yearly fertigation (FP-farmer's practice) of Fe 6%EDDHA (Master Plant-Prod Inc., ON, Canada) as iron at 1.08 kg ha^{-1} in March, Root RX (Redox Bio-Nutrients, ID, USA) as a growth stimulant with 5% K at 3.4 L ha^{-1} in March and April, Root H Blend (Rama Crop Science Pvt. Ltd., Raipur, India) as biostimulant with 12% K and 42% humic acid at 9.12 L ha^{-1} in March, Micro (Biofeed Solutions, Inc., AZ, USA) (1.76 kg ha^{-1}) eight applications from March to June, 30% K as KOH at 4.56 L ha^{-1} in March and April, humic acid (GS Plant Foods, FL, USA) at 4.56 L ha^{-1} in May, DKP Dipotassium Phosphate (0–54–41) (LidoChem, Inc., NJ, USA) at 41.04 L ha^{-1}) three times from June to July, and Mainstay Si (22% SiO_2) (Redox Bio-Nutrients) at 9.12 L ha^{-1} in June and July.

2.3.4 | Grape pomace application

The application of the GP was made in March 2020 at 2721 kg ha^{-1} (1 g kg^{-1} soil in the field compared to 50 g kg^{-1} soil in the pot experiment), which came from their winery facility on the same property by broadcasting on the surface of the soil in the field with FP and GP without incorporation due to their no-till practice in the vineyard. The vines are planted across slope with spacing of 1.5 m within rows and 2 m between rows. First pruning is done in January and February, while canopy and fruit cluster pruning are done in May and June to allow more air flow and quality grapes.

2.3.5 | Watering

Watering was done twice a week at 3.75 L h^{-1} $plant^{-1}$ for each circle for 12 h from spring to fall by drip irrigation tapes hanging 15–20 cm above the soil surface.

2.3.6 | Field sampling

In a randomized design set up of the field with three replications of 6 m × 6 m per plot size, three vineyard rows were selected (high, middle, and bottom of the field slope) from the two treatments soil, plant, and yield data collection. The soil and plant leaf samples were collected on July 9, 2021.

2.3.7 | Leaves elemental analysis

Leaves were sampled by picking five fully developed leaves opposite to the fruit clusters with petiole per plant on five grape plants for each replicate. Plant N was determined by combustion (Havlin & Soltanpour, 1980) using an elemental analyzer (Elementar), whereas P, K, Cu, Fe, Mn, and Zn were determined by an ICP spectrometer (Spectro Analytical Instruments GmbH) after nitric acid digestion (Nelson & Sommers, 1973).

2.3.8 | Fruit yield and sugar content

Five vines were selected randomly from each plot, and the weight and number of fruit clusters collected were recorded. Weight per plant was multiplied by plant density to obtain yield per hectare. For the sugar content (% sugar), 10 fully ripe grapes were picked from the five random vines as replicates and crushed in zipped plastic bags for juice collection. A portable refractometer (portable optical refractometer 68012, Tucson, AZ, USA) was used to measure the sugar content.

2.4 | Post-harvest soil mineral nutrients and pH

2.4.1 | Effects of GP on Soil mineral nutrients

The soil mineral nutrients (N, P, K, Mn, Fe, Zn, and Cu) were measured in only the field experiment with grapes. Topsoil was sampled with a sampling probe at 15 cm depth in 10 spots/replicate from FP and FP + GP plots. The samples were well mixed, subsampled, and shipped in plastic bags to Ward Laboratories Inc. (Kearney, NE, USA) on dry ice. Soil nitrate-N was measured by the Cadmium reduction procedure with a flow injection analyzer (FIA) after water extraction. Soil available P was determined spectrophotometrically with molybdate after Olsen HCO_3-P extraction (WARD Laboratories, 2020). Soil potassium was measured by an inductively coupled argon plasma spectrophotometer (ICAP) after the extraction in 1 N ammonium acetate. Soil micro-nutrients (Mn, Zn, Fe, and Cu) were measured by the ICAP method after the diethylenetriaminepentaacetic acid extraction method (WARD Laboratories, 2020). Soil organic matter was measured using the loss-on-ignition method. Soil samples were placed in crucibles and dried for 2 h at 105°C to drive off hygroscopic water. The samples were then cooled to room temperature and weighed. Then, samples were heated to 360°C for 2 h again, cooled, and weighed. The difference in the first and last weights was calculated as percent organic matter (WARD Laboratories, 2020).

2.4.2 | Effects of GP on soil pH

Both the greenhouse and field study soil samples were collected to determine the soil pH. For the greenhouse experiment, soil pH was examined with different GP application rates (5, 10, 20, and 40%) with the soil per treatment as (1) FP soil, (2) 95% FP + 5% GP, (3) 90% FP + 10% GP, (4) 80% FP + 20% GP, and (5) 60% FP + 40% GP). In the field soil (Table S1b), samples were taken at 15 cm depth from FP and FP + GP. Distilled water was added to the soil samples in a 1:1 ratio based on the method by Miller and Kissel (2010) and shaken to have a paste of well-mixed substrates and the water. The pH values were

TABLE 1 Grape pomace (GP) effects on above-ground dry biomass of greenhouse-grown maize (30 days after sowing) and wheat (40 days after sowing) and field grapes (after fruits set) in semi-arid calcareous soil. The farmer's practice (FP) in the greenhouse and field soils were poultry manure application, which served as the control treatment.

(a) Greenhouse maize shoots biomass (g/plant) and nutrient concentrations (mg/g)								
	Dry shoot	**N**	**P**	**K**	**Mn**	**Zn**	**Fe**	**Cu**
FP	1.6 (0.4) b	32.1 (0.3) b	2.6 (0.4) b	46.7 (0.9) b	0.05 (0.6) b	0.07 (0.2) a	0.4 (0.4) b	0.03 (0.4) b
FP + 5% GP	3.2 (0.2)a	40.7 (0.7) a	3.8 (0.3) a	54.5 (1.1) a	0.08 (0.1) a	0.08 (0.2) a	2.4 (0.7) a	0.10 (0.3) a
Critical deficiency threshold	n/a	30	2.5	20	0.01	0.01	0.01	0.005
(b) Greenhouse wheat shoots biomass (g/pot) and nutrient concentrations (mg/g)								
	Dry shoot	N	P	K	Mn	Zn	Fe	Cu
FP	2.8 (0.4) a	21.4 (0.5) b	2.9 (0.1) b	41.5 (1.5) b	0.02 (0.0) a	0.05 (0.0) b	0.5 (0.0) a	0.03 (0.0) a
FP+5% GP	2.7 (0.0) a	33.2 (2.0) a	6.2 (0.3) a	57.9 (0.9) a	0.03 (0.0) a	0.08 (0.0) a	0.4 (0.0) a	0.03 (0.0) a
Critical deficiency threshold	n/a	30	1.5	20	0.02	0.01	0.01	0.003

Note: Same letters mean no significant difference in *t*-test at 5% *p*-value.

measured with a Bluelab® combo meter plus (Bluelab® Cooperation Limited, New Zealand).

2.5 | PLFA analysis of soil microbial communities

The phospholipid fatty acids (PLFA) analytical method was used to determine soil microbial community composition and biomass for both greenhouse and field soil samples. In the greenhouse, wheat rhizosphere soil was obtained by vigorously shaking off soils closely attached to the roots after pulling them out of the pot. The field sample was obtained using a soil corer to collect soils from the base of grape plants. The soil samples were shipped on ice to the Ward Laboratories Inc. for processing and analysis. The PLFA analyses in Ward Laboratories Inc. are based on the method of Hamel et al. (2006), where total soil lipid fractions were extracted by shaking a mixture of 2 g frozen soil in 9.5 mL of a liquid buffer of dichloromethane, methanol, and citrate buffer (1:2:0.8, v/v) consistently for 1 h. After lipid-class separation and creating fatty acid methyl esters, samples are then analyzed using an Agilent 7890A GC equipped with a 7693 autosampler instrument and a flame ionization detector, which quantified microbial diversity (a percentage of all detectable microbial groups), total bacteria biomass, total fungi biomass, and undifferentiated biomass (Frostegård et al., 2011).

2.6 | Statistical analysis

Shoot biomass, yield, shoot, and soil nutrient data were tested for differences between FP and FP + GP using a *t*-test assuming a two-tailed distribution and two-sample equal variance (homoscedasticity). pH data were tested for normality using QQ-plots with fit diagnostics plots followed by the GLM procedure for one-way analysis of variance using the SAS® OnDemand for Academics © 2021 (SAS Institute Inc., NC, USA), with the means separated at $p \leq 0.05$ using the Turkey test.

3 | RESULTS

This section describes the effects of GP on crops (maize, winter wheat, and grapes) performance in both, greenhouse and field conditions and on soil (organic matter, fertility, pH, and microbial activities).

3.1 | Effects of GP on maize and wheat performance in greenhouse

The application of 5% GP increased maize shoot biomass significantly compared to soil receiving the farmer's standard practice (Table 1a).

For wheat, the addition of GP did not significantly increase shoot (Table 1b). Adding GP significantly increased both macro- and micronutrient concentrations in maize and wheat shoots under greenhouse production compared to the farmer's standard practice with exception of Fe and Cu in wheat (Table 1a,b).

3.2 | Effects of GP on field grape production

Under field conditions, the addition of GP to the farmer's standard practice (fertigation) increased the performance of the grapes by canopy density (Figure S1) and yield parameters (fruits cluster weight per plant and fruit weight per hectare) significantly with no differences in the grape quality (sugar levels) (Table 2a). The significant increase in field grape production with the application of GP (Table 2a) could be associated with better mineral nutrition such as N, K, and Mn, which have significantly higher concentrations in the leaves after fruit set (Table 2b).

TABLE 2 Effects of grape pomace (GP) on grape yield and element concentration in leaves under field conditions.

(a) Grape yield and quality

	Fruits weight per plant (kg plant^{-1})	Fruit weight per hectare (kg ha^{-1})	Fruit sugar (% sugar)
FP	3.9 (0.7) b	25,834.6 (5456.7) b	19.6 (1.0) a
FP + GP	7.5 (1.4) a	49,835.8 (9428.4) a	19.0 (1.6) a

(b) Grape leaves concentrations of macro- and micro-nutrients (mg g^{-1})

	N	P	K	Mn	Zn	Fe	Cu
FP	17.8 (0.8) b	1.7 (0.5)	5.8 (0.9) b	0.03 (0.0) b	0.01 (0.0) a	0.18 (0.0) a	0.01 (0.0) a
FP+GP	25.4 (0.0) a	1.9 (0.7)	7.8 (0.1) a	0.07 (0.0) a	0.02 (0.0) a	0.16 (0.0) a	0.01 (0.0) a

Note: Same letters mean no significant difference in *t*-test at 5% *p*-value.
Abbreviation: FP, standard farmer's practice (fertigation).

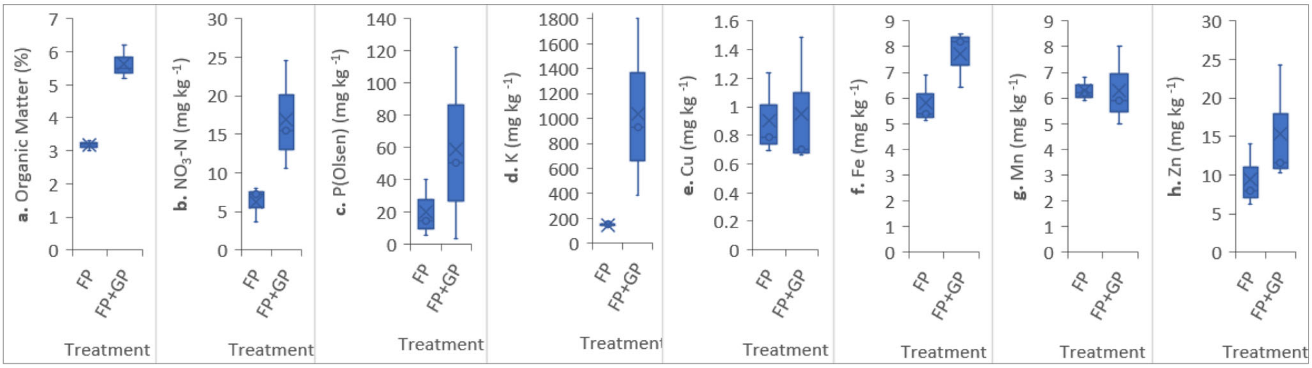

FIGURE 1 Effects of grape pomace (GP) application on soil organic matter and potentially plant-available mineral elements in field vineyard samples compared to the standard farmer's practice (FP). The "X" in each bar represents the mean value.

3.3 | Effects of GP on soil organic matter, pH, and mineral nutrients

The application of GP increased soil organic matter N, P, K, Zn, and Fe when compared to only FP without GP (Figure 1a–c,f,h), while Mn and Cu had no noticeable differences (Figure 1e,g).

In the greenhouse, GP application rates of 5%, 10%, 20, and 40% drastically reduced pH (8.1) to 5.9, 5.5, 4.6, and 4.3, respectively (Figure 2a). However, no changes in soil pH from the application of GP were observed in the field (Figure 2b).

3.4 | Effects of GP on soil-microbial communities

In both experiments, GP application increased soil-microbial biomass determined by PLFA analysis. Bacterial biomass was more dominant in the soil collected under wheat in the greenhouse (Figure 3b), while fungal biomass was more dominant in the soil collected from the vineyard field (Figure 3b). In both the greenhouse and vineyard soils, the largest increase was recorded for the undifferentiated fractions (Figure 3a,b).

For the composition of microbial communities, the PLFA analysis revealed an increase in saprophytic and fungal communities in both soils induced by GP amendments. However, the effect was more expressed in the vineyard soil. As an exception, arbuscular mycorrhizal fungi were suppressed by GP application in the vineyard soil and were not detected in the pot experiment with wheat, which was characterized by a GP-induced promotion of Gram-negative bacteria.

4 | DISCUSSIONS

4.1 | Grape pomace's effect on maize, wheat, and grape performance

GP contains macro- and micro-nutrients (Table S1), which are at least partially plant-available. This is evident in maize, wheat, and grape shoot nutrient concentrations (Tables 1 and 2) as well as nutrients detectable in soil samples (Figure 1). Based on the recommendations by Campbell (2009) on nutrient deficiency thresholds of crops, particularly N and P concentrations were critical for maize and wheat in the control FP treatments but reached the sufficiency range after GP application. This may explain the growth-promoting effects of GP applications observed, particularly in maize. All other nutrients reached the sufficiency range. Despite the high soil pH, Fe was surprisingly high

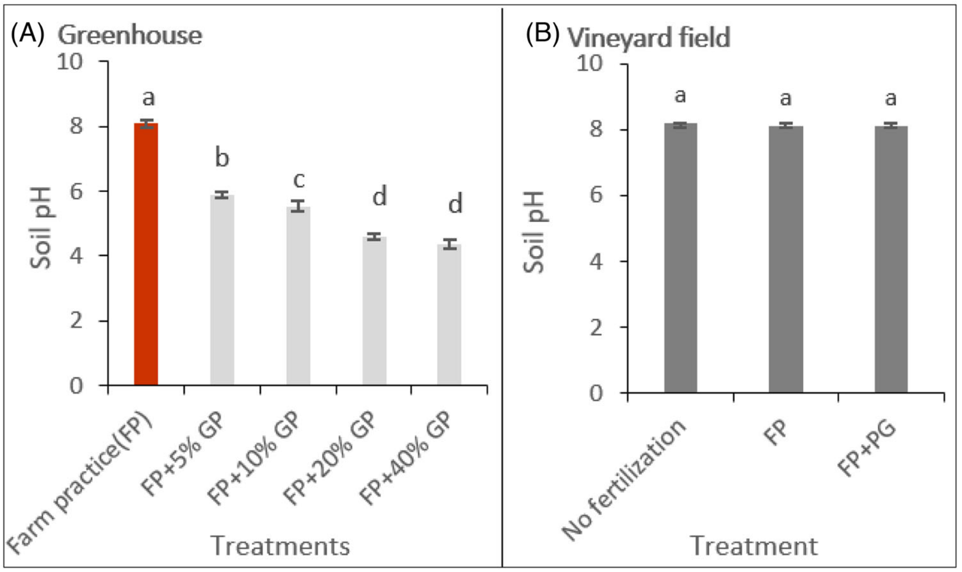

FIGURE 2 Effects of grape pomace (GP) on soil pH in the greenhouse (a) and vineyard field (b) compared to standard farmer's practice (FP). The FP for soil in the greenhouse and field used poultry manure and fertigation, respectively. Different letters indicate significant differences at $p \leq 0.05$ in SAS.

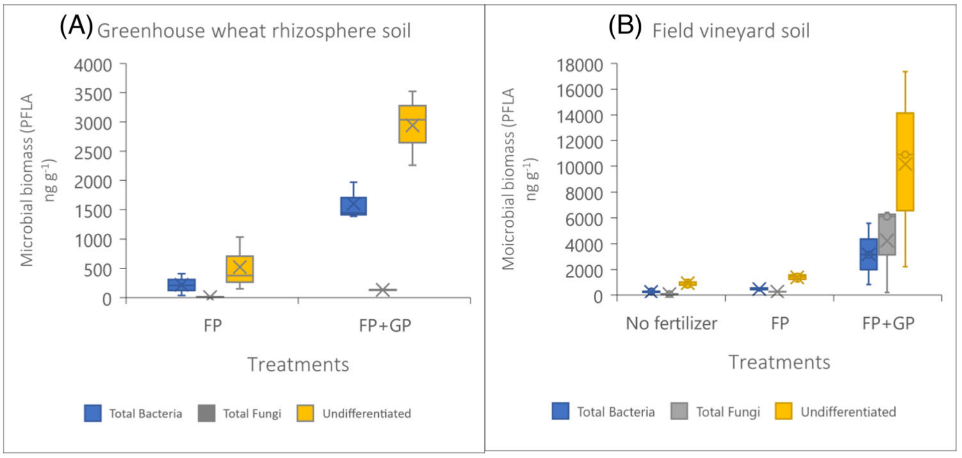

FIGURE 3 Effects of grape pomace (GP) on winter wheat rhizosphere (a) and field vineyard soil (b) microbial biomass. The standard farmer's practices (FP) are poultry manure application in the greenhouse and fertigation in the vineyard field. The "X" in each bar represents the mean.

even in the FP control variants without GP application. This may be attributable to wheat and maize as gramineous test plants, using the release of phytosiderphores as a particularly efficient strategy for Fe acquisition by pH-independent metal chelation (Neumann & Römheld, 2012).

4.2 | Effects of GP on soil-nutrient availability

The ability of GP to supply nutrients more amply than with the FP treatment may also be related to GP's effect on soil pH (Figure 2) or the high content of metal-chelating carboxylates such as organic acids (Eyduran et al., 2015; Sabir et al., 2010) involved in the mobilization of sparingly soluble forms of P and micronutrients (Neumann & Römheld, 2012). Particularly, the P-mobilizing effect of carboxylates by exchange chelation might be important in this context, since the potential plant-available Olsen-P fraction increased after GP application in the vineyard soil, although in this case no soil acidification was detectable, in contrast to the strong acidifying GP effect in the pot experiment. The acidification effect in the pot experiment may relate to rhizosphere effects due to organic acids-induced microbial activities and higher GP application rate (50 g GP kg^{-1} soil in the pot experiment compared to 1 g GP kg^{-1} soil in the vineyard field). Alternatively, increased microbial mineralization of soil organic P related to GP appli-

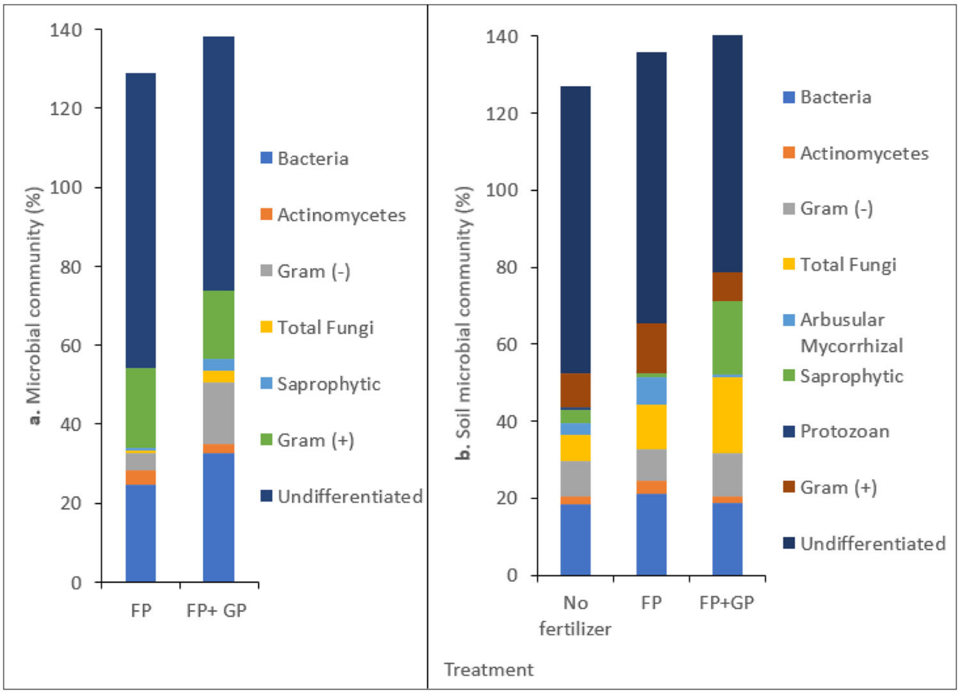

FIGURE 4 Effects of grape pomace (GP) on soil microbial diversity for wheat rhizosphere for 40 days in the greenhouse (a) and in the vineyard field soil after fruit setting of the grapes (b) compared to farmer's practice (FP) and unfertilized area. The FP is poultry manure applied in the greenhouse and fertigation in the vineyard field.

cation might explain the P-mobilizing effect. However, the P status of the grapevine leaves was sufficient even in the FP controls (Table 2b). Hence, no further increase was noted in leaf P status by GP treatments.

However, the N status and particularly K and Mn leaf concentrations were critical in the FP control but reached the sufficiency range after GP application (Table 2b). This may explain the beneficial effects of GP on grapevine yields. Accordingly, GP applications increased the N and K soil contents, although no effect was observed for Mn (Figure 1). However, plant availability of Mn in soils depends on the Mn reduction potential. This process is partially determined by Mn-reducing compounds, such as certain organic acids or phenolics (Neumann & Römheld, 2012), which are present in high amounts, also in GP amendments (Sabir et al., 2010). Additionally, Mn reduction is mediated by the activity of Mn-reducing microorganisms, which might be increased, in line with GP-induced promotion of microbial growth (Figure 3). Moreover, various plant-beneficial microorganisms exhibit Mn-reducing potential including strains of *Bacillus* spp. and *Pseudomonas* spp. (Ijaz et al., 2021), which are promoted by carboxylates present in GP (Sampedro et al., 2015; Yuan et al., 2015).

The stimulation of saprophytic microorganisms and total fungi as a common response to GP application in both experiments (Figure 4), together with increased soil concentrations of nitrate and Olsen-P (Figure 1), may reflect increased mineralization of the high P and N levels sequestered in the GP biomass (Table S1b,c). However, the decline of arbuscular mycorrhizal fungi in the GP treatment of the field experiment may be regarded as a negative effect, although it did not affect the benefits of GP amendments on final yield. By contrast, a direct soil supplementation of K via GP amendments (Figure 1c) is indicated by the extraordinarily high K content of the GP batch used in the experiments (Table S1d).

Altogether, the observed effects suggest that GP amendments increased plant nutrient availability in alkaline soils by different mechanisms including (1) direct supplementation of nutrients (fertilizer effect), (2) nutrient mobilization by soil acidification or metal complexation mediated by carboxylates, and (3) stimulation of microbial activities involved in mineralization and mobilization of nutrients. Although rapid mineralization of organic matter and a high pH buffering capacity can make the related effects on nutrient mobilization observed in alkaline soils temporary (Bustamante et al., 2008), the application of GP seems to aid the availability of P and other nutrients in GP for crop uptake at least during the early and crucial growth stages of crop establishment (Table 1).

5 | CONCLUSIONS

The application of non-composted GP increased maize, wheat, and grape yields under both greenhouse and field conditions and produced higher plant nutrient concentrations. Adding GP to FPs increased the value of field grapes by quantity without affecting quality. Increased soil organic matter, lower soil pH, and enhanced microbial activities (biomass and diversity) are associated factors that made more nutrients available for the plant. Therefore, the use of GP as an amendment may be a viable option for managing the pH of alkaline soils in the short term and improving soil health with environmental benefits as a circular agricultural practice to recycle nutrients back into the fields. Further research is required on a long-term scale to compare composted and non-composted GP effects on different crops in different soil types with assessment on economics, soil and plant health, and phytosanitary (pathogens, salt, and heavy metals), especially in relation to using uncomposed GP directly in the field.

ACKNOWLEDGMENTS

This work received funding from *Organic Transition grant No. 2021–51106–35496* from *USDA* and *NIFA*.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Beres, C., Gislaine, N. S., Costa, I. C., Nina, K., Aline, S. C., Teles, A., P, G., Mellinger-Silva, C. C., Renata, V. T., Lourdes, M. C. C., & Suely, P. F. (2017). Towards integral utilization of grape pomace from winemaking process: A review. *Waste Management*, *68*, 581–594.

Bernardi, A. C., Monte, M. B. D. M., Paiva, P. R. P., Werneck, C. G., Haim, P. G., & Barros, F. D. S. (2010). Dry matter production and nutrient accumulation after successive crops of lettuce, tomato, rice, and andropogongrass in a substrate with zeolite. *Revista Brasileira de Ciência do Solo*, *34*, 435–442.

Brady, N. C., & Weil, R. R. (1999). *Nature and property of soils*. Prentice Hall.

Breulmann, M., Masyutenko, N. P., Kogut, B. M., Schroll, R., Dörfler, U., Buscot, F., & Schulz, E. (2014). Short-term bioavailability of carbon in soil organic matter fractions of different particle sizes and densities in grassland ecosystems. *Science of the Total Environment*, *497*, 29–37.

Bustamante, M. A., Moral, R., Paredes, C., Pérez-Espinosa, A., Moreno-Caselles, J., & Pérez-Murcia, M. D. (2008). Agrochemical characterisation of the solid by-products and residues from the winery and distillery industry. *Waste Management*, *28*(2), 372–380.

Campbell, R. C. (2009). *Reference sufficiency ranges for plant analysis in the southern region of the United States*. North Carolina Department of Agriculture and Consumer Services Agronomic Division.

Castro, E., Uchôa-Thomaz, I. A. M., CariocaII, J., de Morais III, S, M., de Lima, I. A., Martins, C. G., Alexandrino, C. D., Ferreira, P. G., Rodrigues, A. L. M., Rodrigues, S. P., Silva, J d, M., & Rodrigues, L. L. (2014). Chemical composition and bioactive compounds of grape pomace (*Vitis vinifera* L.), Benitaka variety, grown in the semiarid region of Northeast Brazil. *Food Science and Technology*, *34*, 135–142.

Devesa-Rey, R., Vecino, X., Varela-Alende, J. L., Barral, M. T., Cruz, J. M., & Moldes, A. B. (2011). Valorization of winery waste vs. the costs of not recycling. *Waste Management*, *31*(11), 2327–2335.

Eyduran, S. P., Akin, M., Ercisli, S., Eyduran, E., & Maghradze, D. (2015). Sugars, organic acids, and phenolic compounds of ancient grape cultivars (*Vitis vinifera* L.) from Igdir province of Eastern Turkey. *Biological Research*, *48*(1), 1–8.

Fageria, N. K., Santos, D., A, B., & Moraes, M. F. (2010). Influence of urea and ammonium sulfate on soil acidity indices in lowland rice production. *Communications in Soil Science and Plant Analysis*, *41*(13), 1565–1575.

Fanin, N., Hättenschwiler, S., & Fromin, N. (2014). Litter fingerprint on microbial biomass, activity, and community structure in the underlying soil. *Plant and Soil*, *379*, 79–91.

Fanin, N., Kardol, P., Farrell, M., Nilsson, M. C., Gundale, M. J., & Wardle, D. A. (2019). The ratio of Gram-positive to Gram-negative bacterial PLFA markers as an indicator of carbon availability in organic soils. *Soil Biology and Biochemistry*, *128*, 111–114.

Fierer, N., Schimel, J. P., & Holden, P. A. (2003). Variations in microbial community composition through two soil depth profiles. *Soil Biology and Biochemistry*, *35*(1), 167–176.

Ferrer, J., Páez, G., Mármol, Z., Ramones, E., Chandler, C., Marın, M., & Ferrer, A. (2001). Agronomic use of biotechnologically processed grape wastes. *Bioresource Technology*, *76*(1), 39–44.

Frostegård, Å., Tunlid, A., & Bååth, E. (2011). Use and misuse of PLFA measurements in soils. *Soil Biology and Biochemistry*, *43*(8), 1621–1625.

García-Lomillo, J., & González-SanJosé, M. L. (2017). Applications of wine pomace in the food industry: Approaches and functions. *Comprehensive Reviews in Food Science and Food Safety*, *16*(1), 3–22.

Hamel, C., Hanson, K., Selles, F., Cruz, A. F., Lemke, R., McConkey, B., & Zentner, R. (2006). Seasonal and long-term resource-related variations in soil microbial communities in wheat-based rotations of the Canadian prairie. *Soil Biology and Biochemistry*, *38*(8), 2104–2116.

Hassan, Y. I., Kosir, V., Yin, X., Ross, K., & Diarra, M. S. (2019). Grape pomace as a promising antimicrobial alternative in feed: A critical review. *Journal of Agricultural and Food Chemistry*, *67*(35), 9705–9718.

Havlin, J. L., & Soltanpour, P. N. (1980). A nitric acid plant tissue digest method for use with inductively coupled plasma spectrometry. *Communications in Soil Science and Plant Analysis*, *11*(10), 969–980.

Horneck, U., Ellsworth, D., Hopkins, J., Sullivan, B., & Stevens, R. (2007). *Managing salt-affected soils for crop production*. Oregon State University Extension Service. https://ir.library.oregonstate.edu/concern/administrative_report_or_publications/pr76f371k

Ijaz, A., Mumtaz, M. Z., Wang, X., Ahmad, M., Saqib, M., Maqbool, H., Zaheer, A., Wang, W., & Mustafa, A. (2021). Insights into manganese solubilizing *Bacillus* spp. for improving plant growth and manganese uptake in maize. *Frontiers in Plant Science*, *12*, 719504. https://doi.org/10.3389/fpls.2021.719504

Kalembasa, S., & Kalembasa, D. (2016). Conversions and pathways of organic carbon and organic nitrogen in soils. In L. W. Szajdak (Ed.), *Bioactive compounds in agricultural soils* (pp. 53–90). Springer International Publishing.

Kalli, E., Lappa, I., Bouchagier, P., Tarantilis, P. A., & Skotti, E. (2018). Novel application and industrial exploitation of winery by-products. *Bioresources and Bioprocessing*, *5*(1), 1–21.

Lucarini, M., Durazzo, A., Kiefer, J., Santini, A., Lombardi-Boccia, G., Souto, E. B., Romani, A., Lampe, A., Ferrari, N. S., Gabrielli, P., Bevilacqua, N., Campo, M., Morassut, M., & Cecchini, F. (2019). Grape seeds: Chromatographic profile of fatty acids and phenolic compounds and qualitative analysis by FTIR-ATR spectroscopy. *Foods*, *9*(1), 10. https://doi.org/10.3390/foods9010010

Malhi, S. S., Nyborg, M., Harapiak, J. T., & Heaney, D. J. (1995). Long-term effects of ammonium nitrate application on soil pH, and micronutrients in soil and bromegrass hay. *Plant*-soil interactions at low *pH: Principles and* management*: Proceedings of the* third international symposium on plant-soil interactions at low ph (pp. 105–110). Springer Netherlands.

Mendes, J. A., Prozil, S. O., Evtuguin, D. V., & Lopes, L. P. C. (2013). Towards comprehensive utilization of winemaking residues: Characterization of grape skins from red grape pomaces of variety Touriga Nacional. *Industrial Crops and Products*, *43*, 25–32.

Miller, R. O., & Kissel, D. E. (2010). Comparison of soil pH methods on soils of North America. *Soil Science Society of America Journal*, *74*(1), 310–316.

Mpanga, I. K. (2020). *Fertilization strategies to improve the plant growth-promoting potential of microbial bio-effectors* [PhD thesis]. University of Hohenheim, Stuttgart.

Mpanga, I. K., Adjei, E., Dapaah, H. K., & Santo, K. G. (2021). Poultry manure induced garden eggs yield and soil fertility in tropical and semi-arid sandy-loam soils. *Nitrogen*, *2*(3), 321–331.

Mpanga, I. K., Dapaah, H. K., Geistlinger, J., Ludewig, U., & Neumann, G. (2018). Soil type-dependent interactions of P-solubilizing microorganisms with organic and inorganic fertilizers mediate plant growth promotion in tomato. *Agronomy*, *8*(10), 213. https://doi.org/10.3390/agronomy8100213

Mpanga, I. K., Gomez-Genao, N., Moradtalab, N., Wanke, D., Chrobaczek, V., Ahmed, A., Windisch, S., Geistlinger, J., Hafiz, B. F., Walker, F., Ludewig, U., & Neumann, G. (2019). The role of N form supply for PGPM-host plant interactions in maize. *Journal of Plant Nutrition and Soil Science*, *182*(6), 908–920.

Mpanga, I. K., Ludewig, U., Dapaah, H. K., & Neumann, G. (2020). Acquisition of rock phosphate by combined application of ammonium fertilizers and *Bacillus amyloliquefaciens* FZB42 in maize as affected by soil pH. *Journal of Applied Microbiology*, *129*(4), 947–957.

Mpanga, I. K., Nkebiwe, P. M., Kuhlmann, M., Cozzolino, V., Piccolo, A., Geistlinger, J., Berger, N., Ludewig, U., & Neumann, G. (2019). The form of N supply determines plant growth promotion by P-solubilizing microorganisms in maize. *Microorganisms*, *7*(2), 38. https://doi.org/10.3390/microorganisms7020038

Neina, D. (2019). The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*, *2019*, 1–9.

Nelson, D. W., & Sommers, L. E. (1973). Determination of total nitrogen in plant material. *Agronomy Journal*, *65*(1), 109–112.

Nkebiwe, P. M., Weinmann, M., Bar-Tal, A., & Müller, T. (2016). Fertilizer placement to improve crop nutrient acquisition and yield: A review and meta-analysis. *Field Crops Research*, *196*, 389–401.

Neumann, G., & Römheld, V. (2012). Rhizosphere chemistry in relation to plant nutrition. In P. Marschner (Ed.), *Marschner's mineral nutrition of higher plants* (pp. 347–368). Academic Press.

Obreza, T. A., Mongi, Z., & David, V. C. (2015). *Citrus fertilizer management on calcareous soils*. University of Florida.

Sabir, A., Kafkas, E., & Tangolar, S. (2010). Distribution of major sugars, acids, and total phenols in juice of five grapevine (*Vitis* spp.) cultivars at different stages of berry development. *Spanish Journal of Agricultural Research*, *8*(2), 425–433.

Salgado, M. M. M., Blu, R. O., Janssens, M., & Fincheira, P. (2019). Grape pomace compost as a source of organic matter: Evolution of quality parameters to evaluate maturity and stability. *Journal of Cleaner Production*, *216*, 56–63.

Sampedro, I., Parales, R. E., Krell, T., & Hill, J. E. (2015). Pseudomonas chemotaxis. *FEMS Microbiology Reviews*, *39*(1), 17–46.

Spinei, M., & Oroian, M. (2021). The potential of grape pomace varieties as a dietary source of pectic substances. *Foods*, *10*(4), 867. https://doi.org/10.3390/foods10040867

Teixeira, A., Baenas, N., Dominguez-Perles, R., Barros, A., Rosa, E., Moreno, D. A., & Garcia-Viguera, C. (2014). Natural bioactive compounds from winery by-products as health promoters: A review. *International Journal of Molecular Sciences*, *15*(9), 15638–15678.

Trinklein, D. (2013). *Grape: A brief history*. University of Moussori. https://ipm.missouri.edu/MEG/2013/8/Grapes-A-Brief-History/

Tuck, C. O., Pérez, E., Horváth, I. T., Sheldon, R. A., & Poliakoff, M. (2012). Valorization of biomass: Deriving more value from waste. *Science*, *337*(6095), 695–699.

USDA. (n.d.). Soil pH: Soil quality guide kit, guide for educators. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053293.pdf

USDA. (2018). *Nation organic program. Elemental sulfur*. United States department of agriculture agricultural marketing service national organic program. https://www.ams.usda.gov/sites/default/files/media/ElementalSulfurCropsTechnicalReport2018.pdf

WARD Laboratories. (2020). Wards Guide: Guiding producers today to feed the world tomorrow. Wards Laboratory Inc. https://www.wardlab.com/resources/ward-guide/

Westover, F. (2006). Notes on composting grape pomace. Virginia Tech. https://www.arec.vaes.vt.edu/content/dam/arec_vaes_vt_edu/alson-h-smith/grapes/viticulture/extension/growers/documents/composting-grape-pomace.pdf

Yuan, J., Zhang, N., Huang, Q., Raza, W., Li, R., Vivanco, J. M., & Shen, Q. (2015). Organic acids from root exudates of banana help root colonization of PGPR strain Bacillus amyloliquefaciens NJN–6. *Scientific Reports*, *5*(1), 1–8.

Zuin, V. G., & Ramin, L. Z. (2018). Green and sustainable separation of natural products from agro-industrial waste: Challenges, potentialities, and perspectives on emerging approaches. *Topics in Current Chemistry*, *376*, 3.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mpanga, I., Neumann, G., Brown, J., Blankinship, J., Tronstad, R., & Idowu, O. (2023). Grape pomace's potential on semi-arid soil health enhances performance of maize, wheat, and grape crops. *Journal of Plant Nutrition and Soil Science*, 1–10. https://doi.org/10.1002/jpln.202200232