


# Integrating plant growth microorganisms in potato farming reduce soil CO<sub>2</sub> emissions and improve crop quality

Irene Ollio<sup>1,2</sup>  | Manuel González Rosado<sup>1</sup> | Eva Lloret<sup>1,2</sup> |  
Silvia Martínez-Martínez<sup>1</sup> | Catalina Egea-Gilabert<sup>1,2</sup> | David Fernández Calviño<sup>3,4</sup> |  
Raúl Zornoza<sup>1,2</sup> | Juan A. Fernández<sup>1,2</sup>

<sup>1</sup>Departamento de Ingeniería Agronómica, Universidad Politécnica de Cartagena, Cartagena, Spain

<sup>2</sup>Instituto de Biotecnología Vegetal (IBV), Campus Muralla del Mar, Edificio I+D+I, Universidad Politécnica de Cartagena, Cartagena, Spain

<sup>3</sup>Departamento de Biología Vegetal e Ciencia do Solo, Facultade de Ciencias, Universidad de Vigo, Ourense, Spain

<sup>4</sup>Instituto de Agroecología e Alimentación (IAA), Universidade de Vigo—Campus Auga, Ourense, España

## Correspondence

Irene Ollio and Juan A. Fernandez, Departamento de Ingeniería Agronómica, Universidad Politécnica de Cartagena, Paseo Alfonso XIII 48, 30203, Cartagena, Spain.  
Email: [irene.ollio@upct.es](mailto:irene.ollio@upct.es) and [juan.fernandez@upct.es](mailto:juan.fernandez@upct.es)

## Abstract

Current horticultural practices typically require high demands of fertilizers, leading to significant environmental impacts and increased production costs. Alternatives based on microbial inoculants have garnered considerable interest owing to their potential to enhance soil quality whilst reducing external inputs and costs, all without compromising productivity. This study aimed to compare the impact of four fertilizer application strategies, including mineral fertilizers and microbial inoculants, on crop yield, soil fertility and functionality and soil greenhouse gas emissions in potato production in Southern Spain. Four treatments were tested: (i) mineral fertilizers added to meet the crop's nutritional needs (F100); (ii) a 50% reduction of the F100 rate (F50); (iii) a 50% reduction of the F100 rate combined with the application of a formulation containing nutrient-solubilizing bacteria, nitrogen-fixing bacteria and non-mycorrhizal fungi (BAI+FU) and (iv) a 50% reduction of the F100 rate combined with a formulation of N, P and K solubilizing bacteria (BAII). Results showed that crop yield was unaffected by the different fertilizer application treatments. However, the mean tuber weight and firmness were significantly higher under the BAI+FU treatment, indicating improved product quality. CO<sub>2</sub> release rates decreased by 25%, 34% and 42% with F50, BAI+FU and BAII treatments, respectively, compared with F100. The N<sub>2</sub>O and CH<sub>4</sub> emissions or soil nutrient contents were not affected by treatments, except for ammonium content, which was highest under the BAI+FU treatment. Additionally, whilst overall soil bacterial and fungal abundance was not significantly affected, the BAI+FU treatment resulted in a higher number of *nirK* (denitrification) and *cbbL* (carbon fixation) gene copies. Therefore, combining biofertilizers with reduced chemical fertilizer rates could represent a sustainable strategy for mitigating climate change whilst enhancing crop quality in potato production.

This is an open access article under the terms of the [Creative Commons Attribution](https://creativecommons.org/licenses/by/4.0/) License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2025 The Author(s). *Soil Use and Management* published by John Wiley & Sons Ltd on behalf of British Society of Soil Science.

## KEYWORDS

functional genes, plant growth-promoting bacteria, plant growth-promoting fungi, soil greenhouse gas emissions

## 1 | INTRODUCTION

Greenhouse gas (GHG) emissions, including CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>, are key contributors to global climate change, which is expected to increase by 50% between 2000 and 2030 (Kumar et al., 2024; Vergé et al., 2007). Soils from croplands are a significant source of GHGs, though this varies with specific soil management practices (Eggleston et al., 2006). CO<sub>2</sub> is released from soils and plants through root respiration and microbial activity during soil organic matter mineralization (Oertel et al., 2016). N<sub>2</sub>O emissions arise primarily as a by-product of the microbial processes of nitrification and denitrification in soils (Lazcano et al., 2021). CH<sub>4</sub> is produced through anaerobic microbial activities (Hou et al., 2000).

A significant portion of the EU's total net GHG, ca. 13.2%, is attributed to the agricultural sector, excluding those from agricultural fuel usage (European Commission, Directorate General for Climate Action, and Trinomics, 2023). From 2005 to 2018, land use in agriculture was a major contributor to these emissions, representing about 37.8% of the sector's total emissions (Mielcarek-Bocheńska & Rzeźnik, 2021). Particularly, intensive agriculture can significantly impact GHG emissions and environmental sustainability through intensive tillage, excessive use of fertilizers and pesticides and monoculture practices (Scuderi et al., 2021). However, agriculture does not inherently have to be a source of GHG emissions and environmental degradation (Bennetzen et al., 2016; Snyder et al., 2009); rather, it can help mitigate and counteract climate change through the implementation of appropriate management practices (Horowitz & Gottlieb, 2010).

The addition of inorganic fertilizers is commonly related to higher soil GHG emissions and reduced CO<sub>2</sub> fixation owing to the activation of soil decomposers (Liao et al., 2020). To promote sustainable agriculture, a gradual decrease in synthetic agrochemicals is imperative. Microbial-based products, such as biofertilizers containing plant growth-promoting bacteria (PGPB) and fungi (PGPF), can increase soil fertility and mitigate the negative effects of agrochemicals (Adesemoye & Kloepper, 2009; Basu et al., 2021). Biofertilizers, such as those containing PGPB (Gupta et al., 2015) and PGPF (Hossain et al., 2017), may offer the advantage of limiting synthetic fertilizers in agriculture (Adesemoye et al., 2009; Singh et al., 2016),

with the associated decrease in energy consumption and costs (Helsel, 1992). Plant growth-promoting microorganisms (PGPM) (El-Saadony et al., 2022) can fix N (Xu et al., 2018), solubilize minerals such as P (Khan et al., 2009; Wani et al., 2007) and K (Ali et al., 2021; Jaiswal et al., 2016), produce phytohormones and maintain the nutritional balance (Gnanamanickam, 2007), thereby enhancing crop growth and development (Calvo et al., 2014), and decrease the dependence on synthetic fertilizers (Singh et al., 2016). In fact, PGPM inoculation has been efficient in enhancing the efficiency of carbon and nitrogen utilization (Di Benedetto et al., 2017; Imran et al., 2021). In this line, the diazotrophic community, which consists of N-fixing microorganisms, contributes to soil C availability by increasing N availability, thus promoting the degradation of soil organic matter (Chen et al., 2019; Sun et al., 2021). Fungi aid in organic matter decomposition, providing plant nutrients and extractable dissolved organic carbon, which is beneficial for other microbes (Frąc et al., 2018). Additionally, PGPB inoculation has been shown to enhance the ability of soil to sequester N<sub>2</sub>O in conditions where denitrifying microorganisms have enough C sources (Florio et al., 2019). PGPB can also directly promote plant growth, allocating more carbon to plant biomass, which is crucial for carbon recycling (Sarfraz et al., 2019). Moreover, CO<sub>2</sub> sequestration by autotrophic bacteria is an important process in the biogeochemical cycle of C in soils (Yousuf et al., 2012).

Soil microorganisms are essential for crop production in agricultural systems, as they enhance soil multifunctionality and maintain soil health (Cuartero et al., 2022). For instance, the analysis of functional genes representing specific functional capacities to micro-organisms has been recommended as a method for assessing soil functionality (Zhang et al., 2022). These include enzymes that catalyse various stages of the nitrogen and carbon cycles, providing insights into potential soil functionality (Levy-Booth et al., 2014; Liao et al., 2020; Zhang et al., 2022).

After cereals, potato (*Solanum tuberosum* L.) is the most important crop in the Globe, following rice and wheat (FAO, 2023). Potatoes are classified as a staple food, meaning they are consumed regularly and in sufficient quantities to constitute the majority of the diet and provide a considerable share of its total energy (FAO, 2023). Current potato cultivation practices rely heavily on fertilizers and pesticides, which are both costly and detrimental to production, whilst also

being widely recognized as contributors to environmental issues (Abou El-Yazied & Selim, 2007). Potatoes require high amounts of fertilizer (especially nitrogen) to preserve plant health, reduce susceptibility to infections and pathogen insects and increase tuber quality (Hopkins et al., 2008). These high nitrogen fertilizer inputs, frequently provoke high N<sub>2</sub>O emissions compared with those of other typical arable crops (Dandie et al., 2008). Potato plants also face challenges in soil phosphate uptake because of their shallow root system, resulting in excessive fertilizer application by farmers, to meet peak crop demands (Hopkins et al., 2014). Potato tubers are rich in starch, so they require relatively higher potassium than any other vegetable crop (Bista & Bhandari, 2019). Thus, research must focus on the environmental impacts of excessive nutrient use and finding solutions to reduce and improve crop nutrient efficiency (Hopkins et al., 2014; Powlson et al., 2011).

The main objectives of this study were (1) to assess the effects of different fertilizer application practices, including the use of commercial biofertilizers and/or a reduced dose of inorganic fertilizer (compared with conventional applications), on crop yield, soil fertility and overall soil functionality; (2) to investigate the effects of these fertilizer application strategies on soil GHG emissions and (3) to elucidate the relationships between soil GHG emissions, crop yield and soil properties, including biodiversity indicators. The underlying hypotheses of the study were (a) PGPMs improve crop yield, soil fertility and soil functionality by increasing nutrient availability to meet the nutritional requirements of potato crops whilst reducing reliance on inorganic fertilizers and (b) incorporation of PGPMs into the soil can mitigate GHG emissions from potato production by improving carbon and nitrogen use efficiency, thereby minimizing losses associated with over-application of fertilizers. To test these hypotheses, a field experiment was conducted, comparing conventional fertilizer application practices with treatments receiving half the fertilizer amount. Additionally, two commercial products containing a consortium of PGPB and non-mycorrhizal PGPF were applied. This research provides new insights into optimizing potato farming practices to reduce environmental impacts and enhance soil multifunctionality by activating microbial communities.

## 2 | MATERIALS AND METHODS

The study area, cultivation management practices and the use of biofertilizer products described herein are part of a single growing season within a crop rotation project. Detailed information on Materials and Methods

can be consulted in Ollio et al. (2024), which addresses a previous growing season within the same rotation sequence.

### 2.1 | Study site and experimental design

This experiment was performed at the Tomás Ferro Experimental Farm, belonging to the Polytechnic University of Cartagena (UPCT), located in Cartagena, Southeast Spain (37°41'16.6"N, 0°56'55.6"W). The region experiences a semiarid Mediterranean climate, with an average annual precipitation of 300 mm and an average annual temperature of 18°C. The potential evapotranspiration in this area exceeds 1200 mm per year. Soil is classified as Haplic Calcisol (loamic and hypercalcic) according to the IUSS World Reference Base (WRB, 2022), characterized by a clay loam texture, 1.8% organic matter, 25.2% CaCO<sub>3</sub> and a pH of 8.2. The experiment was conducted on a potato crop (*S. tuberosum* var. Spunta) sourced from HZPC, Netherlands, and was grown from 16 December 2022 to 16 May 2023, spanning 151 days post-sowing. Prior to the potato experiment, a melon crop was cultivated on the same field from March to July 2022. As part of the common agricultural practice in this region, crop rotation with vegetables is employed annually to mitigate the adverse effects of monoculture. The potato crop was established using drip irrigation and received mineral fertilizer application according to local practices. Four different fertilizer application treatments were implemented: (1) F100 involves the addition of inorganic fertilizers to meet the complete nutritional needs of the crop; (2) F50 entails applying 50% of the inorganic fertilizer rate used in F100; (3) BAI+FU consists of using the F50 doses along with a biofertilizer formulation containing PGPB and non-mycorrhizal fungi and (4) BAII involves applying the F50 doses along with a biofertilizer formulation containing N-fixing bacteria and P and K solubilizing bacteria.

The BAI+FU formulation (Nuve™) primarily consisted of a mix of PGPB like *Bacillus*, *Azotobacter* and beneficial non-mycorrhizal fungi. The BAII formulation (Bactoneco™) is composed of PGPB such as *Azospirillum*, *Pseudomonas* and *Bacillus*. Fertilizantes y Nutrientes Ecológicos, S.L. (Spain) supplied biofertilizers, the exact composition of which was confidential. However, the company reports that it developed these products using endemic strains of plant growth-promoting rhizobacteria (PGPR) specific to the region to avoid problems of competition and incompatibility with native microorganisms.

In addition, the formulations are stabilized at the peak of their growth activity, allowing almost immediate action when applied in the field. The bacteria in these products have the potential to fix atmospheric nitrogen

and solubilize phosphorus and potassium, making these nutrients readily available for plant uptake. They also synthesize growth-promoting substances such as phytohormones and provide protection through substances such as antibiotics and siderophores that inhibit the growth of pathogens.

We designed an experiment with complete randomized blocks with four treatments, each covering an area of 740 m<sup>2</sup>, and replicated four times. All treatments received equal irrigation volumes (1700 m<sup>3</sup> ha<sup>-1</sup>), with irrigation schedules based on local weather conditions, crop coefficients and evapotranspiration rates. Weather data were recorded using an automatic weather station located at the study site. Soil tillage was performed to a depth of 25 cm across all treatments. The F100 mineral fertilizer application included 96.6 kg ha<sup>-1</sup> of N, 45 kg ha<sup>-1</sup> of P<sub>2</sub>O<sub>5</sub> and 190.3 kg ha<sup>-1</sup> of K<sub>2</sub>O, applied weekly through fertigation between 16 February 2023 and 19 April 2023. The start of fertilizer application and irrigation of the plot was determined when all tubers had reached the final stage of germination and had entered the full vegetative development phase. The doses, which were applied weekly, were distributed according to the needs of the plant based on its stage of development. Fertigation was completed on 19 April, coinciding with the onset of senescence in the plants. During this phase, we began to reduce both the duration and quantity of irrigation to facilitate the final process of tuber skin hardening and to prepare the soil for harvesting. The Fertilizers used were N–P–K (13% N, 40% P<sub>2</sub>O<sub>5</sub> and 13% K<sub>2</sub>O), magnesium nitrate (13.5% N and 15.60% Mg) and potassium nitrate (46.5% K<sub>2</sub>O and 13.6% N). Biofertilizers were administered via drip irrigation following the manufacturer's guidelines. The BAII treatment received two applications of Bactoneco N<sup>®</sup>, Bactoneco P<sup>®</sup> and Bactoneco K<sup>®</sup> on 1 March and 15 March 2023, with a total dosage of 6 L ha<sup>-1</sup>. The BAI+FU treatment was applied at a rate of 30 L ha<sup>-1</sup> over three applications on 1 March, 15 March and 29 March 2023. The manufacturer has specified the dose, frequency and time between applications for both treatments. On 14 April 2023, targeted pesticide treatments were administered to control *Alternaria* spp., moths and potato beetles using Cerial Top (Mandipropamide 25% + Difenconazole 25% [SC]) and Coragen 20SC (Chlorantraniliprole 20% [SC]). Initially, *Alternaria* spp. caused notable crop damage, raising concerns about yield, but the treatment effectively contained the disease, and the crop gradually recovered because of favourable weather and the successful application of control measures. The doses applied following the product registrations outlined by the Ministry of Agriculture, Fisheries and Food of Spain, as listed in Annex II of the Council

of the European Union (2020). Meteorological data were continuously monitored using the on-site weather station, which recorded precipitation, air temperature, global radiation, relative humidity and wind speed and direction, following UNE 176.101: 2010 standards.

## 2.2 | Soil sampling and crop yield and quality

Soil sampling for physicochemical analysis was conducted on 12 April 2023, following the completion of the fertigation schedule across all treatments, coinciding with the phenological flowering stage. The sampling for molecular analyses was carried out on 15 March 2023 before harvest. The sampling methods are described by Ollio et al. (2024). Harvest of tubers was performed on 16 May 2023 as early potatoes. A mechanized harvester lifted the tubers with chisels, after which the potatoes were hand-harvested and placed in special bags with a capacity of ca. 25 kg. The collection area consisted of a region in the centre of the plots, with an area of 280 m<sup>2</sup> for each treatment. All the bags collected were then weighed and the yield was expressed as t ha<sup>-1</sup>. Then, one bag was randomly chosen per plot for evaluation of firmness, density, starch content, weight and size. The firmness analysis was carried out using a penetrometer (Brezmes Llecha et al., 2001). Tuber weight, dimensions and density were determined with a laboratory balance and a Vernier calliper (Glasbey et al., 1988). The content of the tuber starch was estimated through the specific weight (Widmann et al., 2008).

## 2.3 | Soil greenhouse gas measurements

The dynamic closed gas chamber method was used in this experiment. Measurements of CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, soil temperature (T) and soil moisture (M) were made every 7 days in all plots from 16 February 2023 to 11 May 2023, between 9:00 and 12:00 h according to Ollio et al. (2024), using photoacoustic infrared spectroscopy multi-gas analyser with an ultra-sensitive cantilever pressure sensor (Gasera One, Gasera Ltd., Helsinki, Finland). CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> were quantified every 1 min for 5 min to confirm a linear tendency. Numerical integration was used to calculate the cumulative values of CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions. GHG emissions were transformed into CO<sub>2</sub> equivalent (CO<sub>2</sub>e), and then cumulative emission data (g m<sup>-2</sup>) were also expressed on a production basis (g kg<sup>-1</sup>) for the experimental period to assess the emissions per product of each treatment. Soil moisture (M) and soil temperature (T) were measured using a ProCheck and 5TM sensors (Decagon Devices, USA) inserted at 15 cm depth.

## 2.4 | Soil chemical analyses

Exchangeable cations and cation exchange capacity were measured using  $\text{BaCl}_2$ , following the international standard method (ISO 13536) (Quality, 1995). Soil pH and electrical conductivity (EC) were measured in a soil/water ratio of 1:5 (w/v). Total organic carbon (TOC) and total nitrogen (TN) were measured with an elemental CHN analyser (EA-1108, Carlo Erba, Barcelona, Spain). The particulate organic carbon (POC) was measured following Cambardella and Elliott (1992). Soil  $\text{NH}_4^+$  was extracted with 2M KCl in a 1:10 ratio (soil/extractant), and spectrophotometrically measured (Kandeler & Gerber, 1988; Keeney & Nelson, 1983). Soil  $\text{NO}_3^-$  was measured by ion chromatography (Metrohm 861) and extracted 1:10 (soil:deionized water) (Keeney & Nelson, 1983; Sempere et al., 2006). Available P measurement was conducted using the Olsen method (Olsen, 1954). Available Fe, Mn, Cu and Zn were extracted through chelation with DTPA (1:2 w/v ratio) (Kabata-Pendias, 2000; Reichman, 2002). The soluble B content was determined by extraction with deionized water at a 1:5 w/v ratio and a temperature of 50°C (Porta Casanellas et al., 1986). The concentrations of the available nutrients were quantified using inductively ICP-MS (7500CE, Agilent, Santa Clara, CA, USA).

## 2.5 | DNA extraction and quantitative PCR (qPCR) gene analysis

A quantitative PCR (qPCR) analysis was carried out to measure the copy number of selected functional genes related to C and N cycles, according to Ollio et al. (2024). Briefly, soil DNA was extracted and purified. Gene copy numbers were determined by calculating the concentration of the extracted DNA plasmid containing the gene fragment. Tenfold serial dilutions of linearized plasmids were run in each qPCR assay in triplicate to generate a standard curve. Gene copy numbers were quantified by employing the same primers as for cloning (see Table S1). The genes cycling conditions are shown in Tables S2–S6.

## 2.6 | Statistical analysis

The study utilized statistical methods to assess crop yield, soil properties, functional genes and GHG emissions. A one-way ANOVA with Tukey's and Duncan's post hoc tests was used for treatment comparisons, whilst the Kruskal–Wallis test followed by Dunn's test was applied for non-normally distributed data. GHG emissions were analysed using two-way repeated measures ANOVA, considering measurement date and treatment as factors.

Additionally, one-way ANOVA with post hoc tests was applied to GHG data for each date to detect significant differences. A stepwise multiple linear regression ( $Y = m_1X_1 + m_2X_2 + \dots + m_nX_n + b$ ) was performed with GHG emissions as independent variables and soil properties, functional genes analyses and crop yield as dependent variables. Standardized coefficients ( $\beta$ ) identified the most influential independent variables, whilst partial correlations assessed relationships controlling other variables. Unstandardized coefficients ( $m$ ) were used to compare observed GHG values with model predictions. All analyses were performed using IBM SPSS Version 26.

## 3 | RESULTS

### 3.1 | Weather conditions during the trial period

During the crop period from December 2022 to May 2023, the mean temperature was 14.1°C, and the rainfall was 34.8 mm, with a mean daily evapotranspiration of 2.5 mm and a mean relative humidity of 65.7%. January registered the highest amount of rainfall, measuring 17.20 mm of precipitation. Meanwhile, February was the coldest month, with the lowest temperature reaching 0°C and a mean minimum temperature of around 6°C. April recorded the highest temperatures, with an average of 22°C and daily peaks reaching around 30°C, making it warm and sunny (Figure S1).

### 3.2 | Crop yield and quality

There were no significant differences in crop yield between treatments although BAI+FU exhibits a higher value. The total yield was 39.2 t ha<sup>-1</sup> for BAI+FU, 36.7 t ha<sup>-1</sup> for BAI, 36.6 t ha<sup>-1</sup> for F50 and 36.9 t ha<sup>-1</sup> for F100, respectively (Table 1). Concerning quality parameters, tuber volume and starch content showed no significant differences between fertilizer application strategies. However, BAI+FU was the treatment with the highest mean weight and flesh firmness of tubers, with 244 g and 16 kg cm<sup>-2</sup> values, respectively, whilst F100 showed the lowest values with 158 g and 13 kg cm<sup>-2</sup>, respectively.

### 3.3 | Soil greenhouse gas emission rates

During the measurement period, 5 out of the 15 CO<sub>2</sub> emission rate measures were significantly higher in F100 than in the rest of the treatments. CO<sub>2</sub> emission rates were, as an average, 37.90 mg m<sup>-2</sup> h<sup>-1</sup> in F100, 28.97 mg m<sup>-2</sup> h<sup>-1</sup> in F50,

Treatment	Crop yield $\text{t ha}^{-1}$	Mean weight g	Volume $V_{(\text{ellipsoid})} \text{ cm}^{-3}$	Firmness $\text{kg cm}^{-2}$	Starch content %
BAI+FU	39.2 ± 0.4	244.3 ± 24.4a	224.7 ± 39.8	16.0 ± 0.3a	21.4 ± 0.8
BAlI	36.7 ± 0.7	171.6 ± 4.5b	163.0 ± 32.8	15.4 ± 0.4ab	20.9 ± 4.1
F50	36.6 ± 1.8	205.8 ± 17.4b	179.1 ± 20.8	14.8 ± 0.4b	20.3 ± 0.3
F100	36.9 ± 1.4	158.2 ± 7.7c	142.9 ± 12.8	13.1 ± 0.0c	21.0 ± 0.7
F ANOVA	1.04 ns	6.14**	1.48 ns	14.23**	0.05 ns

Note: Values mean ± standard error ( $n=4$ ). F100, inorganic fertilizers applied at a rate to meet the crop's nutritional demands; F50, a 50% reduction in the F100 rate; BAI+FU, a 50% reduction in the F100 rate plus the application of a formulation of bacteria and non-mycorrhizal fungi; BAlI, a 50% reduction in the F100 rate plus the application of nitrogen-fixing and phosphorus- and potassium-solubilizing bacteria. Values followed by different lowercase letters in the same column indicate significant differences between the four treatments (Duncan's test); ns, non-significant differences between cultivation systems ( $p > .05$ ).

\*\* $p < .01$ .

24.68  $\text{mg m}^{-2} \text{ h}^{-1}$  in BAlI and 25.99  $\text{mg m}^{-2} \text{ h}^{-1}$  in BAI+FU for the entire experimental period. There was no direct effect of the application of the biofertilizers on  $\text{CO}_2$  emission peaks. Soil  $\text{CO}_2$  rates followed the soil temperature trend, with a positive significant correlation between both parameters ( $R=0.454$ ;  $p < .01$ ). Nonetheless, there was a significant negative correlation between soil moisture and  $\text{CO}_2$  emission rate ( $R=-0.450$ ;  $p < .01$ ) (Figure 1a,b). Soil moisture level tended to be lower in F100 in comparison to the other treatments, especially to the BAI+FU, despite receiving the same quantity of irrigation. Soil moisture was, as an average, 16.1% in F100, and 18.6% in BAI+FU. Soil  $\text{CO}_2$  emission showed significant differences between treatments, with higher emissions in F100, and lower in BAlI and BAI+FU (Figure 1b). The emission rates of  $\text{N}_2\text{O}$  in the soil remained constant with minor fluctuations around 0.05  $\text{mg m}^{-2} \text{ h}^{-1}$  (Figure 1c). These rates were not correlated by either soil moisture or soil temperature. On 05 March 2023 (4 days after the fertigation and the first application of the biofertilizer in the BAI+FU and BAlI plots), BAlI showed a peak in  $\text{N}_2\text{O}$  (0.030  $\text{mg m}^{-2} \text{ h}^{-1}$ ). As an average,  $\text{CH}_4$  emission rates were 0.25  $\text{mg m}^{-2} \text{ h}^{-1}$  in F100, 0.42  $\text{mg m}^{-2} \text{ h}^{-1}$  in F50, 0.29  $\text{mg m}^{-2} \text{ h}^{-1}$  in BAlI and 0.41  $\text{mg m}^{-2} \text{ h}^{-1}$  in BAI+FU. Soil  $\text{CH}_4$  rates went with the tendency of soil moisture and temperature, with higher emissions and higher soil moisture content after rainfall episodes at high temperatures. There were no significant differences between fertilizer application strategies in terms of  $\text{CH}_4$  emission rates (Figure 1d).

### 3.4 | Overall cumulative soil emissions

There was a significantly highest overall cumulative  $\text{CO}_2$  and  $\text{CO}_2\text{e}$  emissions in F100. During the experiment, the F100 treatment emitted significantly higher levels of  $\text{CO}_2$  and  $\text{CO}_2\text{e}$  than the BAlI and BAI+FU treatments, which emitted

TABLE 1 Crop yield and tuber quality parameters.

less (42% and 34% compared with F100, respectively). The F50 treatment showed 25% less cumulative  $\text{CO}_2$  than F100 (Table 2). There were no significant differences regarding cumulative  $\text{N}_2\text{O}$  and  $\text{CH}_4$  amongst treatments. The average cumulative  $\text{CO}_2\text{e}$  emission expressed on a production basis was 56.05  $\text{g kg}^{-1}$  for BAI+FU, 50.03  $\text{g kg}^{-1}$  for BAlI, 74.17  $\text{g kg}^{-1}$  for F50 and 93.42  $\text{g kg}^{-1}$  for F100. The cumulative  $\text{CH}_4$  emission was positively correlated with crop yield ( $R=0.640$ ;  $p < .05$ ), and there was no significant correlation between cumulative  $\text{CO}_2$  and  $\text{CH}_4$  and either crop yield or other soil properties.

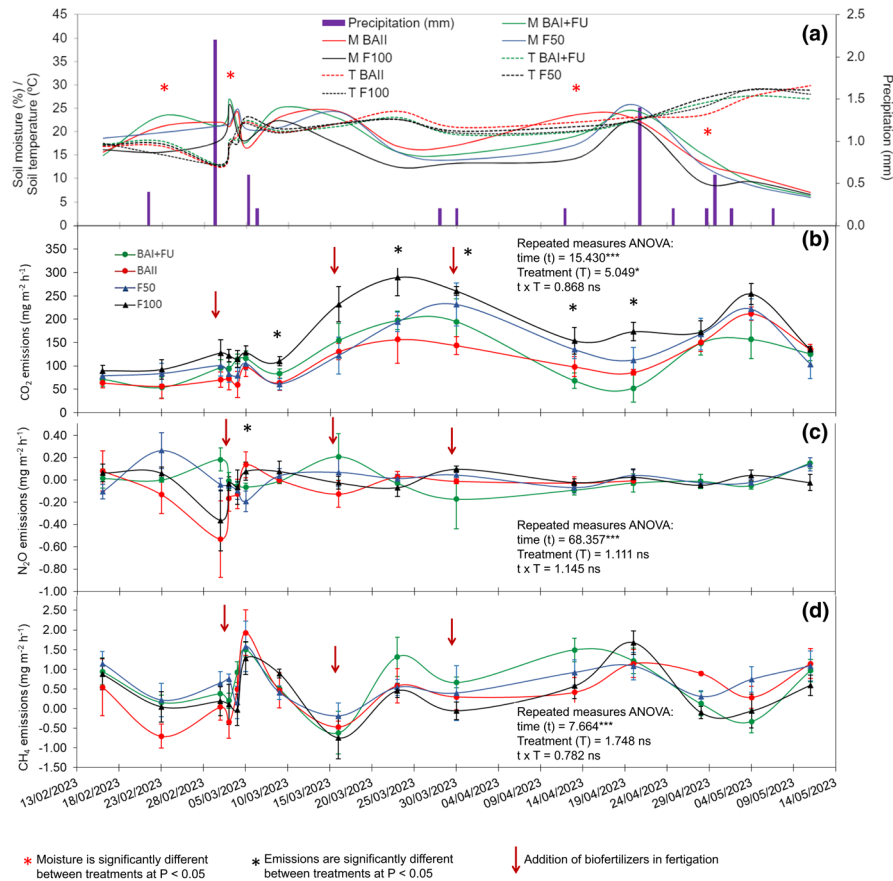
### 3.5 | Soil fertility and functionality

The fertilizer application strategies significantly differ in soil EC, pH and  $\text{NH}_4^+$  content (Table 3). The treatments did not significantly affect the rest of the soil properties (TOC, POC, TN and available nutrients). Specifically, EC was significantly lower in F100 and higher in BAlI, whilst pH followed the opposite trend. BAI+FU showed the highest  $\text{NH}_4^+$  content.

Concerning the content of bacteria (16S rRNA), fungi (ITS region) and functional genes, only *nirK* and *cbbL* showed significant differences between treatments (Table 4). F50 showed a significantly lower number of copies of *nirK* and *cbbL* than the other treatments, with BAI+FU showing the highest number of copies.

### 3.6 | Interrelationship between crop yield, soil properties and GHGs

Cumulative  $\text{CO}_2$  emissions could be estimated by different variables such as a soil macronutrient (P), pH, microbial activity involved in N cycle (*nifH*), fungal abundance (ITS)



**FIGURE 1** Soil temperature and moisture during the experimental period (a), soil CO<sub>2</sub> emission rates (b), soil N<sub>2</sub>O emission rates (c) and CH<sub>4</sub> emission rates (d) in potato cultivation with different fertilizer application treatments. Vertical bars denote the standard error. P, precipitation; T, soil temperature.; M, soil moisture; F100, inorganic fertilizers applied at a rate to meet the crop's nutritional demands; F50, a 50% reduction in the F100 rate; BAI+FU, a 50% reduction in the F100 rate plus the application of a formulation of bacteria and non-mycorrhizal fungi; BAI, a 50% reduction in the F100 rate plus the application of nitrogen-fixing and phosphorus- and potassium-solubilizing bacteria. Red arrows indicate the days of applications of biofertilizers. Red asterisks indicate significant differences in soil moisture, black asterisks indicate significant differences in GHG emissions. For repeated measures ANOVA data: significant at \*\*\* $p < .001$ ; ns, not significant ( $p > .05$ ).

and crop yield ( $R^2 = 0.95$ ;  $F = 34.19$ ;  $p < .01$ ) (Table 5). It is important to highlight that only pH and P were positively related to cumulative CO<sub>2</sub>, whilst the other variables were negatively related. Thus, the lower fungal abundance and N-fixing activity, the higher the CO<sub>2</sub> emissions, associated with lower yields. Cumulative CH<sub>4</sub> emissions could be estimated by crop yield ( $R^2 \text{ adj} = 0.92$ ;  $F = 11.03$ ;  $p < .01$ ) (Table 5). Cumulative N<sub>2</sub>O could not be estimated with the studied properties.

## 4 | DISCUSSION

### 4.1 | Crop yield and tuber quality

Numerous studies have confirmed that combining biofertilizers with organic or mineral fertilizers improves various aspects of plant development, including growth,

photosynthesis, dry matter accumulation, starch content and tuber yield (Abdeldaym et al., 2019; Samet et al., 2022; Yao et al., 2002). In our study, a treatment involving a 50% reduction in mineral fertilizer application, associated with PGPB and PGPF (BAI+FU), resulted in significantly better tuber quality, particularly in terms of increased tuber weight and flesh firmness. Several reports have highlighted the beneficial effects of different PGPB strains on tuber weight under various fertilizer application regimes. For example, Velivelli et al. (2015) observed that bacterial inoculants consistently boosted tuber yield, even when fertilizer levels were reduced. Similarly, Abou El-Yazied and Selim (2007) reported a steady increase in tuber weight when mineral nitrogen levels were reduced, and seed potatoes were inoculated with biofertilizers. They noted that plants receiving half the recommended doses of N and P, along with biofertilizer inoculation, achieved the highest average tuber

**TABLE 2** Cumulative values of soil CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub> and total CO<sub>2</sub> equivalent emissions, crop yield and cumulative CO<sub>2</sub> equivalent emission data expressed on a production basis released from the soil in the potato crop with different fertilizer application treatments.

Treatment	Cumulative CO <sub>2</sub> g m <sup>-2</sup>	Cumulative N <sub>2</sub> O	Cumulative CH <sub>4</sub>	CO <sub>2</sub> e	CO <sub>2</sub> e g kg <sup>-1</sup> of crop yield
BAI+FU	201 ± 16b	-0.06 ± 0.09	1.25 ± 0.18	219 ± 36b	56.05 ± 9.40b
BAII	176 ± 21b	-0.04 ± 0.02	0.67 ± 0.19	182 ± 25b	50.03 ± 7.52b
F50	231 ± 27ab	0.03 ± 0.05	1.07 ± 0.24	269 ± 18ab	74.17 ± 6.97ab
F100	306 ± 23a	0.05 ± 0.02	0.81 ± 0.16	343 ± 14a	93.42 ± 6.49a
F ANOVA	6.300**	0.917 ns	1.742 ns	7.566**	6.502**

Note: Values mean ± standard error ( $n=4$ ). F100, inorganic fertilizers applied at a rate to meet the crop's nutritional demands; F50, a 50% reduction in the F100 rate; BAI+FU, a 50% reduction in the F100 rate plus the application of a formulation of bacteria and non-mycorrhizal fungi; BAII, a 50% reduction in the F100 rate plus the application of nitrogen-fixing and phosphorus- and potassium-solubilizing bacteria. Values followed by different lowercase letters in the same column indicate significant differences between the four treatments (Tukey's post hoc test); (ns) non-significant differences ( $p$ -value > .05).

\*\* $p < .01$ .

**TABLE 3** Main soil properties measured in the different treatments.

		BAI+FU	BAII	F50	F100	F ANOVA
EC	μS cm <sup>-1</sup>	250 ± 16ab	291 ± 18a	275 ± 5ab	245 ± 7b	2.629*
pH		9.01 ± 0.03ab	8.93 ± 0.02c	8.96 ± 0.01bc	9.04 ± 0.02a	4.937**
TOC	g kg <sup>-1</sup>	11.39 ± 0.13	11.37 ± 0.58	11.97 ± 0.47	11.18 ± 0.39	0.652 ns
POC	g kg <sup>-1</sup>	0.84 ± 0.10	0.72 ± 0.07	0.76 ± 0.03	0.71 ± 0.07	0.689 ns
TN	g kg <sup>-1</sup>	1.18 ± 0.06	1.18 ± 0.02	1.17 ± 0.03	1.16 ± 0.03	0.036 ns
NH <sub>4</sub> <sup>+</sup>	mg kg <sup>-1</sup>	4.45 ± 0.82a	2.99 ± 0.07ab	2.67 ± 0.03b	2.65 ± 0.08b	4.300*
NO <sub>3</sub> <sup>-</sup>	mg kg <sup>-1</sup>	38.85 ± 13.96	66.97 ± 21.03	60.70 ± 4.93	38.39 ± 6.42	1.243 ns
Ca	cmol kg <sup>-1</sup>	11.76 ± 0.47	12.25 ± 0.25	12.52 ± 0.4	11.94 ± 0.43	0.711 ns
Mg	cmol kg <sup>-1</sup>	4.68 ± 0.14	4.9 ± 0.07	4.95 ± 0.17	4.76 ± 0.17	0.730 ns
K	cmol kg <sup>-1</sup>	0.28 ± 0.02	0.32 ± 0.02	0.36 ± 0.04	0.29 ± 0.02	1.651 ns
Na	cmol kg <sup>-1</sup>	0.70 ± 0.03	0.75 ± 0.03	0.73 ± 0.03	0.77 ± 0.03	1.103 ns
Fe	mg kg <sup>-1</sup>	0.77 ± 0.06	0.79 ± 0.05	0.80 ± 0.02	0.74 ± 0.02	0.379 ns
Mn	mg kg <sup>-1</sup>	2.60 ± 0.36	3.06 ± 0.42	3.06 ± 0.08	2.75 ± 0.18	0.628 ns
Cu	mg kg <sup>-1</sup>	0.52 ± 0.02	0.50 ± 0.02	0.50 ± 0.01	0.47 ± 0.01	1.732 ns
Zn	mg kg <sup>-1</sup>	1.54 ± 0.23	1.31 ± 0.03	1.33 ± 0.02	1.24 ± 0.03	1.142 ns
P	mg kg <sup>-1</sup>	88.20 ± 3.90	95.53 ± 3.76	93.50 ± 3.83	93.75 ± 5.00	0.580 ns
B	mg kg <sup>-1</sup>	0.87 ± 0.02	0.90 ± 0.05	0.92 ± 0.00	0.89 ± 0.04	0.450 ns

Note: Values mean ± standard error ( $n=4$ ). F100, inorganic fertilizers applied at a rate to meet the crop's nutritional demands; F50, a 50% reduction in the F100 rate; BAI+FU, a 50% reduction in the F100 rate plus the application of a formulation of bacteria and non-mycorrhizal fungi; BAII, a 50% reduction in the F100 rate plus the application of nitrogen-fixing and phosphorus- and potassium-solubilizing bacteria. Values followed by different lowercase letters in the same row indicate significant differences between the four treatments (Duncan's post hoc test); ns, not significant ( $p > .05$ ).

Abbreviations: EC, electrical conductivity; POC, particulate organic carbon; TN, total nitrogen; TOC, total organic carbon.

\* $p < .05$ . \*\* $p < .01$ .

weight. Furthermore, studies by Tahir et al. (2019) and Maslennikova et al. (2023) showed that inoculating potato plants with a consortium of *Bacillus* spp. significantly enhanced plant biomass, tuber number and weight compared with uninoculated controls. PGPB are known to colonize potato roots, enhancing plant growth and tuber quality by solubilizing nutrients, fixing nitrogen, promoting nutrient uptake, producing plant hormones and

providing protection against plant pathogens (Nagrale et al., 2023; Orhan et al., 2006; Vessey, 2003).

## 4.2 | Soil GHG emissions

The CO<sub>2</sub> fluxes exhibit an evident dependence on soil moisture and temperature (Bezyk et al., 2023). It has been

TABLE 4 Copy number per gram of soil of 16S, ITS and functional genes (*amoA*, *nirK*, *ureC*, *nifH*, *cbbL* and *GH7*).

	BAI+FU	BAlI	F50	F100	F ANOVA	Kruskal–Wallis test
<i>amoA</i>	2.35E+06 ± 3.97E+05	2.91E+06 ± 6.06E+05	1.46E+06 ± 5.21E+05	1.37E+06 ± 3.66E+05	2.33 ns	–
<i>ureC</i>	6.16E+05 ± 2.44E+05	1.36E+06 ± 5.52E+05	1.13E+06 ± 3.27E+05	8.86E+05 ± 1.27E+05	0.84 ns	–
<i>nirK</i>	7.27E+06 ± 2.37E+06a	6.16E+06 ± 2.13E+06ab	1.14E+06 ± 3.16E+05b	1.42E+06 ± 1.98E+05b	–	11.49**
<i>cbbL</i>	2.56E+06 ± 5.69E+05a	2.17E+06 ± 4.69E+05ab	9.86E+05 ± 3.34E+05b	1.38E+06 ± 2.25E+05ab	2.91 *	–
GH7	1.39E+05 ± 3.86E+04	2.12E+05 ± 1.20E+05	1.12E+05 ± 3.30E+04	3.58E+04 ± 1.43E+04	1.24 ns	–
<i>nifH</i>	3.62E+06 ± 2.73E+06	5.50E+06 ± 4.11E+06	4.94E+05 ± 2.20E+05	7.67E+05 ± 3.35E+05	0.94 ns	–
ITS	6.85E+06 ± 1.21E+06	8.49E+06 ± 3.89E+06	8.89E+06 ± 4.33E+06	7.98E+06 ± 4.39E+06	0.67 ns	–
16S	4.99E+07 ± 7.79E+06	5.15E+07 ± 8.81E+06	4.08E+07 ± 7.73E+06	3.81E+07 ± 4.75E+06	0.80 ns	–

Note: Values mean ± standard error ( $n=4$ ). F100, inorganic fertilizers applied at a rate to meet the crop's nutritional demands; F50, a 50% reduction in the F100 rate; BAI+FU, a 50% reduction in the F100 rate plus the application of nitrogen-fixing and phosphorus- and potassium-solubilizing bacteria. Values followed by different lowercase letters in the same row indicate significant differences between the four treatments (Duncan's post hoc test, or Dunn's Kruskal–Wallis multiple comparison tests), ns, not significant ( $p > .05$ ). The (–) symbol indicates the test did not proceed.

\*  $p > .05$ . \*\*  $p > .01$ .

previously observed that CO<sub>2</sub> emissions are positively correlated with soil temperature, whilst negative with soil moisture (Ollio et al., 2024; Zornoza et al., 2018), which in our study mostly increased after rainfall episodes. These events could have partially limited the oxygen diffusion between water-filled pore spaces, further limiting aerobic respiration, and ultimately resulting in a decreased CO<sub>2</sub> flux (Fairbairn et al., 2023). During potato growth, the F100 treatment showed the greatest CO<sub>2</sub> emissions compared with other treatments. This is because different fertilizer application methods have a significant impact on soil CO<sub>2</sub> emissions, as reported by Wang, Zhang, et al. (2021). Previous studies have also shown that CO<sub>2</sub> emissions increase after mineral fertilizer application in farmlands (Lamprey et al., 2019; Yan et al., 2021). Furthermore, Gong et al. (2012) suggested that mineral fertilizer application can accelerate the soil organic matter decay by supplying available nutrients and substrates to microbes, which are essential for microbial cell synthesis and activity. When more mineral fertilizers are used, the amount of CO<sub>2</sub> emitted from the soil normally increases; this happens because mineral fertilizers provide nutrients that stimulate the growth of microorganisms, which results in more respiration and more CO<sub>2</sub> being released from soil organic matter mineralization (Chen et al., 2018; Lai et al., 2017). Thus, we hypothesized that if the amount of fertilizer is reduced by half, the amount of soil CO<sub>2</sub> emitted should also decrease, as the microorganisms will have fewer nutrients to consume. Our study confirmed this hypothesis and showed that reducing mineral fertilizer application by 50% resulted in a 25% reduction in CO<sub>2</sub> emissions in F50. Furthermore, the BAI+FU and BAlI treatments, resulted in even greater reductions in CO<sub>2</sub> emissions compared with F100, with decreases of 34% and 42%, respectively. Previous research has highlighted the significant influence of the community composition of soil bacteria in regulating soil CO<sub>2</sub> emissions (Chen, Hao, et al., 2021; Liu et al., 2018; Wang et al., 2022) and that fertilizer inputs, particularly N, can modify microbial taxonomy and shift it toward a population that has similar levels of respiration (Allison et al., 2008; Zeng et al., 2016). According to Nannipieri et al. (2003), there is an important link between microbial activity and microbial diversity. Indeed, one might expect that the addition of microbes will increase soil respiration, for example, because of an increase in biomass. In our case, we observed the opposite trend. The decrease in total CO<sub>2</sub> emissions observed in BAI+FU and BAlI could be attributed to a shift in microbial diversity that results in the establishment of a community that respire less than the community found in F100, where respiration is significantly increased with fertilizer inputs. Some reports are showing that certain bacterial strains can help reduce CO<sub>2</sub> levels in

TABLE 5 Multiple linear regression models for cumulative GHG emissions.

Y	X	m	Partial correlation	$\beta$	$R^2$	$R^2$ adj	F value
Cumulative CO <sub>2</sub> (mg m <sup>-2</sup> )	Constant	-3701.42			0.88	0.83	19.77***
	ITS (copies g <sup>-1</sup> )	-5.773E-6	-0.79	-0.51			
	<i>nifH</i> (copies g <sup>-1</sup> )	-7.32E-6	-0.84	-0.57			
	Crop yield (kg ha <sup>-1</sup> )	-0.01	-0.80	-0.52			
	pH	501.47	0.75	0.45			
Cumulative CH <sub>4</sub> (mg m <sup>-2</sup> )	Constant	-3.42			0.44	0.40	10.74**
	Crop yield (kg ha <sup>-1</sup> )	1.17E-04	0.67	0.67			

\*\* $p < .01$ . \*\*\* $p < .001$ .

the atmosphere by contributing to C sequestration (Han & Lee, 2005; Nie et al., 2015; Thirumalai, 2014). By adding more efficient bacteria that consume C, we can stimulate plant growth (Nie et al., 2015). Examples of such bacteria include those that fix atmospheric CO<sub>2</sub> (Noviana et al., 2024), or convert CO<sub>2</sub> to CaCO<sub>3</sub> (Xiao et al., 2019). BAI+FU had higher values of *cbbL*, a gene present in autotrophic CO<sub>2</sub>-fixing organisms. In fact, by shifting the soil microbial community to autotrophic or facultative autotrophic species that possess the *cbbL* gene, the soil becomes more effective in CO<sub>2</sub> fixation and sequestering organic carbon (Liao et al., 2020; Wang, Xie, et al., 2021).

We observed that the BAI+FU and BAI treatments had higher soil moisture values than F100, throughout the cropping cycle. With this regard, Zheng et al. (2018) reported that the use of PGPB can increase soil water retention because bacteria produce biofilms and mucilage that retain water and change soil porosity, which could explain this finding in our study.

We registered a significant release of N<sub>2</sub>O in the BAI treatment 4 days after the application of the first dose of the PGPB-based product. BAI treatment showed the highest N<sub>2</sub>O emission compared with F50. The observed increase in N<sub>2</sub>O emissions following the first BAI application may be attributed to the activity of nitrifying and denitrifying bacteria, which can elevate N<sub>2</sub>O emissions as a byproduct of these biochemical processes (Ding et al., 2023; Lin et al., 2023). Notably, the BAI treatment involved the application of a bacterial consortium comprising species from the genera *Bacillus*, *Azobacter* and *Pseudomonas*. The latter two genera are known for their ability to perform nitrification and denitrification activities, amongst other processes (Chèneby et al., 2000; Kalkowski & Conrad, 1991; Kim et al., 2005). Previous studies have indicated that nitrous oxide emission rates can be influenced by microbial activity, N availability and high moisture rates (Abbasi & Adams, 2000; Dandie et al., 2008; Lazcano et al., 2021). In fact, the first fertigation application

together with PGPM-based products (in the BAI+FU and BAI treatments), coincided with a major rainfall event, which may have contributed to the increased N<sub>2</sub>O emission in the BAI treatment. Agricultural soil often emits sharp and explosive increases of N<sub>2</sub>O after heavy rains owing to waterlogging (Wang et al., 2017). However, treatment F50, which received half the dose of fertilizer and did not receive PGPM, had significantly lower emissions. This adds to the evidence that microbial activity and N availability are important determinants in influencing N<sub>2</sub>O emission rates (Calvo et al., 2013; Fudjoe et al., 2023; Snyder et al., 2009). However, in this system, N<sub>2</sub>O emissions were minimal, with values close to 0 mg m<sup>-2</sup> h<sup>-1</sup>. The results are consistent with prior studies conducted in the same location, associated with an adjusted N fertilizer application rate (Ollio et al., 2024; Sánchez-Navarro et al., 2022; Zornoza et al., 2018). CH<sub>4</sub> emissions are generated by variations between CH<sub>4</sub> production and oxidation. The former is more temperature-dependent than the latter (Li et al., 2023). However, we recorded an increase in CH<sub>4</sub> emission, which was similar across all treatments, following an important rainfall event, on the same date as we observed a significantly high N<sub>2</sub>O emission in BAI. This provides additional evidence that, as a result of the intense precipitation, anoxic conditions were developed in the soil, resulting in predominantly anaerobic activities performed by microorganisms (Hou et al., 2000; Khalil & Baggs, 2005; Xu et al., 2004). Methane emissions are in line with previous investigations that have monitored emissions in semi-arid Mediterranean soils (Fernández-Ortega et al., 2024; Tellez-Rio et al., 2015).

Our data confirmed a significant reduction in soil cumulative CO<sub>2</sub> emissions and the cumulative CO<sub>2</sub> equivalent associated with the use of biofertilizers. These findings align with previous studies that have highlighted the remarkable potential of inoculation of beneficial microorganisms to decrease GHG emissions from soils (Galindo et al., 2024; Nie et al., 2015).

### 4.3 | Soil fertility and functionality

We found a significantly higher EC and lower pH in the soil where plants were grown with the BAII treatment in comparison with the F100 treatment. This is aligned with previous research that have employed PGPB and explain how bacterial colonization in soil decreases pH as a result of their organic acid production as a secondary metabolite (Orhan et al., 2006; Turan et al., 2006), which is essential to increase nutrient availability in basic soils (Abbaszadeh-Dahaji et al., 2020; Ipek & Esitken, 2017). A decrease in soil pH leads to the breakdown of phosphorus and potassium, increasing available nutrients in the rhizosphere and raising the EC value (Li et al., 2020). A more efficient uptake of nutrients by plants can elucidate the strong correlation observed between the effectiveness of biofertilizers and the response in crop yields (Li et al., 2022). Thus, in the BAII treatment, the higher EC may indicate an increase in soluble nutrients resulting from microbial activity. In addition, we found higher  $\text{NH}_4^+$  levels in BAI+FU. Thus, microbial populations in this soil may be related to higher  $\text{NH}_4^+$  production, by active ammonification (Arce et al., 2015) or by N fixation, an important feature in some bacteria such as *Rhizobium* spp. or *Azotobacter* spp. (Strock, 2008). According to various authors, PGPB's production of  $\text{NH}_4^+$  is crucial for plant growth promotion, as it supplies N to host plants, promoting root and shoot elongation and increasing their biomass (Bhattacharyya et al., 2020; Hyder et al., 2020).

Higher abundances of the *nirK* and the *cbbL* genes in soils that received microorganism-based products, mostly for those receiving bacteria and fungi. The *nirK* gene (encoding copper nitrite reductase) is part of a biochemical pathway called denitrification, which consists of four reaction steps that reduce nitrate to dinitrogen gas (Henry et al., 2006). This gene is critical because it inhibits the accumulation of NO, a cytotoxic byproduct of the denitrification pathway (Giles et al., 2012). Denitrification can either produce  $\text{N}_2\text{O}$  or generate  $\text{N}_2$ , depending on the environmental conditions, the composition and the genetic capabilities of the denitrifying microbial community (via nitrous oxide reductase) (Hagemann et al., 2016). High nitrite reductase activity could suggest a higher potential for producing  $\text{N}_2\text{O}$ , an intermediate in the denitrification process. The process can be stopped at this point or continue until  $\text{N}_2$  is produced (Pinto et al., 2021). Our study did not investigate genes involved in the final stage of denitrification. However, cumulative  $\text{N}_2\text{O}$  emission was not increased in soils treated with biofertilizers, with no significant difference between the four treatments. According to recent studies, several bacterial strains of *Bacillus* and *Pseudomonas*, which are included in the biofertilizers used in this experiment, are denitrifying organisms capable of

reducing nitrate or nitrite whilst producing nitrous oxide or molecular nitrogen (Chen et al., 2018). So, it was expected that the treatments to which microorganisms have been added had a higher denitrification activity. There is general agreement that the primary factor influencing denitrification in soils, especially in cultivated soils, is C availability (Florio et al., 2019). Potato plants may provide root exudates which can serve as C sources for fungi and bacteria (Dandie et al., 2008). Microorganisms inoculation could increase the soil's ability to act as an  $\text{N}_2\text{O}$  sink in soils where denitrifiers are not severely limited by C (Chen et al., 2018; Florio et al., 2019). Thus, we may assume that BAI+FU may be contributing to decreasing the availability of mobile nitrates that may be leached after rainfall. As reported by other authors, PGPB helps reduce N loss through leaching by decreasing the loss of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  (Gallart et al., 2021; Paungfoo-Lonhienne et al., 2019). According to these authors, PGPB can enhance N acquisition and assimilation by plants owing to their growth-promoting effect, which increases the plant absorption of nutrients.

The increased abundance of the *cbbL* gene in BAI+FU and BAII, one of the key functional genes involved in the biochemical pathways of autotrophic C fixation in bacteria (RuBisCO) (Yousuf et al., 2012), may suggest that the introduction of microorganisms into the soil significantly increased  $\text{CO}_2$  fixation, and thus C availability for other biochemical processes.

The abundance of fungi and archaea/bacteria was similar regardless of the fertilizer application strategy. The literature presents conflicting evidence regarding the impact of various fertilizer application regimes on soil fungal and bacterial abundances (Dong et al., 2014). For instance, Tian et al. (2015) reported no significant changes in bacterial abundance after 3 years of chemical fertilizer application compared with an unfertilized control, a result aligned with He et al. (2007), which reported that nitrogen fertilizer application did not affect total bacterial abundance in a wheat–maize rotation system. Similarly, Gallart et al. (2021) found no significant differences in 16S rRNA gene copy numbers when evaluating different nitrogen fertilizer sources, with or without PGPB inoculation, on macadamia tree growth. Yaghoubi Khanghahi et al. (2022) confirmed no variation in 16S rRNA abundance under various stress conditions and fertilizer application management in a wheat–legume rotation. Conversely, some studies, such as that by Chen, Hao, et al. (2021), demonstrated that inoculating maize crops with different PGPB strains significantly increased 16S rRNA gene copy numbers compared with the non-inoculated control.

Also, Wang, Xue, et al. (2016) and Wang, Zhang, et al. (2016) showed how bacterial abundance is not constant and may or not vary significantly depending on

different conditions such as fertilizer application regime, depth, seasonality or plant growth stage. Similarly, there are contradictory results in the literature concerning fungal abundance at different fertilizer application treatments. For instance, Bei et al. (2018) showed that fungal abundance did not change when comparing inorganic fertilizers alone or combined with other amendments in a summer maize and winter wheat rotation. Contrarily, Shen et al. (2013) showed significant differences in the abundance of fungi when different fertilizer application regimes and amendments, including a bioorganic fertilizer based on *Trichoderma* spp., were applied to a banana monoculture.

#### 4.4 | Interrelationship between crop yield, GHG emissions, soil characteristics and microbial activity

The linear regression analysis demonstrated a reverse relation between CO<sub>2</sub> emissions and the abundance of ITS and *nifH* genes. Soil bacteria and fungi are integral to carbon and nutrient cycling, aiding in the fixation of atmospheric N<sub>2</sub> and CO<sub>2</sub> and contributing to carbon sequestration. For example, fungal endophytes may enhance plant photosynthesis by modulating CO<sub>2</sub> concentrations within plant tissues (Suryanarayanan et al., 2022). Additionally, processes such as sclerotia formation, fungal melanin production and soil aggregate formation play a significant role in the long-term storage and stabilization of carbon in soils (Husain et al., 2024; Mason et al., 2023). Biological N fixation, performed by diazotrophs is a key aspect of the terrestrial N cycle (Sepp et al., 2023). The observed negative correlation between the *nifH* gene and cumulative CO<sub>2</sub> emissions and suggests that increased biological nitrogen fixation enhances carbon use efficiency, thereby reducing CO<sub>2</sub> emissions (Ollio et al., 2024). This may occur because diazotrophs require substantial soil carbon and energy to produce bioavailable nitrogen, which in turn reduces microbial processes that generate CO<sub>2</sub> (Tang et al., 2019).

On the contrary, as noted by Wang et al. (2017), N fertilizer application can suppress the abundance of N-fixing bacteria, as excess bioavailable N such as solubilized NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> can inhibit biological N fixation without necessarily impacting the abundance of the diazotrophic population (Cheng et al., 2023; Ramond et al., 2022). This implies that whilst fertilizer application may increase microbial abundance and respiration, it can simultaneously reduce nitrogen fixation.

The analysis also identified a positive correlation between cumulative CO<sub>2</sub> emissions and soil pH, aligning

with previous findings that indicate higher soil pH and nitrogen fertilizer application contribute to increased CO<sub>2</sub> emissions, primarily driven by heterotrophic microbial respiration (Sauze et al., 2017; Wang et al., 2010). Finally, the negative correlation between cumulative CO<sub>2</sub> emissions and crop yield suggests that systems with higher carbon use efficiency, and consequently lower soil organic matter mineralization, tend to have higher productivity. This is likely because of a more efficient microbial community (Manzoni et al., 2012).

## 5 | CONCLUSION

This study investigated the synergistic effects of using biofertilizers based on PGPMs alongside reduced doses of conventional chemical fertilizers in potato cultivation. Various aspects such as crop yield and quality, soil fertility dynamics, soil functionality and GHG emissions were examined. The study confirmed that incorporating PGPM into the soil significantly enhances potato quality by increasing tuber weight and firmness whilst reducing CO<sub>2</sub> emissions during the growing season. The biofertilizers employed also induced changes in soil properties, including an increase in electrical conductivity and a decrease in pH. These alterations suggest a heightened microbial activity, leading to enhanced production of organic acids and increased solubilization of nutrients, compared with conventional fertilizer application methods. Higher NH<sub>4</sub><sup>+</sup> production in the soil with the biofertilizer treatment indicated increased ammonification or nitrogen fixation activity, which is crucial for plant growth. Increased functional gene abundance related to carbon and nitrogen cycles suggested improved soil functionality.

These findings support prior research, highlighting the benefits of inoculating beneficial bacteria and fungi to combat climate change impacts. Incorporating biofertilizers into agricultural practices can enhance crop productivity and quality, reducing the reliance on chemical fertilizers and mitigating their environmental impacts. However, further research is necessary to fully understand how PGPMs impact indigenous soil microbial communities and to determine the exact mechanisms through which they improve soil fertility, reduce GHG emissions and promote crop yield and quality.

## ACKNOWLEDGEMENTS

This work was supported by the European Commission Horizon 2020 project Soil Biodiversity Enhancement in European Agroecosystems to promote their stability and resilience through external inputs reduction and crop performance increase (grant agreement 817819).

## DATA AVAILABILITY STATEMENT

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

## ORCID

Irene Ollio  <https://orcid.org/0000-0002-6952-1141>

## REFERENCES

- Abbasi, M. K., & Adams, W. A. (2000). Gaseous N emission during simultaneous nitrification–denitrification associated with mineral N fertilization to a grassland soil under field conditions. *Soil Biology and Biochemistry*, *32*, 1251–1259. [https://doi.org/10.1016/S0038-0717\(00\)00042-0](https://doi.org/10.1016/S0038-0717(00)00042-0)
- Abbaszadeh-Dahaji, P., Masalehi, F., & Akhgar, A. (2020). Improved growth and nutrition of sorghum (*Sorghum bicolor*) plants in a low-fertility calcareous soil treated with plant growth-promoting rhizobacteria and Fe-EDTA. *Journal of Soil Science and Plant Nutrition*, *20*, 31–42. <https://doi.org/10.1007/s42729-019-00098-9>
- Abdeldaym, E. A., El-Sawy, M. B. I., & El-Helaly, M. A. (2019). Combined application of different sources of nitrogen fertilizers for improvement of potato yield and quality. *Plant Archives*, *19*, 9725210.
- Abou El-Yazied, A., & Selim, S. (2007). Effect of reducing n, p mineral fertilization levels combined with biofertilizer on growth, yield and tuber quality of potato plants. *Journal of Plant Production*, *32*, 2957–2982. <https://doi.org/10.21608/jpp.2007.207697>
- Adesemoye, A. O., & Kloepper, J. W. (2009). Plant–microbes interactions in enhanced fertilizer-use efficiency. *Applied Microbiology and Biotechnology*, *85*, 1–12. <https://doi.org/10.1007/s00253-009-2196-0>
- Adesemoye, A. O., Torbert, H. A., & Kloepper, J. W. (2009). Plant growth-promoting rhizobacteria allow reduced application rates of chemical fertilizers. *Microbial Ecology*, *58*, 921–929. <https://doi.org/10.1007/s00248-009-9531-y>
- Ali, A. M., Awad, M. Y. M., Hegab, S. A., Gawad, A. M. A. E., & Eissa, M. A. (2021). Effect of potassium solubilizing bacteria (*Bacillus cereus*) on growth and yield of potato. *Journal of Plant Nutrition*, *44*, 411–420. <https://doi.org/10.1080/01904167.2020.1822399>
- Allison, S. D., Czimczik, C. I., & Treseder, K. K. (2008). Microbial activity and soil respiration under nitrogen addition in Alaskan boreal forest. *Global Change Biology*, *14*, 1156–1168. <https://doi.org/10.1111/j.1365-2486.2008.01549.x>
- Arce, M. I., del Sánchez-Montoya, M., & Gómez, R. (2015). Nitrogen processing following experimental sediment rewetting in isolated pools in an agricultural stream of a semiarid region. *Ecological Engineering*, *77*, 233–241. <https://doi.org/10.1016/j.ecoleng.2015.01.035>
- Basu, A., Prasad, P., Das, S. N., Kalam, S., Sayyed, R. Z., Reddy, M. S., & El Enshasy, H. (2021). Plant growth promoting rhizobacteria (PGPR) as green bioinoculants: Recent developments, constraints, and prospects. *Sustainability*, *13*, 1140. <https://doi.org/10.3390/su13031140>
- Bei, S., Zhang, Y., Li, T., Christie, P., Li, X., & Zhang, J. (2018). Response of the soil microbial community to different fertilizer inputs in a wheat-maize rotation on a calcareous soil. *Agriculture, Ecosystems and Environment*, *260*, 58–69. <https://doi.org/10.1016/j.agee.2018.03.014>
- Bennetzen, E. H., Smith, P., & Porter, J. R. (2016). Agricultural production and greenhouse gas emissions from world regions—The major trends over 40 years. *Global Environmental Change*, *37*, 43–55. <https://doi.org/10.1016/j.gloenvcha.2015.12.004>
- Bezyk, Y., Dorodnikov, M., Górka, M., Sówka, I., & Sawiński, T. (2023). La temperatura e l'umidità del suolo controllano il flusso di CO<sub>2</sub> e l'ossidazione di CH<sub>4</sub> negli ecosistemi urbani. *Geochemistry*, *83*, 125989. <https://doi.org/10.1016/j.chemer.2023.125989>
- Bhattacharyya, C., Banerjee, S., Acharya, U., Mitra, A., Mallick, I., Haldar, A., Haldar, S., Ghosh, A., & Ghosh, A. (2020). Evaluation of plant growth promotion properties and induction of antioxidative defense mechanism by tea rhizobacteria of Darjeeling, India. *Scientific Reports*, *10*, 15536. <https://doi.org/10.1038/s41598-020-72439-z>
- Bista, B., & Bhandari, D. (2019). Potassium fertilization in potato. *International Journal of Applied Sciences and Biotechnology*, *7*, 153–160. <https://doi.org/10.3126/ijasbt.v7i2.24636>
- Brezmes Llecha, J., Correig, I., Blanchar, X., & Junyent Giralt, G. (2001). *Diseño de una nariz electrónica para la determinación no destructiva del grado de la maduración de la fruta*. Universitat Politècnica de Catalunya. <https://doi.org/10.5821/dissertati-on-2117-94188>
- Calvo, P., Nelson, L., & Kloepper, J. W. (2014). Agricultural uses of plant biostimulants. *Plant and Soil*, *383*, 3–41. <https://doi.org/10.1007/s11104-014-2131-8>
- Calvo, P., Watts, D. B., Ames, R. N., Kloepper, J. W., & Torbert, H. A. (2013). Microbial-based inoculants impact nitrous oxide emissions from an incubated soil medium containing urea fertilizers. *Journal of Environmental Quality*, *42*, 704–712. <https://doi.org/10.2134/jeq2012.0300>
- Cambardella, C. A., & Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, *56*, 777–783. <https://doi.org/10.2136/sssaj1992.03615995005600030017x>
- Chen, J., Shen, W., Xu, H., Li, Y., & Luo, T. (2019). The composition of nitrogen-fixing microorganisms correlates with soil nitrogen content during reforestation: A comparison between legume and non-legume plantations. *Frontiers in Microbiology*, *10*, 508. <https://doi.org/10.3389/fmicb.2019.00508>
- Chen, L., Hao, Z., Li, K., Sha, Y., Wang, E., Sui, X., Mi, G., Tian, C., & Chen, W. (2021). Effects of growth-promoting rhizobacteria on maize growth and rhizosphere microbial community under conservation tillage in Northeast China. *Microbial Biotechnology*, *14*, 535–550. <https://doi.org/10.1111/1751-7915.13693>
- Chen, S., Wang, F., Zhang, Y., Qin, S., Wei, S., Wang, S., Hu, C., & Liu, B. (2018). Organic carbon availability limiting microbial denitrification in the deep vadose zone. *Environmental Microbiology*, *20*, 980–992. <https://doi.org/10.1111/1462-2920.14027>
- Chèneby, D., Philippot, L., Hartmann, A., Hénault, C., & Germon, J.-C. (2000). 16S rDNA analysis for characterization of denitrifying bacteria isolated from three agricultural soils. *FEMS Microbiology Ecology*, *34*, 121–128. <https://doi.org/10.1111/j.1574-6941.2000.tb00761.x>

- Cheng, Z., Meng, L., Yin, T., Li, Y., Zhang, Y., & Li, S. (2023). Changes in soil rhizobia diversity and their effects on the symbiotic efficiency of soybean intercropped with maize. *Agronomy*, *13*, 997. <https://doi.org/10.3390/agronomy13040997>
- Council of the European Union. (2020). *The member states of the European Union*. Publications Office, LU.
- Cuartero, J., Özbolat, O., Sánchez-Navarro, V., Weiss, J., Zornoza, R., Pascual, J. A., Vivo, J.-M., & Ros, M. (2022). Long-term compost amendment changes interactions and specialization in the soil bacterial community, increasing the presence of beneficial N-cycling genes in the soil. *Agronomy*, *12*, 316. <https://doi.org/10.3390/agronomy12020316>
- Dandie, C. E., Burton, D. L., Zebarth, B. J., Henderson, S. L., Trevors, J. T., & Goyer, C. (2008). Changes in bacterial denitrifier community abundance over time in an agricultural field and their relationship with denitrification activity. *Applied and Environmental Microbiology*, *74*, 5997–6005. <https://doi.org/10.1128/AEM.00441-08>
- Di Benedetto, N. A., Corbo, M. R., Campaniello, D., Cataldi, M. P., Bevilacqua, A., Sinigaglia, M., & Flagella, Z. (2017). The role of plant growth promoting bacteria in improving nitrogen use efficiency for sustainable crop production: A focus on wheat. *AIMS Microbiology*, *3*, 413–434. <https://doi.org/10.3934/microbiol.2017.3.413>
- Ding, Y., Li, C., Li, Z., Liu, S., Zou, Y., Gao, X., Cai, Y., Siddique, K. H. M., Wu, P., & Zhao, X. (2023). Greenhouse gas emission responses to different soil amendments on the loess plateau, China. *Agriculture, Ecosystems & Environment*, *342*, 108233. <https://doi.org/10.1016/j.agee.2022.108233>
- Dong, W.-Y., Zhang, X.-Y., Dai, X.-Q., Fu, X.-L., Yang, F.-T., Liu, X.-Y., Sun, X.-M., Wen, X.-F., & Schaeffer, S. (2014). Changes in soil microbial community composition in response to fertilization of paddy soils in subtropical China. *Applied Soil Ecology*, *84*, 140–147. <https://doi.org/10.1016/j.apsoil.2014.06.007>
- Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., & Tanabe, K. (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies.
- El-Saadony, M. T., Saad, A. M., Soliman, S. M., Salem, H. M., Ahmed, A. I., Mahmood, M., El-Tahan, A. M., Ebrahim, A. A. M., Abd El-Mageed, T. A., Negm, S. H., Selim, S., Babalghith, A. O., Elrys, A. S., El-Tarabily, K. A., & AbuQamar, S. F. (2022). Plant growth-promoting microorganisms as biocontrol agents of plant diseases: Mechanisms, challenges and future perspectives. *Frontiers in Plant Science*, *13*, 923880.
- European Commission, Directorate General for Climate Action, Trinomics. (2023). *Pricing agricultural emissions and rewarding climate action in the agri-food value chain*. Publications Office, LU.
- Fairbairn, L., Rezanezhad, F., Gharasoo, M., Parsons, C. T., Macrae, M. L., Slowinski, S., & Van Cappellen, P. (2023). Relationship between soil CO<sub>2</sub> fluxes and soil moisture: Anaerobic sources explain fluxes at high water content. *Geoderma*, *434*, 116493. <https://doi.org/10.1016/j.geoderma.2023.116493>
- FAO. (2023). *World food and agriculture—Statistical yearbook 2023, FAO statistical yearbook—World food and agriculture*. FAO. <https://doi.org/10.4060/cc8166en>
- Fernández-Ortega, J., Álvaro-Fuentes, J., & Cantero-Martínez, C. (2024). Double-cropping, tillage and nitrogen fertilization effects on soil CO<sub>2</sub> and CH<sub>4</sub> emissions. *Agriculture, Ecosystems and Environment*, *359*, 108758. <https://doi.org/10.1016/j.agee.2023.108758>
- Florio, A., Bréfort, C., Gervais, J., Bérard, A., & Le Roux, X. (2019). The responses of NO<sub>2</sub><sup>-</sup> and N<sub>2</sub>O-reducing bacteria to maize inoculation by the PGPR *Azospirillum lipoferum* CRT1 depend on carbon availability and determine soil gross and net N<sub>2</sub>O production. *Soil Biology and Biochemistry*, *136*, 107524. <https://doi.org/10.1016/j.soilbio.2019.107524>
- Fraç, M., Hannula, S. E., Belka, M., & Jędryczka, M. (2018). Fungal biodiversity and their role in soil health. *Frontiers in Microbiology*, *9*, 707. <https://doi.org/10.3389/fmicb.2018.00707>
- Fudjoe, S. K., Li, L., Anwar, S., Shi, S., Xie, J., Wang, L., Xie, L., & Yongjie, Z. (2023). Nitrogen fertilization promoted microbial growth and N<sub>2</sub>O emissions by increasing the abundance of nirS and nosZ denitrifiers in semiarid maize field. *Frontiers in Microbiology*, *14*, 1265562. <https://doi.org/10.3389/fmicb.2023.1265562>
- Galindo, F. S., Pagliari, P. H., da Silva, E. C., de Lima, B. H., Fernandes, G. C., Thiengo, C. C., Bernardes, J. V. S., Jalal, A., Oliveira, C. E. S., de Sousa Vilela, L., Furlani Junior, E., Nogueira, T. A. R., do Nascimento, V., Teixeira Filho, M. C. M., & Lavres, J. (2024). Impact of nitrogen fertilizer sustainability on corn crop yield: The role of beneficial microbial inoculation interactions. *BMC Plant Biology*, *24*, 268. <https://doi.org/10.1186/s12870-024-04971-3>
- Gallart, M., Paungfoo-Lonhienne, C., Gonzalez, A., & Trueman, S. J. (2021). Nitrogen source influences the effect of plant growth-promoting rhizobacteria (PGPR) on *Macadamia integrifolia*. *Agronomy*, *11*, 1064. <https://doi.org/10.3390/agronomy11061064>
- Giles, M., Morley, N., Baggs, E. M., & Daniell, T. J. (2012). Soil nitrate reducing processes—Drivers, mechanisms for spatial variation, and significance for nitrous oxide production. *Frontiers in Microbiology*, *3*, 407. <https://doi.org/10.3389/fmicb.2012.00407>
- Glasbey, C. A., McRAE, D. C., & Fleming, J. (1988). The size distribution of potato tubers and its application to grading schemes. *The Annals of Applied Biology*, *113*, 579–587. <https://doi.org/10.1111/j.1744-7348.1988.tb03335.x>
- Gnanamanickam, S. S. (2007). *Plant-associated bacteria*. Springer Science & Business Media.
- Gong, W., Yan, X., & Wang, J. (2012). The effect of chemical fertilizer on soil organic carbon renewal and CO<sub>2</sub> emission—A pot experiment with maize. *Plant and Soil*, *353*, 85–94. <https://doi.org/10.1007/s11104-011-1011-8>
- Gupta, G., Parihar, S., Ahirwar, N., Snehi, S. K., & Singh, V. (2015). Plant growth promoting rhizobacteria (PGPR): Current and future prospects for development of sustainable agriculture. *Journal of Microbial and Biochemical Technology*, *7*, 96–102.
- Hagemann, N., Harter, J., & Behrens, S. (2016). Chapter 7—Elucidating the impacts of biochar applications on nitrogen cycling microbial communities. In T. K. H. Ralebitso-Senior & C. Orr (Eds.), *Biochar application* (pp. 163–198). Elsevier. <https://doi.org/10.1016/B978-0-12-803433-0.00007-2>
- Han, H. S., & Lee, K. D. (2005). Phosphate and potassium solubilizing bacteria effect on mineral uptake, soil availability and growth of eggplant. *Research Journal of Agriculture and Biological Sciences*, *1*, 176–180.
- He, J., Shen, J., Zhang, L., Zhu, Y., Zheng, Y., Xu, M., & Di, H. (2007). Quantitative analyses of the abundance and composition of ammonia-oxidizing bacteria and ammonia-oxidizing archaea of a Chinese upland red soil under long-term fertilization practices. *Environmental Microbiology*, *9*, 2364–2374. <https://doi.org/10.1111/j.1462-2920.2007.01358.x>

- Helsel, Z. R. (1992). Energy and alternatives for fertilizer and pesticide use. *Energy in Farm Production*, 6, 177–201.
- Henry, S., Bru, D., Stres, B., Hallet, S., & Philippot, L. (2006). Quantitative detection of the nosZ gene, encoding nitrous oxide reductase, and comparison of the abundances of 16S rRNA, narG, nirK, and nosZ genes in soils. *Applied and Environmental Microbiology*, 72, 5181–5189. <https://doi.org/10.1128/AEM.00231-06>
- Hopkins, B. G., Horneck, D. A., & MacGuidwin, A. E. (2014). Improving phosphorus use efficiency through potato rhizosphere modification and extension. *American Journal of Potato Research*, 91, 161–174. <https://doi.org/10.1007/s12230-014-9370-3>
- Hopkins, B. G., Rosen, C. J., Shiffler, A. K., & Taysom, T. W. (2008). Enhanced efficiency fertilizers for improved nutrient management: Potato (*Solanum tuberosum*). *Crop Management*, 7, 1–16. <https://doi.org/10.1094/CM-2008-0317-01-RV>
- Horowitz, J. K., & Gottlieb, J. (2010). *The role of agriculture in reducing greenhouse gas emissions*. US Department of Agriculture, Economic Research Service. <https://doi.org/10.22004/AG.ECON.138910>
- Hossain, M. M., Sultana, F., & Islam, S. (2017). Plant growth-promoting fungi (PGPF): Phytostimulation and induced systemic resistance. In D. P. Singh, H. B. Singh, & R. Prabha (Eds.), *Plant-microbe interactions in agro-ecological perspectives: Volume 2: Microbial interactions and agro-ecological impacts* (pp. 135–191). Springer. [https://doi.org/10.1007/978-981-10-6593-4\\_6](https://doi.org/10.1007/978-981-10-6593-4_6)
- Hou, A. X., Chen, G. X., Wang, Z. P., Van Cleemput, O., & Patrick, W. H., Jr. (2000). Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. *Soil Science Society of America Journal*, 64, 2180–2186. <https://doi.org/10.2136/sssaj2000.6462180x>
- Husain, H., Keitel, C., & Dijkstra, F. A. (2024). Fungi are more important than bacteria for soil carbon loss through priming effects and carbon protection through aggregation. *Applied Soil Ecology*, 195, 105245. <https://doi.org/10.1016/j.apsoil.2023.105245>
- Hyder, S., Gondal, A. S., Rizvi, Z. F., Ahmad, R., Alam, M. M., Hannan, A., Ahmed, W., Fatima, N., & Inam-ul-Haq, M. (2020). Characterization of native plant growth promoting rhizobacteria and their anti-oomycete potential against phytophthora capsici affecting chilli pepper (*Capsicum annum* L.). *Scientific Reports*, 10, 13859. <https://doi.org/10.1038/s41598-020-69410-3>
- Imran, M., Abulreesh, H. H., Monjed, M. K., Elbanna, K., Samreen, & Ahmad, I. (2021). Multifarious functional traits of free-living rhizospheric fungi, with special reference to *Aspergillus* spp. isolated from north Indian soil, and their inoculation effect on plant growth. *Annales de Microbiologie*, 71, 31. <https://doi.org/10.1186/s13213-021-01643-7>
- Ipek, M., & Esitken, A. (2017). The actions of PGPR on micronutrient availability in soil and plant under calcareous soil conditions: An evaluation over Fe nutrition. In *Plant-microbe interactions in agro-ecological perspectives* (pp. 81–100). Springer Singapore. [https://doi.org/10.1007/978-981-10-6593-4\\_4](https://doi.org/10.1007/978-981-10-6593-4_4)
- IUSS Working Group WRB (2022). *World reference base for soil resources*. In International soil classification system for naming soils and creating legends for soil maps (4th, ed.). International Union of Soil Sciences (IUSS).
- Jaiswal, D. K., Verma, J. P., Prakash, S., Meena, V. S., & Meena, R. S. (2016). Potassium as an important plant nutrient in sustainable agriculture: A state of the art. In V. S. Meena, B. R. Maurya, J. P. Verma, & R. S. Meena (Eds.), *Potassium solubilizing microorganisms for sustainable agriculture* (pp. 21–29). Springer India. [https://doi.org/10.1007/978-81-322-2776-2\\_2](https://doi.org/10.1007/978-81-322-2776-2_2)
- Kabata-Pendias, A. (2000). *Trace elements in soils and plants*. CRC Press.
- Kalkowski, I., & Conrad, R. (1991). Metabolism of nitric oxide in denitrifying *Pseudomonas aeruginosa* and nitrate-respiring *Bacillus cereus*. *FEMS Microbiology Letters*, 82, 107–112. <https://doi.org/10.1111/j.1574-6968.1991.tb04848.x>
- Kandeler, E., & Gerber, H. (1988). Short-term assay of soil urease activity using colorimetric determination of ammonium. *Biology and Fertility of Soils*, 6, 68–72. <https://doi.org/10.1007/BF00257924>
- Keeney, D. R., & Nelson, D. W. (1983). Nitrogen—Inorganic forms. In *Methods of soil analysis* (pp. 643–698). John Wiley & Sons, Ltd. <https://doi.org/10.2134/agronmonogr9.2.2ed.c33>
- Khalil, M. I., & Baggs, E. M. (2005). Ossidazione di CH<sub>4</sub> ed emissioni di N<sub>2</sub>O a varie concentrazioni di CH<sub>4</sub> e spazi di testa pieni d'acqua nel suolo. *Soil Biology and Biochemistry*, 37, 1785–1794. <https://doi.org/10.1016/j.soilbio.2005.02.012>
- Khan, A. A., Jilani, G., Akhtar, M. S., Saqlan, S. M., & Rasheed, M. (2009). Phosphorus solubilizing bacteria: Occurrence, mechanisms and their role in crop production. *Journal of Agricultural and Biological Science*, 1, 48–58.
- Kim, J. K., Park, K. J., Cho, K. S., Nam, S.-W., Park, T.-J., & Bajpai, R. (2005). Nitrificazione-denitrificazione aerobica da parte di ceppi eterotrofi di *Bacillus*. *Bioresource Technology*, 96, 1897–1906. <https://doi.org/10.1016/j.biortech.2005.01.040>
- Kumar, R., Bordoloi, N., Kumar, R., & Bordoloi, N. (2024). Agriculture's contribution to the emission of greenhouse gas nitrous oxide (N<sub>2</sub>O) and its feasible mitigation strategies. In *Climate smart greenhouses—Innovations and impacts*. IntechOpen. <https://doi.org/10.5772/intechopen.113021>
- Lai, R., Arca, P., Lagomarsino, A., Cappai, C., Seddaiu, G., Demurtas, C. E., & Roggero, P. P. (2017). La fertilizzazione con letame aumenta la respirazione del suolo e crea un bilancio negativo del carbonio in un sistema di coltivazione basato sul mais mediterraneo (*Zea mays* L.). *Catena*, 151, 202–212. <https://doi.org/10.1016/j.catena.2016.12.013>
- Lampety, S., Xie, J., Li, L., Coulter, J. A., & Jagadabhi, P. S. (2019). Influence of organic amendment on soil respiration and maize productivity in a semi-arid environment. *Agronomy*, 9, 611. <https://doi.org/10.3390/agronomy9100611>
- Lazcano, C., Zhu-Barker, X., & Decock, C. (2021). Effects of organic fertilizers on the soil microorganisms responsible for N<sub>2</sub>O emissions: A review. *Microorganisms*, 9, 983. <https://doi.org/10.3390/microorganisms9050983>
- Levy-Booth, D. J., Prescott, C. E., & Grayston, S. J. (2014). Microbial functional genes involved in nitrogen fixation, nitrification and denitrification in forest ecosystems. *Soil Biology and Biochemistry*, 75, 11–25. <https://doi.org/10.1016/j.soilbio.2014.03.021>
- Li, H., Qiu, Y., Yao, T., Ma, Y., Zhang, H., & Yang, X. (2020). Effects of PGPR microbial inoculants on the growth and soil properties of *Avena sativa*, *Medicago sativa*, and *Cucumis sativus* seedlings. *Soil and Tillage Research*, 199, 104577. <https://doi.org/10.1016/j.still.2020.104577>
- Li, J., Pei, J., Fang, C., Li, B., & Nie, M. (2023). Opposing seasonal temperature dependencies of CO<sub>2</sub> and CH<sub>4</sub> emissions from

- wetlands. *Global Change Biology*, 29, 1133–1143. <https://doi.org/10.1111/gcb.16528>
- Li, J., Van Gerrewey, T., & Geelen, D. (2022). A meta-analysis of bio-stimulant yield effectiveness in field trials. *Frontiers in Plant Science*, 13, 836702. <https://doi.org/10.3389/fpls.2022.836702>
- Liao, H., Qin, F., Wang, K., Zhang, Y., Hao, X., Chen, W., & Huang, Q. (2020). Long-term chemical fertilization-driving changes in soil autotrophic microbial community depresses soil CO<sub>2</sub> fixation in a Mollisol. *Science of the Total Environment*, 748, 141317. <https://doi.org/10.1016/j.scitotenv.2020.141317>
- Lin, J., Xu, Z., Xue, Y., Sun, R., Yang, R., Cao, X., Li, H., Shao, Q., Lou, Y., Wang, H., Yang, Q., Pan, H., & Zhuge, Y. (2023). Le emissioni di N<sub>2</sub>O provenienti da suoli sottoposti a ritorno di paglia a breve termine in un sistema di rotazione grano-mais sono associate a cambiamenti nell'abbondanza di microbi funzionali. *Agriculture, Ecosystems and Environment*, 341, 108217. <https://doi.org/10.1016/j.agee.2022.108217>
- Liu, Y.-R., Delgado-Baquerizo, M., Wang, J.-T., Hu, H.-W., Yang, Z., & He, J.-Z. (2018). New insights into the role of microbial community composition in driving soil respiration rates. *Soil Biology and Biochemistry*, 118, 35–41. <https://doi.org/10.1016/j.soilbio.2017.12.003>
- Manzoni, S., Taylor, P., Richter, A., Porporato, A., & Ågren, G. I. (2012). Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. *The New Phytologist*, 196, 79–91. <https://doi.org/10.1111/j.1469-8137.2012.04225.x>
- Maslennikova, V. S., Tsvetkova, V. P., Shelikhova, E. V., Selyuk, M. P., Alikina, T. Y., Kabilov, M. R., & Dubovskiy, I. M. (2023). *Bacillus subtilis* and *Bacillus amyloliquefaciens* mix suppresses Rhizoctonia disease and improves rhizosphere microbiome, growth and yield of potato (*Solanum tuberosum* L.). *Journal of Fungi*, 9, 1142. <https://doi.org/10.3390/jof9121142>
- Mason, A. R. G., Salomon, M. J., Lowe, A. J., & Cavagnaro, T. R. (2023). Microbial solutions to soil carbon sequestration. *Journal of Cleaner Production*, 417, 137993. <https://doi.org/10.1016/j.jclepro.2023.137993>
- Mielcarek-Bocheńska, P., & Rzeźnik, W. (2021). Greenhouse gas emissions from agriculture in EU countries—State and perspectives. *Atmosphere*, 12, 1396. <https://doi.org/10.3390/atmos12111396>
- Nagrle, D. T., Chaurasia, A., Kumar, S., Gawande, S. P., Hiremani, N. S., Shankar, R., Gokte-Narkhedkar, N., Renu, & Prasad, Y. G. (2023). PGPR: The treasure of multifarious beneficial microorganisms for nutrient mobilization, pest biocontrol and plant growth promotion in field crops. *World Journal of Microbiology and Biotechnology*, 39, 100. <https://doi.org/10.1007/s11274-023-03536-0>
- Nannipieri, P., Ascher, J., Ceccherini, M. T., Landi, L., Pietramellara, G., & Renella, G. (2003). Microbial diversity and soil functions. *European Journal of Soil Science*, 54, 655–670. <https://doi.org/10.1046/j.1351-0754.2003.0556.x>
- Nie, M., Bell, C., Wallenstein, M. D., & Pendall, E. (2015). Increased plant productivity and decreased microbial respiratory C loss by plant growth-promoting rhizobacteria under elevated CO<sub>2</sub>. *Scientific Reports*, 5, 9212. <https://doi.org/10.1038/srep09212>
- Noviana, Z., Dewi, T. K., Ruhimat, R., Mulyani, N., Purwaningsih, S., Agustiyani, D., & Antonius, S. (2024). Seeing beyond the surface: Soil microbes govern soil ecosystem functions and affect global climate. In *Microbiome drivers of ecosystem function* (pp. 249–259). Elsevier.
- Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmí, S. (2016). Greenhouse gas emissions from soils—A review. *Geochemistry*, 76, 327–352. <https://doi.org/10.1016/j.chemer.2016.04.002>
- Ollio, I., Santás-Miguel, V., Gómez, D. S., Lloret, E., Sánchez-Navarro, V., Martínez-Martínez, S., Egea-Gilabert, C., Fernández, J. A., Calviño, D. F., & Zornoza, R. (2024). Effect of biofertilizers on broccoli yield and soil quality indicators. *Horticulturae*, 10, 42. <https://doi.org/10.3390/horticulturae10010042>
- Olsen, S. R. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate*. US Department of Agriculture.
- Orhan, E., Esitken, A., Ercisli, S., Turan, M., & Sahin, F. (2006). Effects of plant growth promoting rhizobacteria (PGPR) on yield, growth and nutrient contents in organically growing raspberry. *Scientia Horticulturae*, 111, 38–43. <https://doi.org/10.1016/j.scienta.2006.09.002>
- Paungfoo-Lonhienne, C., Redding, M., Pratt, C., & Wang, W. (2019). Plant growth promoting rhizobacteria increase the efficiency of fertilisers while reducing nitrogen loss. *Journal of Environmental Management*, 233, 337–341. <https://doi.org/10.1016/j.jenvman.2018.12.052>
- Pinto, R., Weigelhofer, G., Brito, A. G., & Hein, T. (2021). Effects of dry-wet cycles on nitrous oxide emissions in freshwater sediments: A synthesis. *PeerJ*, 9, e10767. <https://doi.org/10.7717/peerj.10767>
- Porta Casanellas, J., López Acevedo Requerin, M., & Rodríguez Ochoa, R. (1986). *Técnicas y experimentos en Edafología*. Romanyá/Valls.
- Powelson, D. S., Gregory, P. J., Whalley, W. R., Quinton, J. N., Hopkins, D. W., Whitmore, A. P., Hirsch, P. R., & Goulding, K. W. T. (2011). Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy, the Challenge of Global Food Sustainability*, 36, S72–S87. <https://doi.org/10.1016/j.foodpol.2010.11.025>
- Quality, I. S. (1995). *Determination of the potential cation exchange capacity and exchangeable cations using barium chloride solution buffered at pH*. ISO.
- Ramond, J.-B., Jordaan, K., Díez, B., Heinzelmann, S. M., & Cowan, D. A. (2022). Microbial biogeochemical cycling of nitrogen in arid ecosystems. *Microbiology and Molecular Biology Reviews*, 86, e00109-21. <https://doi.org/10.1128/membr.00109-21>
- Reichman, S. M. (2002). *The responses of plants to metal toxicity: A review focusing on copper, manganese & zinc*. Australian Minerals & Energy Environment Foundation Melbourne.
- Samet, M., Ghazala, I., Karray, F., Abid, C., Chiab, N., Nouri-Ellouz, O., Sayadi, S., & Gargouri-Bouazid, R. (2022). Isolation of bacterial strains from compost teas and screening of their PGPR properties on potato plants. *Environmental Science and Pollution Research*, 29, 75365–75379. <https://doi.org/10.1007/s11356-022-21046-8>
- Sánchez-Navarro, V., Shahrokh, V., Martínez-Martínez, S., Acosta, J. A., Almagro, M., Martínez-Mena, M., Boix-Fayos, C., Díaz-Pereira, E., & Zornoza, R. (2022). Perennial alley cropping contributes to decrease soil CO<sub>2</sub> and N<sub>2</sub>O emissions and increase soil carbon sequestration in a Mediterranean almond orchard. *Science of the Total Environment*, 845, 157225. <https://doi.org/10.1016/j.scitotenv.2022.157225>
- Sarfraz, R., Hussain, A., Sabir, A., Ben Fekih, I., Ditta, A., & Xing, S. (2019). Role of biochar and plant growth promoting

- rhizobacteria to enhance soil carbon sequestration—A review. *Environmental Monitoring and Assessment*, 191, 251. <https://doi.org/10.1007/s10661-019-7400-9>
- Sauze, J., Ogée, J., Maron, P.-A., Crouzet, O., Nowak, V., Wohl, S., Kaisermann, A., Jones, S. P., & Wingate, L. (2017). The interaction of soil phototrophs and fungi with pH and their impact on soil CO<sub>2</sub>, CO<sub>18</sub>O and OCS exchange. *Soil Biology and Biochemistry*, 115, 371–382. <https://doi.org/10.1016/j.soilbio.2017.09.009>
- Scuderi, A., Cammarata, M., Branca, F., & Timpanaro, G. (2021). Agricultural production trends towards carbon neutrality in response to the EU 2030 Green Deal: Economic and environmental analysis in horticulture. *Agricultural Economics/Zemědělská Ekonomika*, 67, 435–444. <https://doi.org/10.17221/145/2021-AGRICECON>
- Sempere, A., Oliver, J., & Ramos, C. (2006). Simple determination of nitrate in soils by second-derivative spectroscopy. *Journal of Soil Science*, 44, 633–639. <https://doi.org/10.1111/j.1365-2389.1993.tb02328.x>
- Sepp, S.-K., Vasar, M., Davison, J., Oja, J., Anslan, S., Al-Quraishy, S., Bahram, M., Bueno, C. G., Cantero, J. J., Fabiano, E. C., Decocq, G., Drenkhan, R., Fraser, L., Garibay Oriel, R., Hiiesalu, I., Koorem, K., Kõljalg, U., Moora, M., Mucina, L., ... Zobel, M. (2023). Global diversity and distribution of nitrogen-fixing bacteria in the soil. *Frontiers in Plant Science*, 14, 1100235. <https://doi.org/10.3389/fpls.2023.1100235>
- Shen, Z., Zhong, S., Wang, Y., Wang, B., Mei, X., Li, R., Ruan, Y., & Shen, Q. (2013). Induced soil microbial suppression of banana fusarium wilt disease using compost and biofertilizers to improve yield and quality. *European Journal of Soil Biology*, 57, 1–8. <https://doi.org/10.1016/j.ejsobi.2013.03.006>
- Singh, M., Dotaniya, M., Mishra, A., Dotaniya, C. K., Regar, K. L., & Lata, M. (2016). Role of biofertilizers in conservation agriculture. In *Conservation agriculture: An approach to combat climate change in Indian Himalaya* (pp. 113–134). Springer Singapore. [https://doi.org/10.1007/978-981-10-2558-7\\_4](https://doi.org/10.1007/978-981-10-2558-7_4)
- Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, 133, 247–266. <https://doi.org/10.1016/j.agee.2009.04.021>
- Strock, J. S. (2008). Ammonification. In *Encyclopedia of ecology* (pp. 162–165). Elsevier. <https://doi.org/10.1016/B978-008045405-4.00256-1>
- Sun, W., Shahrajabian, M. H., & Cheng, Q. (2021). Nitrogen fixation and diazotrophs—A review. *Romanian Biotechnological Letters*, 26, 2834–2845. <https://doi.org/10.25083/rbl/26.4/2834.2845>
- Suryanarayanan, T. S., Ayesha, M. S., & Shaanker, R. U. (2022). Leaf photosynthesis: Do endophytes have a say? *Trends in Plant Science*, 27, 968–970. <https://doi.org/10.1016/j.tplants.2022.07.009>
- Tahir, M., Ahmad, I., Shahid, M., Shah, G. M., Farooq, A. B. U., Akram, M., Tabassum, S. A., Naeem, M. A., Khalid, U., Ahmad, S., & Zakir, A. (2019). Regulation of antioxidant production, ion uptake and productivity in potato (*Solanum tuberosum* L.) plant inoculated with growth promoting salt tolerant *Bacillus* strains. *Ecotoxicology and Environmental Safety*, 178, 33–42. <https://doi.org/10.1016/j.ecoenv.2019.04.027>
- Tang, Y., Yu, G., Zhang, X., Wang, Q., Tian, J., Niu, S., Tian, D., & Ge, J. (2019). Different strategies for regulating free-living N<sub>2</sub> fixation in nutrient-amended subtropical and temperate forest soils. *Applied Soil Ecology*, 136, 21–29. <https://doi.org/10.1016/j.apsoil.2018.12.014>
- Tellez-Rio, A., García-Marco, S., Navas, M., López-Solanilla, E., Tenorio, J. L., & Vallejo, A. (2015). N<sub>2</sub>O and CH<sub>4</sub> emissions from a fallow–wheat rotation with low N input in conservation and conventional tillage under a Mediterranean agroecosystem. *Science of the Total Environment*, 508, 85–94. <https://doi.org/10.1016/j.scitotenv.2014.11.041>
- Thirumalai, K. (2014). Biological carbon dioxide sequestration potential of *Bacillus pumilus*. *Sains Malaysiana*, 43, 1149–1156.
- Tian, W., Wang, L., Li, Y., Zhuang, K., Li, G., Zhang, J., Xiao, X., & Xi, Y. (2015). Responses of microbial activity, abundance, and community in wheat soil after three years of heavy fertilization with manure-based compost and inorganic nitrogen. *Agriculture, Ecosystems and Environment*, 213, 219–227. <https://doi.org/10.1016/j.agee.2015.08.009>
- Turan, M., Ataoğlu, N., & Şahin, F. (2006). Evaluation of the capacity of phosphate solubilizing bacteria and fungi on different forms of phosphorus in liquid culture. *Journal of Sustainable Agriculture*, 28, 99–108.
- Velivelli, S. L. S., Kromann, P., Lojan, P., Rojas, M., Franco, J., Suarez, J. P., & Prestwich, B. D. (2015). Identification of mVOCs from Andean rhizobacteria and field evaluation of bacterial and mycorrhizal inoculants on growth of potato in its center of origin. *Microbial Ecology*, 69, 652–667. <https://doi.org/10.1007/s00248-014-0514-2>
- Vergé, X. P. C., De Kimpe, C., & Desjardins, R. L. (2007). Agricultural production, greenhouse gas emissions and mitigation potential. *Agricultural and Forest Meteorology*, 142, 255–269. <https://doi.org/10.1016/j.agrformet.2006.06.011>
- Vessey, J. K. (2003). Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 255, 571–586. <https://doi.org/10.1023/A:1026037216893>
- Wang, J., Xie, J., Li, L., Effah, Z., Xie, L., Luo, Z., Zhou, Y., & Jiang, Y. (2022). Fertilization treatments affect soil CO<sub>2</sub> emission through regulating soil bacterial community composition in the semiarid loess plateau. *Scientific Reports*, 12, 20123. <https://doi.org/10.1038/s41598-022-21108-4>
- Wang, J., Xie, J., Li, L., Luo, Z., Zhang, R., Wang, L., & Jiang, Y. (2021). The impact of fertilizer amendments on soil autotrophic bacteria and carbon emissions in maize field on the semiarid loess plateau. *Frontiers in Microbiology*, 12, 664120. <https://doi.org/10.3389/fmicb.2021.664120>
- Wang, J., Xue, C., Song, Y., Wang, L., Huang, Q., & Shen, Q. (2016). Wheat and rice growth stages and fertilization regimes alter soil bacterial community structure, but not diversity. *Frontiers in Microbiology*, 7, 1207. <https://doi.org/10.3389/fmicb.2016.01207>
- Wang, J., Zhang, D., Zhang, L., Li, J., Raza, W., Huang, Q., & Shen, Q. (2016). Temporal variation of diazotrophic community abundance and structure in surface and subsoil under four fertilization regimes during a wheat growing season. *Agriculture, Ecosystems and Environment*, 216, 116–124. <https://doi.org/10.1016/j.agee.2015.09.039>
- Wang, L., Han, Z., & Zhang, X. (2010). Effects of soil pH on CO<sub>2</sub> emission from long-term fertilized black soils in northeastern China. In *Proceedings of Conference on Environmental Pollution and Public Health (CEPPH 2010)*, Wuhan, China.
- Wang, Y., Uchida, Y., Shimomura, Y., Akiyama, H., & Hayatsu, M. (2017). Responses of denitrifying bacterial communities to

- short-term waterlogging of soils. *Scientific Reports*, 7, 803. <https://doi.org/10.1038/s41598-017-00953-8>
- Wani, P. A., Khan, M. S., & Zaidi, A. (2007). Synergistic effects of the inoculation with nitrogen-fixing and phosphate-solubilizing rhizobacteria on the performance of field-grown chickpea. *Journal of Plant Nutrition and Soil Science*, 170, 283–287. <https://doi.org/10.1002/jpln.200620602>
- Widmann, N., Goian, M., Ianculov, I., Dumbrava, D., & Moldovan, C. (2008). Method to starch content determination from plants by specific weight. *Scientific Papers Animal Science and Biotechnologies*, 41(1), 814.
- Xiao, Z., Rasmann, S., Yue, L., Lian, F., Zou, H., & Wang, Z. (2019). The effect of biochar amendment on N-cycling genes in soils: A meta-analysis. *Science of the Total Environment*, 696, 133984. <https://doi.org/10.1016/j.scitotenv.2019.133984>
- Xu, J., Kloeppe, J. W., Huang, P., McInroy, J. A., & Hu, C. H. (2018). Isolation and characterization of N<sub>2</sub>-fixing bacteria from giant reed and switchgrass for plant growth promotion and nutrient uptake. *Journal of Basic Microbiology*, 58, 459–471. <https://doi.org/10.1002/jobm.201700535>
- Xu, Y. C., Shen, Q. R., Li, M. L., Dittert, K., & Sattelmacher, B. (2004). Effect of soil water status and mulching on N<sub>2</sub>O and CH<sub>4</sub> emission from lowland rice field in China. *Biology and Fertility of Soils*, 39, 215–217. <https://doi.org/10.1007/s00374-003-0692-4>
- Yaghoubi Khanghahi, M., Crecchio, C., & Verbruggen, E. (2022). Shifts in the rhizosphere and endosphere colonizing bacterial communities under drought and salinity stress as affected by a biofertilizer consortium. *Microbial Ecology*, 84, 483–495. <https://doi.org/10.1007/s00248-021-01856-y>
- Yan, W., Zhong, Y., Liu, J., & Shanguan, Z. (2021). Response of soil respiration to nitrogen fertilization: Evidence from a 6-year field study of croplands. *Geoderma*, 384, 114829. <https://doi.org/10.1016/j.geoderma.2020.114829>
- Yao, M. K., Tweddell, R. J., & Désilets, H. (2002). Effect of two vesicular-arbuscular mycorrhizal fungi on the growth of micro-propagated potato plantlets and on the extent of disease caused by *Rhizoctonia solani*. *Mycorrhiza*, 12, 235–242. <https://doi.org/10.1007/s00572-002-0176-7>
- Yousuf, B., Keshri, J., Mishra, A., & Jha, B. (2012). Application of targeted metagenomics to explore abundance and diversity of CO<sub>2</sub>-fixing bacterial community using cbbL gene from the rhizosphere of *Arachis hypogaea*. *Gene*, 506, 18–24. <https://doi.org/10.1016/j.gene.2012.06.083>
- Zeng, J., Liu, X., Song, L., Lin, X., Zhang, H., Shen, C., & Chu, H. (2016). Nitrogen fertilization directly affects soil bacterial diversity and indirectly affects bacterial community composition. *Soil Biology and Biochemistry*, 92, 41–49. <https://doi.org/10.1016/j.soilbio.2015.09.018>
- Zhang, H., Fang, Y., Chen, Y., Li, Y., Lin, Y., Wu, J., Cai, Y., & Chang, S. X. (2022). Enhanced soil potential N<sub>2</sub>O emissions by land-use change are linked to AOB-*amoA* and *nirK* gene abundances and denitrifying enzyme activity in subtropics. *Science of the Total Environment*, 850, 158032. <https://doi.org/10.1016/j.scitotenv.2022.158032>
- Zheng, W., Zeng, S., Bais, H., LaManna, J. M., Hussey, D. S., Jacobson, D. L., & Jin, Y. (2018). Plant growth-promoting rhizobacteria (PGPR) reduce evaporation and increase soil water retention. *Water Resources Research*, 54, 3673–3687. <https://doi.org/10.1029/2018WR022656>
- Zornoza, R., Acosta, J. A., Gabarrón, M., Gómez-Garrido, M., Sánchez-Navarro, V., Terrero, A., Martínez-Martínez, S., Faz, Á., & Pérez-Pastor, A. (2018). Greenhouse gas emissions and soil organic matter dynamics in woody crop orchards with different irrigation regimes. *Science of the Total Environment*, 644, 1429–1438. <https://doi.org/10.1016/j.scitotenv.2018.06.398>

## 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:** Ollio, I., González Rosado, M., Lloret, E., Martínez-Martínez, S., Egea-Gilabert, C., Calviño, D. F., Zornoza, R., & Fernández, J. A. (2025). Integrating plant growth microorganisms in potato farming reduce soil CO<sub>2</sub> emissions and improve crop quality. *Soil Use and Management*, 41, e13140. <https://doi.org/10.1111/sum.13140>