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Effects of organic acid regulation on the respiration of reclaimed soil

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Abstract: Soil respiration is a critical process in the terrestrial carbon cycle. This study examined the effects of citric acid (CA) addition on CO_2 emissions from reclaimed soils at the Pan No. 1 Coal Mine in Huainan, China. A controlled incubation experiment was conducted using an LI-7810 analyser to monitor the CO_2 flux. The results revealed that the soil CO_2 respiration rate exhibited a concentration-dependent rise-and-fall pattern with increasing CA levels. Within the promoting concentration range, cumulative CO_2 emissions followed a logarithmic model ($y = a\ln x + b$, R^2 = 0.951–0.969). CA addition significantly reduced the soil pH (to as low as 6.67 at > 20 mmol/L) and increased the contents of alkali-hydrolysable N, available P and K, and organic matter, with the pH and organic matter being most responsive. The cumulative emissions increased rapidly and then stabilized under varying temperature and moisture conditions, with the highest emissions observed at 25 °C and 25% moisture content. Structural equation modelling indicated that temperature and moisture directly drove cumulative CO_2 emissions, whereas the CA concentration indirectly influenced emissions by altering the soil organic matter content and pH. These findings reveal the interactive effects of exogenous acids and environmental factors on soil respiration in reclaimed mining areas, providing insights for managing soil carbon dynamics in disturbed ecosystems.

Keywords: citric acid; reclamation soil; soil carbon emissions; soil respiration; structural equation model

Soil constitutes the largest carbon pool in terrestrial ecosystems. Slight changes in carbon storage can influence atmospheric carbon emissions, thereby impacting the global climate (Raich & Schlesinger 1992; Buchmann 2000; Schlesinger & Andrews 2000). China is the major producer and consumer of coal products, accounting for more than 45% of the world's total coal production and consumption (Xu et al. 2020). Although coal mining activities have enhanced China's national economic development,

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they have resulted in severe ecological degradation in mining regions and widespread land subsidence (Liu et al. 2014). As a result, numerous measures have been implemented to reclaim subsidence areas and reconstruct soils, as published by Hu (2022). Nevertheless, the associated mechanical compaction and disturbance have negatively affected the original soil structure and profile layers, leading to soil nutrient and biodiversity losses. Soil respiration refers to carbon dioxide (CO_2) emissions from undisturbed soils into the atmosphere. This emission process can be categorised into root respiration, microbial respiration within the rhizosphere, and respiration resulting from soil organic matter mineralisation (Cao et al. 2025). In fact, soil respiration is a critical component of the terrestrial carbon cycle and plays a key role in energy flow and material cycling (Shen et al. 2023). The total annual amount of carbon emitted into the atmosphere via soil respiration is estimated at 6.8×10^{13} kg. On the other hand, carbon emissions from global fuel combustion account for only 8 to 9% of those released by soil respiration (Geng 2020). This further demonstrates the strong impact of soil respiration on global climate change.

Soil respiration is influenced by multiple environmental factors, of which soil temperature is the most important. Soil temperature not only directly impacts soil microbial and plant root activities but also indirectly affects soil nutrient availability and plant growth (Cao et al. 2025). Nottingham et al. (2020) and Nyberg & Hovenden (2020) reported 55% and 28% increases in soil respiration in tropical forests and Tasmanian grasslands, respectively, following temperature warming. Soil humidity, texture, pore size, and specific surface area are also critical abiotic factors that significantly influence soil respiration. Therefore, soil respiration can be considered an important indicator for assessing soil quality and fertility, partially reflecting microbial activities, root biomass, root activities, and soil material cycling (Huang et al. 2025).

Organic acids are important components of plant root exudates and strongly affect soil physicochemical properties, soil microbial composition/diversity, and soil respiration intensity through direct or indirect effects (Gu et al. 2020; Li et al. 2024a). Organic acids are functional organic compounds commonly found in soil and litter layers and are typically low-molecular-weight organic acids (molecular weights less than 250). These compounds usually contain one or more hydroxyl, carboxyl, or amino groups. In addition to their ability to improve soil properties, they can stimulate and regulate plant growth (Fang et al. 2005; Xu et al. 2021). Moreover, low-molecular-weight organic acids constitute one of the major energy sources for microbial growth and reproduction, significantly influencing the structure of microbial communities by affecting their type and abundance. Because they are readily available carbon and energy sources, organic acids can selectively stimulate copiotrophic microorganisms, reshape bacterial and fungal community composition, and alter microbial co-occurrence networks and functional gene expression (Gu et al. 2020; Ren et al. 2023; Li et al. 2024b). Such shifts in microbial community structure and activity are closely linked to soil respiration, because heterotrophic microbial metabolism is a major source of CO_2 efflux. In addition, organic acids can modify rhizosphere pH and nutrient availability, further indirectly affecting microbial diversity and respiratory activity (Haynes & Mokolobate 2001; Wu et al. 2003; Xiao et al. 2004).

Citric acid (CA), a type of low-molecular-weight organic acid, has low toxicity and high degradability (Liu et al. 2025). Its addition can serve as a carbon source and substrate available to microorganisms, significantly altering the structure of soil microbial communities (Liu 2021). Currently, research on citric acid has focused mainly on its effects on soil physical and chemical properties, nutrients, enzyme activities, the forms and mobility of soil heavy metal elements, and plant growth regulation (He et al. 2022; Ren et al. 2023), whereas studies on the impact of citric acid addition on soil respiration and CO_2 emissions are scarce. The specific mechanism by which citric acid addition affects soil respiration remains unclear.

Although CA has been widely studied for nutrient mobilisation and plant growth regulation, its effects on soil respiration in reclaimed coal-mine soils remain poorly understood. We hypothesised that: (1) CA addition would affect soil CO_2 respiration in a concentration-dependent manner, with a promoting effect at low-to-moderate concentrations and inhibition at high concentrations; (2) CA would indirectly regulate cumulative CO_2 emissions by decreasing soil pH and increasing soil organic matter and available nutrients; (3) temperature and moisture would directly control cumulative CO_2 emissions, with an optimum at 25 °C and 25% moisture. Therefore, this study investigated the CO_2 respiration rate and cumulative emissions of reclaimed soil from the Pan No. 1 Mine under exogenous CA addition and different temperature and moisture conditions and

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used structural equation modelling to identify the direct and indirect pathways controlling soil carbon emissions. The results are expected to provide a theoretical basis for carbon management and ecological restoration in coal-mine reclamation areas.

MATERIAL AND METHODS

Study area. The study area is situated approximately 1 km east of the Pan No. 1 Mine (116.84°E, 32.80°N), bordering a coal gangue dump mountain to the south, as shown in Figure 1. The soil in this region is classified as sandy loess, with parent material derived from ancient alluvial loess deposits. The soil texture is heavy loam, with a pH of 8.81, soil organic matter content of 5.08 g/kg, alkali-hydrolysable nitrogen content of 54.54 mg/kg, available phosphorus content of 4.13 mg/kg, and available potassium content of 282.85 mg/kg. The average annual temperature and precipitation are approximately 15.3 °C and 926 mm, respectively. In 2005, the Huainan Mining Group initiated a soil-covering and land reclamation project within the coal mining subsidence zone surrounding the coal gangue dump of the Pan No. 1 Mine. This project resulted in the reclamation of 37.96 ha of subsidence land, with an average covering-soil thickness of 100 cm (Zheng et al. 2014, 2022).



Figure 1. Overview map of study area

Sample collection and experimental design. In this study, surface soil samples (0–10 cm) were collected in May 2023 from the reclaimed soil of Pan No.1 A random point selection method was used to investigate the potential for CO_2 release and the major mechanisms underlying the impacts of external factors (temperature, pH, and exogenous carbon addition). The fine roots, debris, and small stones were removed from the collected soil samples. The samples were subsequently thoroughly mixed, naturally air-dried, ground, and sieved through a 2 mm screen for subsequent analyses.

To investigate the effects of CA addition on the CO_2 respiration rate in reclaimed soil, 300 g of soil passed through a 2 mm sieve was placed in widemouth culture bottles. CA solutions were added at concentrations of 0, 1.17, 2.34, 4.69, 5.86, 7.03, 8.20, 10.54, 11.71, 12.88, 16.5 and 20.00 mmol/L, with 100 mL of each solution added to 300 g of soil. All treated samples were incubated in a constant-temperature incubator at 25 °C.

The concentrations of citric acid that were selected for addition were those at the ascending stage of the soil CO_2 respiration rate, with concentration gradients of 5 mmol/L, 10 mmol/L, and 20 mmol/L. One hundred millilitres of citric acid solutions of different concentrations were added to culture bottles containing 300 g of reclaimed soil that had passed through a 2 mm sieve; the control group (CK) was treated with an equal volume of ultrapure water. All the experimental samples were placed in a constant-temperature incubator at 25 °C for a 20-day cultivation period, during which the moisture content of the reclaimed soil was maintained at 25%. The CO_2 respiration rate of the reclaimed soil was measured daily, and the cumulative CO_2 emissions were calculated.

The influence of citric acid on the chemical properties of soil was investigated. Concurrently, separate analyses were conducted to evaluate the effects of temperature (15 °C, 25 °C, 35 °C) and moisture content (15%, 25%, 35%) on soil CO_2 respiration. During the 20-day cultivation process, the weight of each bottle was measured every day, and ultra-pure water was added to restore the initial total weight, thereby maintaining the target moisture content through the weighing method.

Sample determination. During the cultivation period, the LI-7810 automated soil carbon flux measurement system was employed to measure the CO_2 respiration rate of the reclaimed soil at regular daily

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intervals, and the cumulative soil CO_2 emissions were subsequently calculated. The calculation formula for cumulative soil CO_2 emissions is as follows:

$$F_c = \frac{10VP_0\left(1-\frac{W_0}{1000}\right)}{8.314S\left(T_0+273.15\right)}\frac{\vartheta C'}{\vartheta t} \quad (1)$$

where:

F_c – the CO_2 respiration rate (μmol/m^2/s);
V – the total volume (cm^3);
P_0 – the initial atmospheric pressure (kPa);
W_0 – the initial H_2O concentration (mmol/mol);
T_0 – the initial air temperature (°C);
S – the soil surface area (cm^2);
$\vartheta C'/\vartheta t$ – the initial rate of dry CO_2 change (μmol/mol).

$$M = \frac{F_c S}{10^4 W} \times 44 \times 86400 \quad (2)$$

where:

M – the cumulative soil CO_2 emission (μg/g);
S – the soil surface area (cm^2);
W – the dry soil weight (g);
44 – the molar mass of CO_2.

The soil chemical properties, including pH, alkali-hydrolysable nitrogen, available potassium, available phosphorus, and organic matter, were measured at both the beginning and the end of the incubation period. Each index was determined according to different methods. Soil pH was measured by potentiometry according to HJ 962-2018 using a FE28 pH meter (Mettler-Toledo, Switzerland). Soil organic matter (SOM) was determined by elemental analysis according to NY/T 4606-2025 using an Vario EL cube elemental analyser (Elementar, Germany). Soil alkali-hydrolysable nitrogen (AN) was determined by the alkaline hydrolysis diffusion method according to LY/T 1228-2015. Soil available phosphorus (AP) was determined by sodium bicarbonate extraction-molybdenum-antimony colourimetry according to HJ 704-2014 using a TU-1950 UV-Vis spectrophotometer (Puxi General, China). Soil available potassium (AK) was determined by ammonium acetate extraction-inductively coupled plasma optical emission spectrometry (ICP-OES) according to DB63/T 1820-2020 using an Avio 550 Max ICP-OES (PerkinElmer, USA).

Data analysis. The CO_2 emission rates of the reclaimed soil under the different treatment scenarios were determined in triplicate. The cumulative CO_2 emissions were calculated and expressed using the weighted average cumulative method. Model fit was evaluated using Chi-square, degree od freedom (*df*), comparative fit index (CFI), and root mean square error of approximation (RMSEA); standardised path coefficients and *P* values were reported. Statistical analyses were performed in SPSS 24.0, and graphs were produced in Origin 2024. Differences were considered significant at $P < 0.05$.

RESULTS

Effects of citric acid addition on the CO_2 emission rate of reclaimed soil. The variation characteristics of the CO_2 respiration rate in reclaimed soil during cultivation with the addition of CA are presented in Figure 2. In the CA-amended treatments, the CO_2 respiration rate initially increased but subsequently decreased with increasing CA concentration. The measured CO_2 respiration rates ranged from 0.1645 to 0.3935 μmol/m^2/s. The peak value of 0.3935 μmol/m^2/s was observed at a CA concentration of approximately 7.03 mmol/L, which was 62.6% higher than that of the control group (0.2420 μmol/m^2/s). These findings indicate that the promoting effect on soil respiration gradually increases as the concentration rises below 7.03 mmol/L, whereas this promoting effect gradually diminishes when the concentration exceeds this threshold. At the highest CA concentration tested (16.5 mmol/L), the respiration rate decreased to its lowest value of 0.1645 μmol/m^2/s, which corresponds to 68.0% of the control level. This

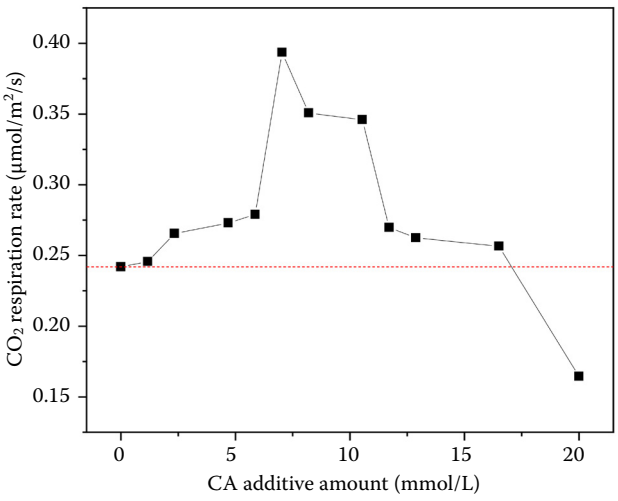


Figure 2. Effects of citric acid on the CO_2 respiration rate in reclaimed soil
CA – citric acid

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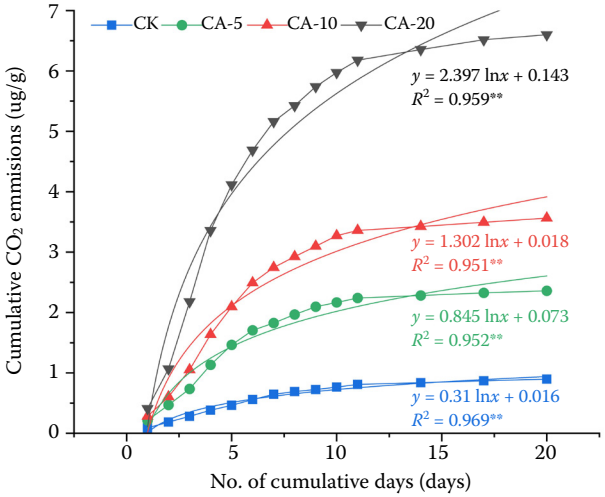


Figure 3. Effects of citric acids on cumulative CO_2 emissions from reclaimed soil
CK – control; CA – citric acid

concentration was found to exert an inhibitory effect on soil respiration.

Effects of citric acid on the cumulative CO_2 emissions of the reclaimed soil. Citric acid at concentrations of 5 , 10 , and 20 mmol/L was selected for subsequent experiments. The variation in cumulative CO_2 emission from reclaimed soil over incubation time was observed. As shown in Figure 3, the cumulative CO_2 emission increased rapidly during the initial incubation stage and began to level off after day 10. Linear fitting of cumulative CO_2 emission against incubation time indicated a logarithmic relationship, expressed as $y = a \ln x + b$, with R^2 values ranging from 0.951–0.969.

After 20 days of incubation, the cumulative CO_2 emissions under the CA treatments followed the order CA-20 > CA-10 > CA-5 > CK. Specifically, the cumulative CO_2 emission rates were 6.600, 3.563, 2.359, and 0.897 µg/g, which were 7.36, 3.97, and 2.63 times higher than those of the CK group, respectively (0.897 µg/g).

Effects of citric acid addition on nutrients in the reclaimed soil. The pH of the reclaimed soil gradually decreased with increasing CA concentration, particularly at the initial stage (day 1 of cultivation) (Figure 4A). Compared with CK, the rates of decrease in soil pH under CA-5, CA-10, and CA-20 were –5.62%, –11.94%, and –17.15%, respectively, at the initial stage. After 20 days of incubation, the pH of the CA-amended soil gradually increased to above 8.0 but remained lower than that of CK. Notably, at the initial stage, CA addition reached 20 mmol/L decreased the soil pH to 6.67, indicating temporary acidification. Therefore, CA concentrations should not exceed 20 mmol/L.

In addition to soil organic matter, the available N, K, and P contents in the reclaimed soil tended to increase with increasing CA concentration at both the initial and final stages (Figure 4B, 4C, and 4E), generally exceeding those of the CK group. How-

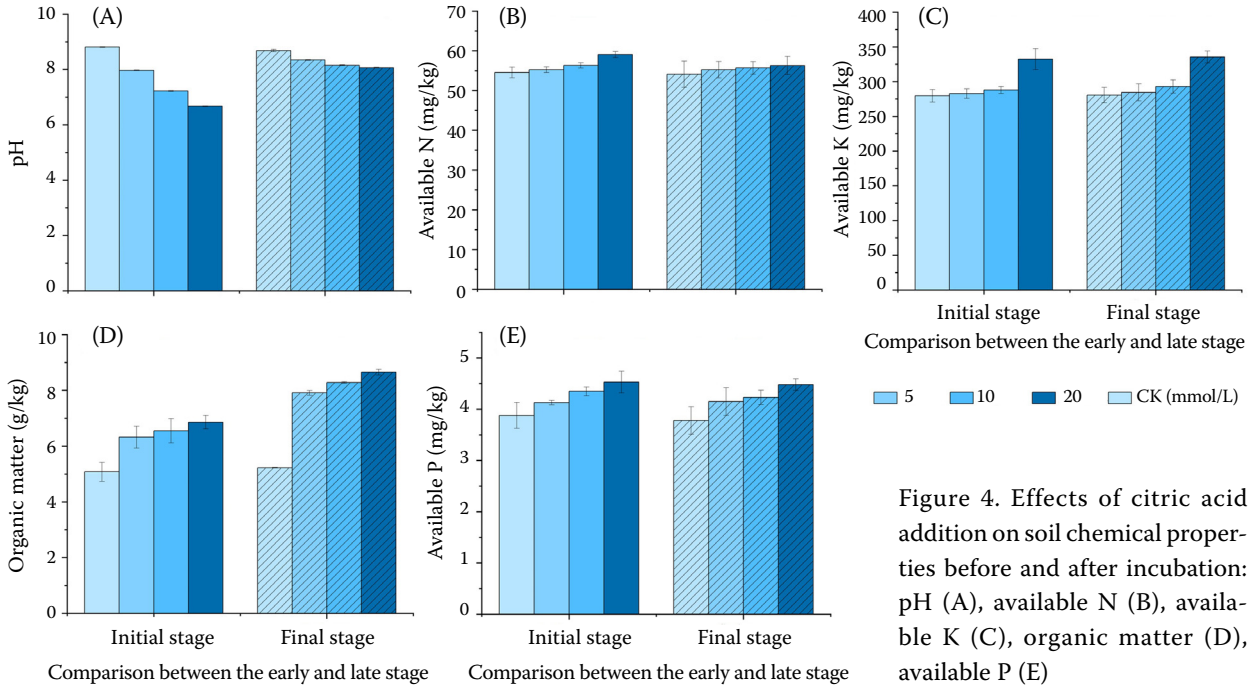


Figure 4. Effects of citric acid addition on soil chemical properties before and after incubation: pH (A), available N (B), available K (C), organic matter (D), available P (E)

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ever, the magnitude of the response differed among nutrients and between stages. For available N, CA addition increased the content relative to CK at both stages, with the highest values under CA-20 at the initial stage and under CA-10 or CA-20 at the final stage (Figure 4B). For available K, the differences among CA treatments were relatively small; CA-20 was close to or slightly higher than CK, while CA-5 and CA-10 showed only minor changes (Figure 4C). For available P, CA addition generally increased the content, and CA-20 had the highest value at the final stage, although the differences among treatments were not significant (Figure 4E). The organic matter content increased markedly with increasing CA concentration at both stages and was higher than that of CK, with a more pronounced increase at the final stage (Figure 4D). In summary, CA addition significantly influenced the chemical properties of the reclaimed soil, particularly soil pH and organic matter content.

Effects of environmental factors on the cumulative CO_2 emissions of reclaimed soil. Figure 5 shows the effects of temperature on the cumulative CO_2 emissions of the reclaimed soil under CA addition. The cumulative CO_2 emissions under varying temperature conditions exhibited a sharp increasing trend followed by gradual stabilisation. Specifically, the cumulative CO_2 emissions under the different temperature conditions were in the order CA-25 °C > CA-35 °C > CA-15 °C. The cumulative CO_2 emissions reached the highest value of 6.600 μg/g at 25 °C, which was 2.22 and 1.02 times higher than those observed at 15 °C (2.968 μg/g) and 35 °C (6.501 μg/g), respectively.

The effects of soil moisture content on cumulative CO_2 emissions are shown in Figure 6. The cumulative CO_2 emissions first increased and then decreased with increasing soil moisture content, following the order CA-25% > CA-35% > CA-15%. Specifically, the cumulative CO_2 emissions reached a maximum value of 6.600 μg/g at 25% moisture content. This maximum value was 1.01 and 1.24 times higher than those observed at 35% (6.528 μg/g) and 15% (5.344 μg/g), respectively.

Interactions between cumulative soil CO_2 emissions and multiple factors. The results of this study demonstrated the strong effects of CA addition on the pH values and organic matter contents of the reclaimed soil. Consequently, multiple factors, including CA concentrations, environmental factors (temperature and moisture content), pH, and organic matter content, were selected to further investigate the effects of CA and environmental factors on cumulative soil CO_2 emissions using structural equation modelling (SEM). In fact, SEM can consider the overall external influence by integrating the interactions between variables, thereby effectively elucidating causal pathways. This modelling method can be used to reveal complex relationships between factors. This method can, therefore, be useful for providing a comprehensive understanding of the response relationships between cumulative soil CO_2 emissions and other variables (Yang et al. 2024).

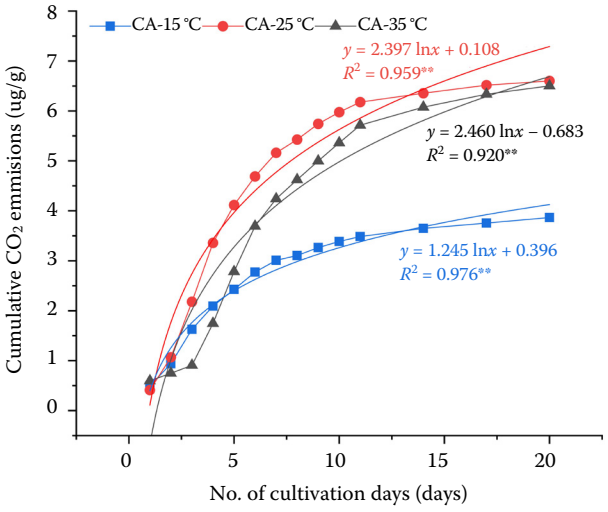


Figure 5. Effect of temperature on cumulative CO_2 emissions from reclaimed soil
CA – citric acid

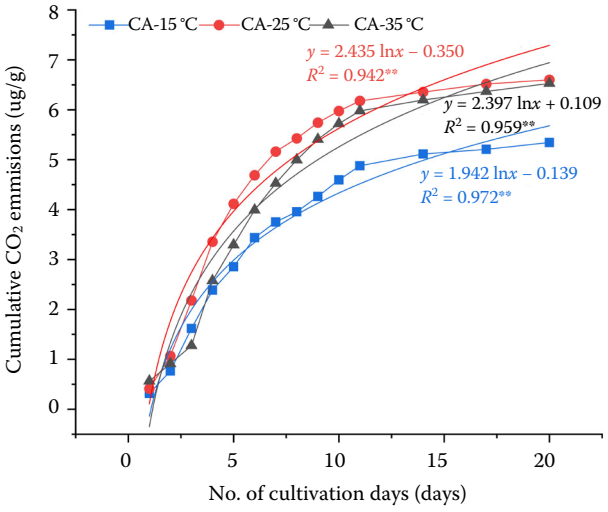


Figure 6. Effect of moisture content on cumulative CO_2 emissions from reclaimed soil
CA – citric acid

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Table 1. Structural equation modelling path analysis of cumulative CO_2 emissions from citric acid soil

Lval	Rval	Path coefficients	*P*-value
pH	CA concentration	–0.769	0
Organic matter	CA concentration	0.930	0
Cumulative CO_2 emissions	pH	–0.402	0.0193
Cumulative CO_2 emissions	CA concentration	0.116	0.8974
Cumulative CO_2 emissions	temperature	0.337	0.0004
Cumulative CO_2 emissions	moisture content	0.173	0.0345
Cumulative CO_2 emissions	organic matter	0.372	0.0464

Lval – left-hand side variable; Rval – right-hand side variable; CA – citric acid

In this study, SEM analysis was performed using the semopy package in Python, following the framework of covariance structure analysis and employing a weighted least squares optimisation algorithm with correlations (Table 1). The results revealed significant effects of the soil moisture content, temperature, organic matter content, and pH on the cumulative soil CO_2 emissions (Figure 7). Specifically, the soil moisture content and temperature had significant ($P < 0.05$) and extremely significant ($P < 0.001$) direct effects on the cumulative CO_2 emissions, respectively. The CA concentrations substantially affected the soil organic matter contents ($P < 0.001$) and pH values ($P < 0.001$). These effects significantly influenced the cumulative soil CO_2 emissions through the mediating effects of organic matter ($P < 0.05$) and pH values ($P < 0.05$). The indirect effect of the CA concentration on the cumulative soil CO_2 emissions through the soil organic matter content was greater than that induced by the soil pH.

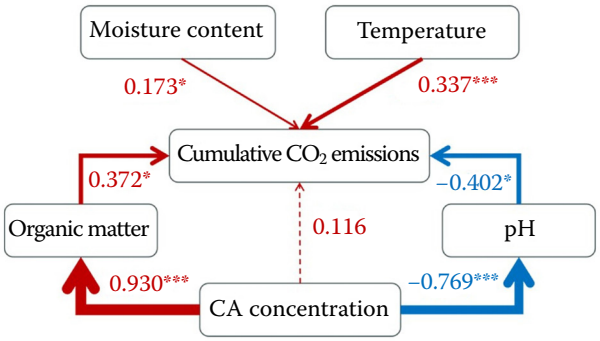


Figure 7. Structural equation model of cumulative CO_2 emissions from citric acid soil

The rectangles denote the observed variables; the red lines signify positive correlations, whereas the blue lines indicate negative correlations; the solid lines represent statistically significant paths, whereas the dashed lines correspond to insignificant paths; the thickness of the lines reflects the magnitude of the path coefficients; structural equation model results: Chi-square = 1.3855, degree of freedom (*df*) = 11, comparative fit index (CFI) = 0.9953, root mean square error of approximation (RMSEA) = 0.0000; *,**,***$P < 0.05$, 0.01, 0.001

DISCUSSION

Following the addition of CA, the CO_2 respiration rate in the reclaimed soil initially increased but then decreased with increasing CA concentration. This trend may be attributed to the role of low concentrations of citric acid as a readily available soluble carbon and energy source, which can be directly utilised by soil microorganisms to increase metabolic activity and CO_2 emission. Additionally, small amounts of citric acid have been shown to improve the bioavailability of essential nutrients such as phosphorus and potassium (Luo 2025; Song & Wang 2026), thereby stimulating microbial growth and respiratory activity. However, at higher application levels, elevated citric acid concentrations significantly lowered the soil pH, surpassing the physiological tolerance of many microbial species. This acidic environment likely inhibited microbial metabolism and proliferation, altered solution osmotic pressure, and impaired microbial cellular functions, ultimately reducing CO_2 respiration rates. Furthermore, soil acidification may induce the mobilisation of phytotoxic elements such as aluminium (Al) and manganese (Mn) (Li 2024), which can further suppress microbial community viability and activity (Chen 2025), contributing to the observed decline in soil CO_2 respiration.

The chemical properties of the reclaimed soil were affected by CA addition. This organic acid can release

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hydrogen ions into the soil, substantially decreasing the soil pH (Xu 2015). Nevertheless, soil microbial activities may be enhanced following a certain period of organic acid addition (Ding et al. 2005), increasing the utilisation and transformation of organic acids. This process can result, on the other hand, in the depletion of hydrogen ions, gradually increasing the soil pH. The higher the CA concentration is, the more pronounced the initial acidification effect. However, the self-regulation capability of soils can gradually increase over time, resulting in equilibrium (Chen et al. 1991). CA addition increased the soil alkali-hydrolysable N content, potentially because of the decrease in the soil pH, followed by an increase in the solubility of N-containing compounds. Zhao et al. demonstrated the strong activation effect of CA on soil P (Zhao et al. 2016), which is in line with the results of the present study. CA addition also increased the available K content in the reclaimed soil, which might be attributed to the acidification and chelation effects of the organic acid (Zhu et al. 2018). Organic acids can stimulate microbial activity and thereby influence soil organic matter (SOM) dynamics (Kong et al. 2016). Specifically, CA addition can provide additional carbon sources for microorganisms in reclaimed soil, promoting their reproduction and activities. Although enhanced microbial activity may accelerate the decomposition of labile organic acids, this process does not directly increase SOM. The observed SOM increase after CA addition was more likely due to exogenous CA-derived carbon input, microbial assimilation into biomass and metabolites, and the stabilization of organic carbon through organo-mineral interactions. Thus, the net SOM accumulation depended on the balance between microbial carbon assimilation and mineralisation. This finding is in line with that reported by Zhang et al. (2011).

The cumulative soil CO_2 emissions under the different temperature conditions decreased in the following order: CA-25 °C > CA-35 °C > CA-15 °C. This finding might be attributed to the increase in soil temperature at the post-reclamation stage, which increased microbial activity and consequently promoted the transformation and utilisation of soil carbon. This can subsequently increase cumulative soil CO_2 emissions (Kirschbaum 2004; Allison et al. 2010). However, microbial activities may be inhibited under excessively high soil temperature conditions. On the other hand, continuous and high soil temperature conditions can reduce the soil moisture content, mitigate microbial respiration and consequently lead to a decline in cumulative soil CO_2 emissions (Liu et al. 2009; Ma et al. 2018; Yu 2023). This further demonstrated greater cumulative soil CO_2 emissions at 25 °C than at 15 °C and 35 °C, which is in line with findings reported by Yang et al. (2011) and Alster et al. (2022).

In this study, the cumulative soil CO_2 emissions observed at 25% soil moisture content exceeded those at 15% and 35% moisture content. Indeed, soil moisture is a major factor influencing soil respiration. A reduced soil moisture content can decrease the total amount of soil CO_2 emission by affecting the abundance and activities of microorganisms, as well as other influencing factors of soil respiration (Conant et al. 2004). The soil CO_2 emission rates generally increase with increasing soil moisture level. Nevertheless, microbial communities can be negatively affected under saturated soil conditions. Specifically, in addition, excessively high soil moisture does not reduce the total number of soil pores; rather, water fills the pore space and decreases air-filled porosity and pore connectivity. This limits oxygen diffusion into the soil, creates oxygen-limited or anaerobic microsites, and suppresses aerobic heterotrophic microbial respiration. As a result, both CO_2 production and CO_2 efflux are reduced.

CONCLUSION

(a) Following the addition of citric acid (CA), the CO_2 respiration rate of the reclaimed soil initially increased but then decreased with increasing CA concentration. The cumulative CO_2 emissions initially increased rapidly and subsequently rose at a slower rate. A logarithmic relationship was observed between cumulative CO_2 emissions and incubation time, described by the equation $y = a \ln x + b$.

(b) The pH value of the reclaimed soil progressively decreased with increasing CA concentration at the initial and final stages. The effect on the soil pH was more pronounced at the initial stage of CA addition. Nevertheless, a decrease in the soil pH value to 6.67 was observed at CA concentrations above 20 mmol/L. On the other hand, the soil organic matter and available N, P, and K contents in the reclaimed soil increased with increasing CA concentration at the initial and final stages of the treatment. Nevertheless, differences in the change rates of these soil indicators were observed between the initial and

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final stages. CA addition had the strongest effects on the soil pH values and organic matter contents.

(c) Cumulative CO_2 emissions sharply increased under various soil temperatures and moisture contents before stabilising. The effects of the soil temperature and moisture content conditions on the cumulative CO_2 emissions followed the order of 25 °C > 35 °C > 15 °C and 25% > 35% > 15%, respectively.

(d) SEM results revealing the effects of multiple factors on cumulative CO_2 emissions. Specifically, the temperature and moisture content conditions directly affected the cumulative CO_2 emissions, whereas the CA concentration had indirect effects by influencing the soil organic matter content and pH. The interactions between these factors highlight the complexity of the soil respiration process, suggesting that further research on soil carbon emissions is needed.

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