



OPEN ACCESS

EDITED BY

Anoop Kumar Srivastava,
Central Citrus Research Institute (ICAR), India

REVIEWED BY

Shah Jahan Leghari,
Northwest A&F University, China
Mohamed Hafez,
City of Scientific Research and Technological
Applications, Egypt

*CORRESPONDENCE

Lijuan Yang

✉ lijuanyangsyau@126.com

Hongdan Fu

✉ fuhongdan@syau.edu.cn

[†]These authors have contributed equally to
this work

RECEIVED 10 January 2025

ACCEPTED 28 February 2025

PUBLISHED 31 March 2025

CITATION

Wang T, Yu L, Wang Z, Yang C, Dong F,
Yang D, Xi H, Sun Z, Bol R, Awais M, Yang L
and Fu H (2025) Effect of simulated
acidification on soil properties and plant
nutrient uptake of eggplant in greenhouse.
Front. Plant Sci. 16:1558458.
doi: 10.3389/fpls.2025.1558458

COPYRIGHT

© 2025 Wang, Yu, Wang, Yang, Dong, Yang, Xi,
Sun, Bol, Awais, Yang and Fu. This is an open-
access article distributed under the terms of
the [Creative Commons Attribution License](#)
(CC BY). The use, distribution or reproduction
in other forums is permitted, provided the
original author(s) and the copyright owner(s)
are credited and that the original publication
in this journal is cited, in accordance with
accepted academic practice. No use,
distribution or reproduction is permitted
which does not comply with these terms.

Effect of simulated acidification on soil properties and plant nutrient uptake of eggplant in greenhouse

Tianqi Wang^{1,2†}, Leixin Yu^{3†}, Zhen Wang⁴, Chuang Yang⁵,
Feiyu Dong¹, Diwen Yang¹, Haijun Xi⁶, Zhoupeng Sun²,
Roland Bol⁷, Muhammad Awais², Lijuan Yang^{1*}
and Hongdan Fu^{2*}

¹College of Land and Environment, Shenyang Agricultural University, Shenyang, China, ²College of Horticulture, Shenyang Agricultural University, Shenyang, China, ³Shenyang Urban Construction University, Shenyang, China, ⁴College of Agricultural Science and Technology, Shandong Agriculture and Engineering University, Shandong, Jinan, China, ⁵Shenyang Hengxin Technology Management Consulting Service Co., Ltd, Shenyang, China, ⁶Chaoyang Agricultural Development Service Center, Chaoyang, China, ⁷Institute of Bio- and Geosciences, IBG3 Agrosphere, Forschungszentrum Juelich, Juelich, Germany

Soil acidification adversely affects plant growth and development by decreasing the accessibility of roots to essential nutrients. Thus, it decreases crop yield. However, there has been a lack of systematic research on how soil acidification influences nutrient absorption in eggplant cultivated in greenhouse. To address this research gap, an experiment was conducted in a greenhouse with seven different acidity levels (4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.5), achieved by adding dilute H₂SO₄. The findings indicated that the soil organic matter (SOM) content at pH 4.5 decreased by 49% - 50% compared to pH levels of 7.0 - 7.5. In addition, the levels of exchangeable aluminum (Al³⁺) and soil electrical conductivity (EC) were highest at pH 4.5, with increases of 82 - 88 mg kg⁻¹ and 1.78 - 1.82 ms cm⁻¹, respectively, compared to pH 7.0 - 7.5. The total nitrogen (TN), phosphorus (TP), and potassium (TK) content in the soil declined as acidity increased, reaching their lowest levels of 0.59, 0.42, and 3.79 g kg⁻¹ at pH 4.5. Among the available nutrients, only potassium levels did not exhibit significant variation across treatments. However, the levels of macro elements in the soil consistently decreased, while the concentrations of trace elements (Fe, Cu, Zn) increased with rising acidity; conversely, the levels of other trace elements (B, Mo, Mn) decreased. The amounts of exchangeable calcium (Ca²⁺) and magnesium (Mg²⁺) at pH levels of 4.5 - 5.0 dropped by 61% - 66% and 70% - 78%, respectively, compared to pH 7.5. Further analyses indicated that soil pH values between 6.0 - 4.5 reduced the nutrient absorption capacity of eggplant, with the lowest nutrient content observed at pH 4.5. Mantel analyses confirmed that soil pH significantly affects plant nutrient uptake. This research provides both theoretical insights and practical guidance for the effective management of vegetable soil in greenhouse.

KEYWORDS

greenhouse, eggplant, soil pH, elements nutrient, macro elements, trace elements

1 Introduction

The vegetables industry in China has experienced rapid development since the 20th century. According to the 2019 census conducted by the [National Bureau of Statistics of China \(2020\)](#), the area dedicated to vegetables cultivation in the country has reached 20 million hectares ([Shen et al., 2021](#)). This cultivated area has been gradually increasing and ranks first globally ([Puissant et al., 2019](#); [Lv et al., 2020](#); [Yuan et al., 2024](#)). The advent of greenhouse cultivation has become a vital component of agricultural practices, establishing a stable ecological environment conducive to vegetables growth. It helps to extend the planting season, increase yields, boost farmers' incomes, and ensure a year-round supply of vegetables ([Bai et al., 2020](#); [Das et al., 2022](#)). Despite the numerous advantages offered by facility agriculture, it simultaneously confronts a succession of challenges ([Zhou et al., 2021](#)).

The widespread adoption of facility agriculture and the practice of multi-stubble cultivation in numerous greenhouse have contributed to an increased prevalence of soil acidification. For example, the overuse of ammonium-based nitrogen fertilizers has been shown to facilitate the accumulation of hydrogen ions (H^+) in the soil, thereby elevating soil acidity ([Li et al., 2018](#); [Zhang et al., 2022b](#); [Wang et al., 2023a, b](#)). In addition, the application of various acidic fertilizers, including potassium chloride, ammonium sulfate, and ammonium chloride, in facility production has resulted in the retention of significant quantities of acidic ions such as sulfate (SO_4^{2-}), chloride (Cl^-), and nitrate (NO_3^-) in the soil over extended cultivation periods. These ions are either not absorbed or are infrequently utilized by plant, leading to their interaction with H^+ in the soil and a subsequent reduction in soil pH ([Benelli et al., 2020](#); [Liang et al., 2024](#)). Research conducted by [Lv et al. \(2020\)](#) indicates that the long-term application of nitrogen fertilizers contributes to decline in soil pH. This includes the use of nitrogen-containing alkaline fertilizers (such as ammonium bicarbonate and ammonia) or neutral fertilizers (such as ammonium nitrate and urea), where excessive ammonium (NH_4^+) is converted into nitrate (NO_3^-) and nitrite (NO_2^-), further exacerbating soil acidification. Notably, ammonium nitrogen also promotes the production of substantial amounts of H^+ , which perpetuates the increase in soil acidity ([Hafez et al., 2020](#); [Lv et al., 2020](#); [Zhang et al., 2024](#)).

Soil nutrients play a crucial role in agriculture and plant growth ([Yang et al., 2024](#)). A significant amount of soil exchange calcium (Ca^{2+}) has been leached out due to soil acidification, leading to severe damage to soil structure and compaction ([Babin et al., 2019](#); [Liang et al., 2024](#)). The inadequate development of soil aggregates impairs the soil's capacity to act as a buffer and facilitate aeration ([Zhang et al., 2016](#); [Latifah et al., 2017](#); [Arwenyo et al., 2023](#)). As soil acidity changes, the availability of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), molybdenum (Mo) and other elements also reacts accordingly ([Shi et al., 2018](#); [Yao et al., 2024](#)). Soil acidification makes phosphorus and potassium easily fixed, low uptake and utilization of medium and trace elements, and weak root growth, resulting in increased fertilizer use but poor plant growth ([Wang et al., 2020b](#); [Zhang et al., 2022a](#)). Soil acidity not only leads to deficiencies in essential nutrients but also contributes to the

accumulation of harmful substances, such as exchangeable aluminum (Al^{3+}) in the soil ([Guo et al., 2018](#); [Munyaneza et al., 2024](#)). When the soil pH drops below 5.5, Al^{3+} becomes highly soluble in the soil solution, significantly affecting the fluidity of phospholipids within root cell membranes and potentially leading to membrane peroxidation. This phenomenon can subsequently result in stunted growth of lateral roots and root tips ([Ballagh et al., 2023](#)). In addition, elevated concentrations of NH_4^+ , produced through microbial nitrification, can inhibit plant growth ([Shoghi Kalkhoran et al., 2021](#)). Such as conditions may cause leaves to lose their green pigmentation, disrupt biochemical processes, alter energy transfer mechanisms, and ultimately impede overall plant development ([Fan et al., 2024](#)).

Eggplant (*Solanum melongena* L.) is one of the most significant greenhouse vegetables crop in China, contributing approximately 64.48% of the global output. Due to its high economic value and market demand, the excessive use of nitrogen fertilizers in greenhouse conditions has become a prevalent issue. The increased fertilizer application can lead to soil acidification and other problems, which seriously threaten the eggplant market and industry ([Wang et al., 2020a](#); [Adamczewska-Sowińska et al., 2022](#)).

Despite the significance of soil acidification, there is a lack of research examining its effects on the growth and development of eggplant, as well as its influence on nutrient distribution within the soil and plant tissues. Consequently, we designed a pot experiment to simulate a soil acidification environment by applying dilute sulfuric acid under controlled greenhouse conditions. This approach is based on the understanding that soil acidification primarily results from an increase H^+ . Dilute sulfuric acid, which can fully dissociate in aqueous solutions, serves as a significant source of H^+ ions for the soil. Unlike alternative acidification methods, eggplant was chosen as the experimental subject for this study. The primary goals of our current research were: 1) to study the effects of soil acidification on soil properties, and 2) to explore the effects of soil acidification on nutrient absorption in eggplant.

2 Materials and methods

2.1 Experimental site and design

The experiment was conducted in greenhouse (41°48'N, 123°25'E) at Shenyang Agricultural University, Liaoning Province, China. The eggplant variety "Xi 'an green" was used as a test material. We initially collected soil from an adjacent field to the greenhouse, the soil type is meadow soil, the basic properties of the original soil are detailed in [Supplementary Table S1](#). Polyethylene plastic pots, each measuring 27.00 cm in width and 30.00 cm in height, were utilized to contain equal. Before planting, 190.00g of chicken manure was applied to each pot as a base fertilizer, and 15.00g of NPK (15:15:15) compound fertilizer was applied to each pot after planting. We established seven acidity levels and repeated each treatment four times. The pH of each treatment was checked every seven days and H_2SO_4 (with corresponding acid solution concentrations of 0.10, 0.13, 0.20, 0.53, 0.70, 0.95 and 1.00 mL L^{-1}) was added as needed to maintain the target soil pH values ([Supplementary Table S2](#)).

2.2 Sample collection

On 28th June 2023, plants were carefully uprooted, and the fresh weights of the stem, root, and leaf were recorded before being transferred to an oven for drying. Subsequently, the dry weights of the plant were measured and used to determine nutrient absorption in the dried plant parts. Meanwhile, the soil auger was used to collect soil samples from a depth of 0 - 10.00 cm at five different points in each pot for each treatment. The fresh soil was passed through 2.00 mm sieve to remove stones, pebbles and roots. The collected samples were left to dry at room temperature for the measurement of chemical properties.

2.3 Measurement methods

2.3.1 Determination of soil basic properties

Soil pH (deionized water: soil, 2.5: 1) was measured using a standard pH meter (pHS - 25). Soil electrical conductivity (EC) (deionized water: soil, 5: 1) was determined by a conductometer (DDS - 241 307A, INESA Scientific Instrument, Shanghai, China). Total nitrogen (TN) was measured through an automatic Kjeldahl distillation titration method (Cabrera and Beare, 1993). Total calcium (TCa), total magnesium (TMg), total copper (TCu), total iron (TFe), total manganese (TMn), total zinc (TZn) and total potassium (TK) in soil were determined by H₂SO₄ - HClO₄ digestion method and analyzed by flame spectrophotometer. Total phosphorus (TP) was determined by H₂SO₄ - HClO₄ digestion method and analyzed by ultraviolet spectrophotometer (Nobile et al., 2020). Bao (2000) method was utilized to measure Alkali-hydrolyzed nitrogen (AN). The NaHCO₃ leaching molybdenum antimony colorimetric technique was used to measure available phosphorus (AP). Leaching NH₄OAC (pH=7.00) solution in 1.00 mol L⁻¹ was used, and then the rapid available potassium (AK), exchange calcium (Ca²⁺) and exchange magnesium (Mg²⁺) were analyzed by flame photometer (Bao, 2000). Soil organic matter (SOM) was determined by H₂SO₄ - K₂Cr₂O₇ titration (Kalembasa and Jenkinson, 2006). After digestion with HNO₃ - HClO₄, total molybdenum (TMO) was determined by ICP - MS method, and total boron (TB) was measured by methimine colorimetry. The available molybdenum (AMo) was determined by ICP - MS method after leaching with oxalic acid and ammonium oxalate. Soil available copper (ACu) and available zinc (AZn) were analyzed by 0.10mol L⁻¹ HCl extraction and flame spectrophotometer. The leaching was carried out by DTPA - TEA with flame separation. Soil available manganese (AMn) and available iron (AFe) were analyzed by optical photometer. Leaching with boiling water and determination of available boron (AB) by methylimine colorimetry (Bao, 2000).

2.3.2 Plant nutrient determination

Plant total potassium (PK), calcium (PCa), magnesium (PMg), copper (PCu), iron (PFe), zinc (PZn) and manganese (PMn) were analyzed by flame spectrophotometer after digestion with H₂SO₄ -

H₂O₂, and plant total nitrogen (PN) was measured through an automatic Kjeldahl distillation titration method. Total phosphorus (PP) was determined by vanadium-molybdenum yellow colorimetric method. Total boron (PB) was analyzed by curcumin colorimetric method (Bao, 2000).

2.4 Statistical analyses

Excel 2021 was utilized for basic data collation and processing analyses, SPSS Statistics 26.0 (IBM, New York, USA) was employed to conduct one-way ANOVA ($p < 0.05$), while Duncan's test was used for multiple comparisons of the data. RDA and Pearson correlation analyses were performed to investigate the relationships between soil chemical properties and soil nutrients. In addition, Principal Coordinate Analyses (PCA) was conducted using the vegan package in R software to compare nutrient absorption differences among various treatments. Mantel correlation was applied to analyses the relationship between soil chemical properties and plant nutrients. The Origin2021 was used to visualize the results.

3 Results

3.1 Effect of simulated acidification on soil basic chemical properties and nutrients of eggplant in greenhouse

3.1.1 Effect of acidification on soil EC, SOM and Al³⁺

The results showed that soil organic matter (SOM) content decreased by 49% - 50% to 5.57 g kg⁻¹ at pH 4.5 compared with pH 7.0 - 7.5 (Table 1). Meanwhile, the soil electrical conductivity (EC) value at pH 4.5 was significantly different from that at pH 7.5, and the exchangeable aluminum (Al³⁺) content in soil reached the maximum value (113 mg kg⁻¹) at pH 4.5, which was 4.42 times that at pH 7.5. Soil Al³⁺ content at pH 7.0 and 7.5 was significantly different from that at pH 4.5 and 5.0 (Table 1).

TABLE 1 Effects of acidification on EC, SOM and Al³⁺.

Treatment pH	EC (ms cm ⁻¹)	SOM (g kg ⁻¹)	Al ³⁺ (mg kg ⁻¹)
7.50	0.19 ± 0.01e	11.08 ± 0.45a	25.65 ± 4.48d
7.00	0.23 ± 0.01e	10.90 ± 0.95a	31.72 ± 2.02d
6.50	0.56 ± 0.02d	9.19 ± 0.99ab	50.62 ± 6.46c
6.00	0.68 ± 0.01d	9.53 ± 0.33ab	62.10 ± 3.31c
5.50	1.22 ± 0.08c	8.51 ± 0.33ab	93.82 ± 2.78b
5.00	1.70 ± 0.03b	7.98 ± 0.49b	99.90 ± 7.31ab
4.50	2.01 ± 1.07a	5.57 ± 1.42c	113.40 ± 11.76a

The same letter in the same column indicates that the results are not significant ($P < 0.05$).

3.1.2 Effect of acidification on macro elements content

Soil total nitrogen (TN) peaked at pH 7.5, 55% higher than at pH 4.5. Alkali-hydrolyzed nitrogen (AN) increased with acidity, ranging from 51 - 81 mg kg⁻¹ (Table 2). The content of soil total phosphorus (TP) at soil pH7.5 was significantly higher than that at soil pH 4.5. Available phosphorus (AP) varied greatly, with the highest (278 mg kg⁻¹) at pH 4.5 and the lowest (134 mg kg⁻¹) at pH 6.5, and the difference between treatments was significant (Table 2). The data indicated that the trend in the variation of total potassium (TK) and available potassium (AK) content in the soil decreased as soil pH decreased, the soil pH content at 7.5 was significantly different from that at 4.5 (Table 2).

3.1.3 Effect of acidification on medium elements content

With the decrease in soil pH, the contents of calcium (Ca) and magnesium (Mg) in the soil also gradually decreased, as presented in Table 2; soil total calcium (TCa), total magnesium (TMg), exchange calcium (Ca²⁺) and exchange magnesium (Mg²⁺) in soil

were consistent with the changes of total potassium, and the highest content at soil pH7.5 was significantly different from that at soil pH 4.5, which significantly increased by 346%, 173%, 196% and 346%, respectively (Table 2).

3.1.4 Effect of acidification on trace elements content

Soil total iron (TFe) and available iron (AFe) content exhibited an increasing trend as soil pH decreased. The highest TFe content (12.71 g kg⁻¹) was recorded at pH 4.5, while the lowest values (9.09 and 9.13 g kg⁻¹) were observed at pH levels of 7.0 and 7.5 (Table 2). The maximum AFe concentration of 90 mg kg⁻¹ and the minimum concentration of 9.09 mg kg⁻¹ were measured at pH 4.5 and 7.5, both treatments were statistically significant (Table 2). In addition, available manganese (AMn) at pH levels of 7.0 - 7.5 was statistically significant when compared to pH 4.5 (Table 2).

Soil total copper (TCu) content at pH 4.5 was statistically significant when compared to pH 7.0, while the other treatments were comparable and not statistically significant (Table 2). The content of soil available copper (ACu) at pH 4.5 was 0.17 mg kg⁻¹

TABLE 2 Effect of acidification on soil nutrients of eggplant in greenhouse.

pH	7.5	7.0	6.5	6.0	5.5	5.0	4.5
TN(g kg ⁻¹)	1.30 ± 0.06a	1.00 ± 0.21ab	0.87 ± 0.08bc	0.81 ± 0.04bc	0.72 ± 0.08bc	0.75 ± 0.08bc	0.59 ± 0.13b
TP(g kg ⁻¹)	0.66 ± 0.05a	0.60 ± 0.02ab	0.51 ± 0.13ab	0.50 ± 0.04ab	0.50 ± 0.03ab	0.48 ± 0.01ab	0.42 ± 0.03b
TK(g kg ⁻¹)	6.12 ± 1.10a	5.18 ± 0.15ab	4.94 ± 0.34ab	4.90 ± 0.09ab	4.39 ± 0.63ab	4.52 ± 0.71ab	3.79 ± 0.60b
TCa(g kg ⁻¹)	2.81 ± 0.08a	2.44 ± 0.12a	1.97 ± 0.14b	1.77 ± 0.20b	1.57 ± 0.14b	0.93 ± 0.23c	0.63 ± 0.05c
TMg(g kg ⁻¹)	8.73 ± 0.36a	7.32 ± 0.87ab	6.11 ± 1.01abc	7.12 ± 1.09ab	5.84 ± 1.46bcd	3.58 ± 0.36cd	3.20 ± 0.23d
TFe(g kg ⁻¹)	9.13 ± 0.48c	9.09 ± 0.22c	10.98 ± 0.35b	11.00 ± 0.30b	11.00 ± 0.35b	12.27 ± 0.44ab	13.71 ± 1.22a
TMn(mg kg ⁻¹)	189 ± 25a	208 ± 33a	185 ± 27a	156 ± 13a	167 ± 10a	194 ± 16a	173 ± 23a
TCu(mg kg ⁻¹)	6.09 ± 0.59b	6.06 ± 0.38b	7.32 ± 0.74b	6.46 ± 0.38b	7.26 ± 0.81b	7.63 ± 0.63b	11.29 ± 0.44a
TZn(mg kg ⁻¹)	23.17 ± 0.83c	26.02 ± 0.53bc	28.92 ± 1.15ab	29.61 ± 2.56ab	30.03 ± 0.21ab	31.75 ± 1.86a	33.44 ± 2.27a
TB(mg kg ⁻¹)	460 ± 14a	429 ± 20ab	368 ± 30bc	311 ± 21cd	280 ± 31de	235 ± 12ef	215 ± 9.3f
TMo(mg kg ⁻¹)	8.37 ± 0.96a	8.22 ± 1.04a	6.85 ± 0.16a	4.35 ± 0.85b	2.63 ± 0.47bc	1.99 ± 0.46c	1.58 ± 0.30c
AN(mg kg ⁻¹)	51 ± 6.47c	54 ± 2.26c	54 ± 2.26c	59 ± 2.99bc	67 ± 3.20b	67 ± 3.78b	817 ± 3.61a
AP(mg kg ⁻¹)	140 ± 15.20b	156 ± 7.18b	134 ± 9.64b	176 ± 13b	178 ± 17b	178 ± 7.40b	278 ± 20.19a
AK(mg kg ⁻¹)	870 ± 2.35a	810 ± 31ab	784 ± 28bc	749 ± 9.51bc	731 ± 25c	669 ± 24d	640 ± 2.72d
Ca ²⁺ (mg kg ⁻¹)	1227 ± 54a	1053 ± 4.79b	1052 ± 22b	827 ± 94c	756 ± 36c	473 ± 42d	414 ± 40d
Mg ²⁺ (mg kg ⁻¹)	147 ± 8.51a	132 ± 11.82a	114 ± 7.95ab	94 ± 23.62b	79 ± 8.24bc	45 ± 9.77cd	33 ± 8.41d
AFe(mg kg ⁻¹)	9.09 ± 0.61d	10.85 ± 0.29d	19.50 ± 5.34d	38.46 ± 3.34c	51.30 ± 6.04c	68.00 ± 6.21b	90.36 ± 4.52a
AMn(mg kg ⁻¹)	4.89 ± 0.39c	4.14 ± 0.30c	7.06 ± 1.11c	12.22 ± 0.49b	15.89 ± 1.18ab	18.85 ± 3.42a	20.19 ± 1.85a
ACu(mg kg ⁻¹)	0.20 ± 0.02d	0.28 ± 0.02c	0.31 ± 0.01bc	0.30 ± 0.02bc	0.34 ± 0.00ab	0.34 ± 0.01ab	0.37 ± 0.01a
AZn(mg kg ⁻¹)	8.02 ± 0.26b	8.36 ± 0.44b	8.52 ± 0.16b	8.37 ± 0.30b	9.47 ± 0.90ab	9.57 ± 1.29ab	10.74 ± 0.43a
AB(mg kg ⁻¹)	52.14 ± 1.11a	43.43 ± 8.59ab	33.82 ± 3.02bc	30.84 ± 1.59c	31.59 ± 0.67c	27.24 ± 2.97c	27.83 ± 1.69c
AMo(mg kg ⁻¹)	0.13 ± 0.00a	0.12 ± 0.00b	0.10 ± 0.00bc	0.10 ± 0.00cd	0.09 ± 0.00cde	0.08 ± 0.00de	0.08 ± 0.01e

The same letter in the same line means the difference is not significant (p<0.05).

higher than that at pH 7.5 (Table 2). The highest values of total and available zinc (TZn and AZn) content were recorded at pH 4.5, which were statistically significant compared to pH 6.0, 7.0, and 7.5. The variation trend of boron (B) and molybdenum (Mo) contents in soil is consistent with that of zinc (Zn) contents in soil, and the difference between the content of pH 4.5 and the content of pH 7.5 is very significant (Table 2).

In summary, the contents and availability of soil trace elements B and Mo are the highest in the neutral range of soil pH 7.0 and 7.5, while the contents and availability of soil Fe, Cu and Zn are the highest in the strong acidic range of pH 4.5 and 5.0.

3.2 Effect of simulated soil acidification on nutrient uptake of eggplant plant in greenhouse

3.2.1 Effect of soil acidification on plant uptake of macro elements nutrient

The growth rate of eggplant exhibited a declining trend with increasing soil acidity (Figure 1). Meanwhile, the macro elements composition data (nitrogen, phosphorus, and potassium - NPK) in various plant parts, including root, stem, leaf, and fruit tissues, were statistically significant (Figure 2). The total nitrogen content in plant (PN) reached its maximum at pH levels of 7.0 - 7.5, showing a significant increase of 263% - 322% compared to plant grown at pH 4.5 (Figure 2A). The distribution of phosphorus in each part of the plant was significant. The maximum contents of total phosphorus (PP), leaf phosphorus (LP) and stem phosphorus (SP) at pH 7.5 were significantly different from those at pH 4.5 (Figure 2B). The absorption of fruit potassium (FK) was the highest, while the absorption of root potassium (RK) was the lowest and decreased with the decrease of soil pH. At pH 5.5 and 6.0, leaf potassium (LK) and stem potassium (SK) contents were slightly higher than pH 6.5 (Figure 2C).

3.2.2 Effect of soil acidification on plant uptake of medium elements nutrient

Soil acidification significantly reduced the distribution of calcium in plant tissues. The calcium concentration and absorption of fruits (FCa) and roots (RCa) were higher than those of leaves (LCa) and stems (SCa). The maximum total calcium content (PCa) of plant was $1.19 \text{ g plant}^{-1}$ at pH 7.5, which was significantly different from that at soil pH 4.5 (Figure 3A). The results showed that with the increase of soil pH, the magnesium distribution of fruit (FMg) was the highest, and that of root (RMg) was the lowest (Figure 3B).

3.2.3 Effect of soil acidification on plant uptake of trace elements nutrient

Soil acidification will affect the significant absorption and distribution of trace element nutrients in eggplant plants (Figure 4). Most absorbed boron (B) was found in fruit tissues at pH 7.5, followed by stems. The plants total boron content (PB) at pH 7.5 was 235% - 299% higher than at pH 4.5 - 5.0 (Figure 4A). Furthermore, total plant molybdenum content (PMo) at pH 7.5 was significantly higher than at pH 4.5 - 5.0 (Figure 4B). With the pH set at 6.5, the copper content in fruits (FCu) registered a significant 139% rise as compared to the value at pH 4.5 (Figure 4C). Total plant copper (PCu) ranged from $1.58 - 3.09 \text{ g plant}^{-1}$, peaking at pH 7.5 and dipping at pH 5.0 (Figure 4C). Total plant zinc (PZn) followed similar trend, with the highest levels at pH 7.5 and the lowest at pH 4.5 (Figure 4D).

Data on total plant iron (PFe) content are shown in Figure 4E, revealing significant differences in leaf iron (LFe) and root iron (RFe) among treatments. The impact of seven pH treatments on plant manganese (PMn) content was statistically significant, with levels ranging from $7.13 - 19.49 \text{ mg plant}^{-1}$, peaking at pH 5.0 and lowest at pH 7.0 (Figure 4F). In summary, the total amounts of boron (B), molybdenum (Mo), copper (Cu), zinc (Zn), and iron (Fe) were lowest at pH 4.5 and 5.0, while manganese (Mn) was highest.



FIGURE 1
Growth performance of eggplant under varied acidification treatments.

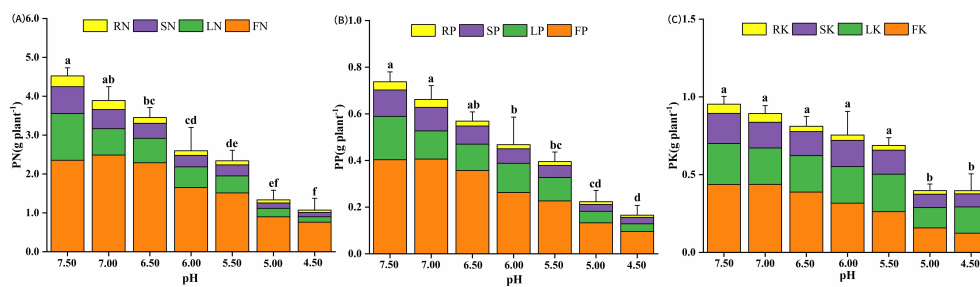


FIGURE 2

Effect of soil acidification on macro elements nutrient uptake of eggplant in greenhouse. (A) Total plant nitrogen; (B) Total plant phosphorus; (C) Total plant potassium ($p < 0.05$). Different lower-case letters indicate significant differences between treatment ($p < 0.05$).

3.3 Principal component analyses of soil acidification on nutrient uptake of eggplant in greenhouse

Principal component analyses of soil acidification on nutrient uptake of eggplant (Figure 5). PCA analyses is used to demonstrate the effects of different simulated acidification treatments on plant nutrients. PCA analyses shows that the nutrient distribution capacity of plant organs at soil pH 4.5, 5.0, 5.5 and 6.0 is well separated from the other four acidity ranges on the PCA1. And the two axes together explained 94% of the total variation. Adonis results also confirmed that soil acidification had a significant effect on plant nutrients ($R^2 = 0.996$, $P = 0.032$).

3.4 Comprehensive analyses of nutrient absorption of greenhouse eggplant by soil acidification

As can be seen from Table 3, the three most important chemical factors for macro elements nutrient uptake of eggplant in greenhouse under simulated soil acidification conditions were Mg^{2+} ($r = 0.99$,

$p = 0.001$), pH ($r = 0.60$, $p = 0.001$) and TB ($r = 0.59$, $p = 0.001$). The three most important chemical factors of medium elements nutrient uptake in eggplant plants in solar greenhouse were Mg^{2+} ($r = 0.94$, $p = 0.001$), TCa ($r = 0.61$, $p = 0.001$) and pH ($r = 0.58$, $p = 0.001$). The three most important chemical factors of trace elements nutrient uptake in eggplant in greenhouse were Mg^{2+} ($r = 0.69$, $p = 0.001$), pH ($r = 0.32$, $p = 0.001$) and TB ($r = 0.30$, $p = 0.001$). In conclusion, soil pH and Mg^{2+} play a crucial role in regulating plant nutrient uptake under simulated acidification conditions. Therefore, we should monitor and control the soil pH in the greenhouse and avoid the application of excessive and concentrated physiological acids and nitrogen-containing fertilizers to ensure the healthy growth of eggplant in the greenhouse.

4 Discussion

4.1 Effect of simulated soil acidification on soil physicochemical properties in greenhouse

Soil nutrients are essential for the growth and development of plants. However, intensive use of chemicals in all cropping systems

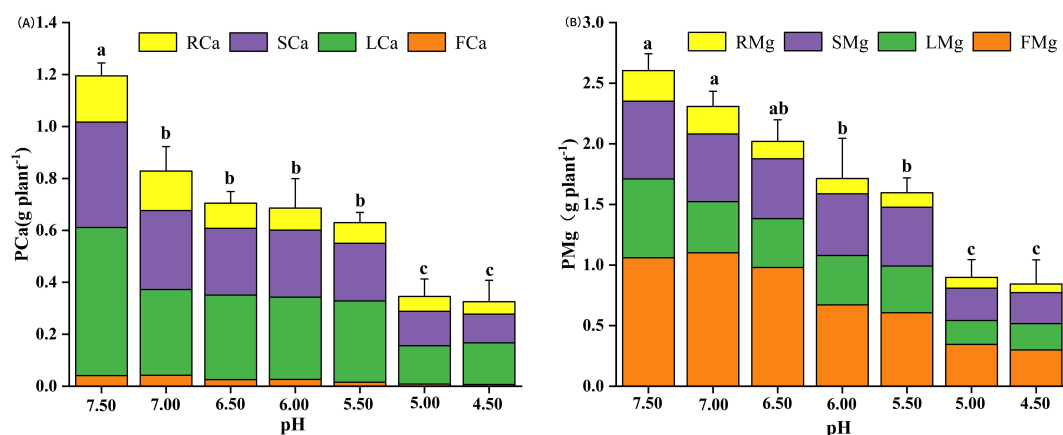


FIGURE 3

Effect of soil acidification on medium elements nutrient uptake of eggplant in greenhouse. (A) Total plant calcium; (B) Total Plant magnesium ($p < 0.05$). Different lower-case letters indicate significant differences between treatment ($p < 0.05$).

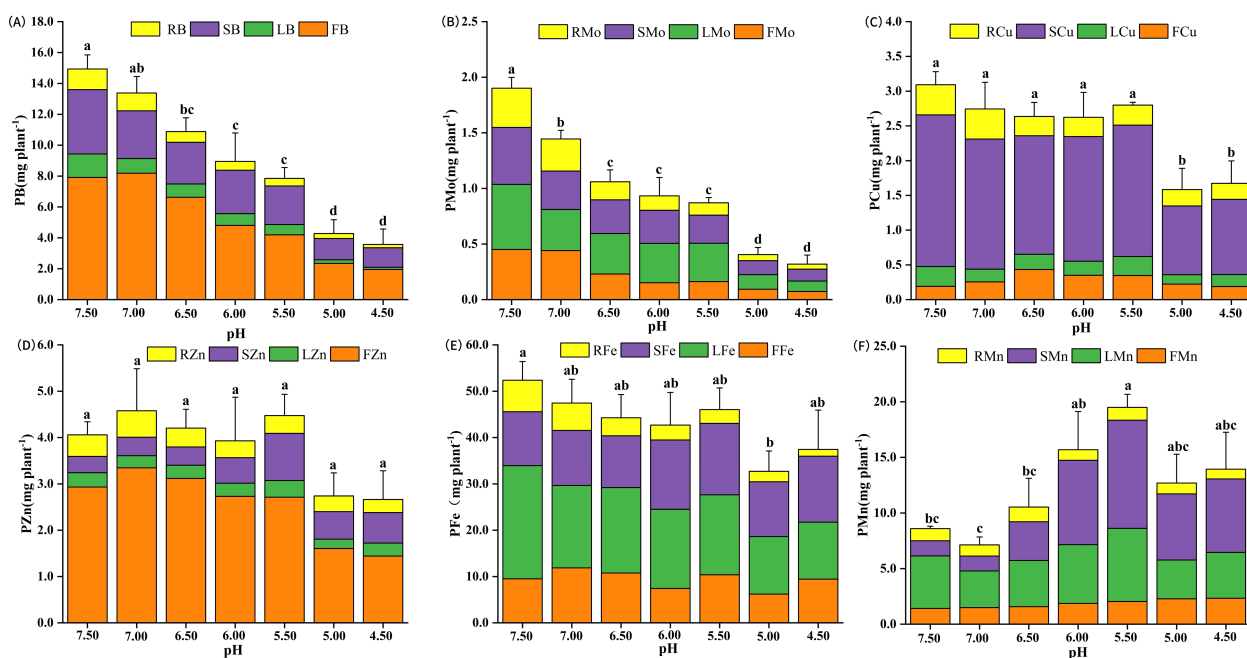


FIGURE 4

Effect of soil acidification on trace elements nutrient uptake of eggplant in greenhouse. (A) Total plant boron. (B) Total plant molybdenum. (C) Total plant copper. (D) Total plant zinc. (E) Total plant iron. (F) Total plant manganese ($p < 0.05$). Different lower-case letters indicate significant differences between treatment ($p < 0.05$).

led to environmental pollution and soil degradation issues (Leghari et al., 2024). In greenhouse conditions fertilizers are excessively applied, which resulted in the soil acidification and consequently affected nutrient availability in eggplant (Wang et al., 2022). The continued application of dilute sulfuric acid results in a decrease in soil pH, leading to an increase in soil EC value (Zhang et al., 2020; Zhou et al., 2020). In this study, EC was observed to be highest, ranging from 1.70 - 2.01 ms cm^{-1} , at pH levels between 5.00 - 4.50

(Table 1, $p < 0.05$). This increase in H^+ concentration significantly impacts the alteration of physicochemical properties (Junior et al., 2020; Raza et al., 2020). Soil acidification contributes to the depletion of essential basic cations, including K^+ , Ca^{2+} , and Mg^{2+} (Cai et al., 2021; Du et al., 2024b), which aligns with the findings of the present study. Meanwhile, the results concerning Mg^{2+} in our research diverge from those reported by Vogels et al. (2024). This inconsistency may be explained by the increased production of H^+ under acidic conditions, which can lead to enhanced leaching losses of Ca^{2+} and Mg^{2+} (Cusack et al., 2016). In addition, soil acidification may diminish the soil's capacity to retain N, P, K, and other essential nutrients (Li et al., 2018; Bai et al., 2020; Cai et al., 2021).

Soil acidification leads to the production of toxic substances, such as Al^{3+} , which can accumulate significantly when soil $\text{pH} < 5.00$ (Wang et al., 2023b; Borges et al., 2024; Du et al., 2024a). This phenomenon restricts the availability of phosphorus in the soil (Brownrigg et al., 2022; Xie et al., 2022; Baccari and Krouma, 2023). The highest concentration of Al^{3+} recorded was 113.40 mg kg^{-1} at soil pH of 4.5 (Table 1), which is 5 - 6 times the critical threshold for aluminum toxicity symptoms in plant (Cai et al., 2017). Under acidic soil conditions, aluminum is released into the soil solution in its active and toxic form, reaching levels that can inhibit root growth and damage root, thereby hindering the growth and development of eggplant (Bonomelli and Artacho, 2021). Some scholars have found that increasing soil acidification leads to an imbalance in soil nutrients, while heightened acidity reduces the decomposition rate of soil organic matter. In addition, a study on the excessive fertilization of tomatoes in solar greenhouses revealed that the content of AN remains at a

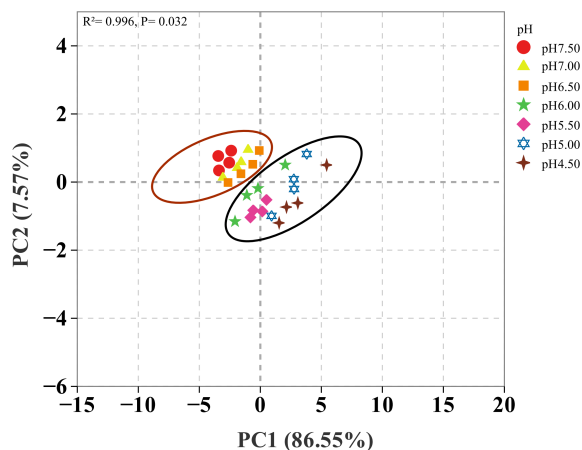


FIGURE 5

Principal component analyses of soil acidification on nutrient uptake of eggplant in greenhouse.

TABLE 3 Mantel test of acidification on the relationship between nutrient uptake and soil basic chemical properties of eggplant in greenhouse.

Soil properties	Macro elements in plant		Medium elements in plant		Trace elements in plant	
	Mantel r	P	Mantel r	P	Mantel r	P
pH	0.60	0.001	0.58	0.001	0.32	0.001
EC	0.44	0.001	0.43	0.001	0.20	0.007
Al ³⁺	0.32	0.122	0.31	0.002	0.01	0.333
SOM	0.13	0.036	0.12	0.133	0.06	0.258
TP	0.31	0.019	0.36	0.014	0.32	0.059
AP	0.33	0.010	0.28	0.016	0.02	0.369
TN	0.08	0.169	0.08	0.189	0.02	0.339
AN	0.25	0.036	0.21	0.058	0.07	0.212
TK	0.28	0.027	0.25	0.052	0.26	0.002
AK	0.39	0.001	0.43	0.001	0.24	0.006
TCa	0.57	0.001	0.61	0.001	0.39	0.005
Ca ²⁺	0.58	0.001	0.58	0.001	0.33	0.004
TMg	0.40	0.001	0.40	0.001	0.20	0.007
Mg ²⁺	0.99	0.001	0.94	0.001	0.69	0.001
TZn	0.32	0.005	0.36	0.002	0.34	0.017
AZn	0.28	0.012	0.31	0.009	0.24	0.059
TMn	0.02	0.354	0.04	0.317	0.03	0.334
AMn	0.33	0.001	0.30	0.001	0.16	0.019
TFe	0.42	0.001	0.46	0.001	0.29	0.023
AFe	0.43	0.001	0.40	0.001	0.23	0.002
TCu	0.20	0.040	0.21	0.041	0.10	0.151
ACu	0.20	0.067	0.22	0.066	0.06	0.229
TB	0.59	0.001	0.52	0.001	0.30	0.001
AB	0.31	0.001	0.30	0.019	0.13	0.154
TMo	0.47	0.001	0.43	0.001	0.26	0.004
AMo	0.53	0.001	0.55	0.001	0.31	0.015

Bold indicates the most influential factors.

moderate level (Lv et al., 2020). However, the finding that the content of AP was four times higher than the relative abundance standard aligns with this experiment's results (Table 3, $p < 0.05$), yet it contradicts the findings of Wang et al. (2023b). This discrepancy may be attributed to the increased production of phosphatase in acidic soils (Long et al., 2016; Hafez et al., 2022; Wang et al., 2022). In addition, it is important to highlight that as soil acidity increases, the content of soil AK tends to rise. This may be explained by the secretion of lower organic acids by the root system, which increases the net negative charge on the soil surface, there by facilitating the accumulation of K⁺ in the soil (Wang et al., 2022; Liu et al., 2023; Wang et al., 2023b).

Consequently, soil pH is a critical factor in regulating various soil properties (Hong et al., 2019; Wan et al., 2020; Mosley et al., 2024).

4.2 Effect of simulated soil acidification on nutrient uptake of eggplant in greenhouse

The ability of crops to absorb and utilize various nutrients is significantly influenced by soil acidification. Under acidic conditions, plants encounter difficulties in absorbing and utilizing essential elements necessary for their growth and development. Our findings demonstrate that plants absorb higher concentrations of Ca and Mg, a

result that aligns with the observations made by Wang et al. (2024). Mielcarek et al. (2023) reported that the P content in tomato plants decreased as pH increased, with the highest absorption of N, P, and K occurring at pH of 6.50. In our study, the absorption of N, P, and K by eggplant was highest at pH of 7.50 and lowest at pH of 4.50. These results indicate that the absorption of macronutrients by plant is severely inhibited under acidic conditions, with EC also identified as a primary factor affecting the absorption of substantial amounts of elements by plants. In addition, soil pH significantly impacts the absorption of trace elements (Yang et al., 2019). For instance, when soil pH decreased from 7.50 - 4.50, the absorption of B by plants declined from 4.19 - 2.30 g plant⁻¹, and the absorption of Mo exhibited a significant decreasing trend (Shi et al., 2018; Zhang et al., 2021).

Through our analyses, we hypothesized that soil acidification significantly impacts the nutrient absorption of eggplant, potentially by altering the availability of soil nutrients. For instance, soil acidification can lead to the release of substantial amount of Al, which inhibits the uptake of essential nutrient elements such as P, K and Fe by plant roots, as confirmed by Baccari and Krouma (2023). This occurs because acidification diminishes the soil's capacity to retain and supply fertilizers, exacerbates the loss of essential elements, and reduces the overall availability of soil nutrients. Furthermore, the quantity of nutrients absorbed by plants is contingent upon a specific subset of nutrients available in the surrounding soil (Brownrigg et al., 2022). The Mantell test revealed for the first time that the soil pH of eggplant grown in a solar greenhouse under simulated acidification significantly affects the amount of nutrients absorbed by the plants, thereby demonstrating that soil nutrient content is closely linked to the nutrient absorption capacity of the plants (Sánchez-Moreno and Curiel Yuste, 2022).

5 Conclusions

Elevated soil acidity significantly impacts the nutrient absorption process in eggplant. The SOM dropped to 325 5.57g kg⁻¹ at pH 4.50, while EC and Al³⁺ peaked at 2.01 ms cm⁻¹ and 113.40 mg kg⁻¹, respectively. At this pH level, the concentrations of macroelements, medium elements, and trace elements (B and Mo) were minimized, whereas the levels of other nutrients were maximized. Elements deficiencies in soil can diminish nutrient content in eggplant, with soil pH being the main factor. The findings provides useful insights for maintaining soil health and promoting sustainable greenhouse vegetable. However, present study primarily focused on the relationship between soil nutrients and plant nutrients. The future research should navigate the dynamic association between rhizosphere microorganisms and plant nutrient uptake in the context of soil acidification. This research is crucial for maintaining soil health and promoting sustainable greenhouse vegetable production.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

TW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. LXY: Methodology, Writing – original draft. ZW: Software, Writing – original draft. CY: Validation, Writing – original draft. FD: Investigation, Writing – original draft. DY: Resources, Writing – original draft. HX: Data curation, Writing – original draft. ZS: Data curation, Writing – original draft. RB: Writing – original draft. MA: Writing – original draft. LJY: Funding acquisition, Visualization, Writing – original draft. HF: Supervision, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This research was financially supported by the Program of Distinguished Professor of Liaoning Province China (01062920001).

Conflict of interest

Author CY was employed by the company Shenyang Hengxin Technology Management Consulting Service Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fpls.2025.1558458/full#supplementary-material>

References

- Adamczewska-Sowińska, K., Wojciechowski, W., Krygier, M., and Sowiński, J. (2022). Effect of soil regenerative practice on selected soil physical properties and eggplant (*Solanum melongena* L.) yield. *Agronomy* 12, 1686. doi: 10.3390/agronomy12071686
- Arwenyo, B., Varco, J. J., Dygert, A., Brown, S., Pittman, C. U., and Mlsna, T. (2023). Contribution of modified P-enriched biochar on pH buffering capacity of acidic soil. *J. Environ. Manage.* 339, 117863. doi: 10.1016/j.jenvman.2023.117863
- Babin, D., Deubel, A., Jacquiod, S., Sørensen, S. J., Geistlinger, J., Grosch, R., et al. (2019). Impact of long-term agricultural management practices on soil prokaryotic communities. *Soil Biol. Biochem.* 129, 17–28. doi: 10.1016/j.soilbio.2018.11.002
- Baccari, B., and Krouma, A. (2023). Rhizosphere acidification determines phosphorus availability in calcareous soil and influences faba bean (*Vicia faba*) tolerance to P deficiency. *Sustainability* 15, 6203. doi: 10.3390/su15076203
- Bai, X., Gao, J., Wang, S., Cai, H., Chen, Z., and Zhou, J. (2020). Excessive nutrient balance surpluses in newly built solar greenhouses over five years leads to high nutrient accumulations in soil. *Agriculture Ecosyst. Environ.* 288, 106717. doi: 10.1016/j.agee.2019.106717
- Ballagh, A., Cox, E. K., Lofton, J., and Arnall, D. B. (2023). Impacts of soil pH and extractable aluminum on winter canola production in the southern Great Plains. *J. Plant Nutr.* 47, 257–267. doi: 10.1080/01904167.2023.2275074
- Bao, S. D. (2000). *Soil and agricultural chemistry analysis* (Beijing, China: Soil and Agricultural Chemistry Analysis).
- Benelli, S., Ribaudou, C., Bertrin, V., Bartoli, M., and Fano, E. A. (2020). Effects of macrophytes on potential nitrification and denitrification in oligotrophic lake sediments. *Aquat. Bot.* 167, 103287. doi: 10.1016/j.aquabot.2020.103287
- Bonomelli, C., and Artacho, P. (2021). Aluminum toxicity in sweet cherry trees grown in an acidic volcanic soil. *Agronomy* 11, 1259. doi: 10.3390/agronomy11061259
- Borges, W. L. B., Andreotti, M., Pianta da Cruz, L. C., Osaki de Oliveira, D. Y., Borges, J. F., and Silva, L. (2024). Changes in soil chemical attributes in an agrosilvopastoral system six years after thinning of eucalyptus. *Plants* 13, 3050. doi: 10.3390/plants13213050
- Brownrigg, S., McLaughlin, M. J., McBeath, T., and Vadakattu, G. (2022). Effect of acidifying amendments on P availability in calcareous soils. *Nutrient Cycling Agroecosystems* 124, 247–262. doi: 10.1007/s10705-022-10241-1
- Cabrera, M. L., and Beare, M. H. (1993). Alkaline persulfate oxidation for determining total nitrogen in microbial biomass extracts. *Soil Sci. Soc. America J.* 57, 1007–1012. doi: 10.2136/sssaj1993.03615995005700040021x
- Cai, Z., Wang, B., Zhang, L., Wen, S., Xu, M., Misselbrook, T. H., et al. (2021). Striking a balance between N sources: Mitigating soil acidification and accumulation of phosphorus and heavy metals from manure. *Sci. Total Environ.* 754, 142189. doi: 10.1016/j.scitotenv.2020.142189
- Cai, J., Weiner, J., Wang, R., Luo, W., Zhang, Y., Liu, H., et al. (2017). Effects of nitrogen and water addition on trace element stoichiometry in five grassland species. *J. Plant Res.* 130, 659–668. doi: 10.1007/s10265-017-0928-2
- Cusack, D. F., Macy, J., and McDowell, W. H. (2016). Nitrogen additions mobilize soil base cations in two tropical forests. *Biogeochemistry* 128, 67–88. doi: 10.1007/s10533-016-0195-7
- Das, P. P., Singh, K. R. B., Nagpure, G., Mansoori, A., Singh, R. P., Ghazi, I. A., et al. (2022). Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices. *Environ. Res.* 214, 113821. doi: 10.1016/j.envres.2022.113821
- Du, L., Tian, S., Zhao, N., Zhang, B., Mu, X., Tang, L., et al. (2024a). Evaluating soil acidification risk and its effects on biodiversity-ecosystem multifunctionality relationships in the drylands of China. *For. Ecosyst.* 11, 1001789. doi: 10.1016/j.fecs.2024.100178
- Du, L., Zhang, Z., Chen, Y., Wang, Y., Zhou, C., Yang, H., et al. (2024b). Heterogeneous impact of soil acidification on crop yield reduction and its regulatory variables: A global meta-analysis. *Field Crops Res.* 319, 109643. doi: 10.1016/j.fcr.2024.109643
- Fan, Z., Lali, M. N., Xiong, H., Luo, Y., Wang, Y., Wang, Y., et al. (2024). Seedlings of *Poncirus trifoliata* exhibit tissue-specific detoxification in response to NH_4^+ toxicity. *Plant Biol.* 26, 467–475. doi: 10.1111/plb.13621
- Guo, F., Ding, C., Zhou, Z., Huang, G., and Wang, X. (2018). Stability of immobilization remediation of several amendments on cadmium contaminated soils as affected by simulated soil acidification. *Ecotoxicol. Environ. Saf.* 161, 164–172. doi: 10.1016/j.ecoenv.2018.05.088
- Hafez, M., Abdallah, A. M., Mohamed, A. E., and Rashad, M. (2022). Influence of environmental-friendly bio-organic ameliorants on abiotic stress to sustainable agriculture in arid regions: A long term greenhouse study in northwestern Egypt. *J. King Saud Univ. - Sci.* 34, 246–256. doi: 10.1016/j.jksus.2022.102212
- Hafez, M., Popov, A. I., and Rashad, M. (2020). Evaluation of the effects of new environmental additives compared to mineral fertilizers on the leaching characteristics of some anions and cations under greenhouse plant growth of saline-sodic soils. *Open Agric. J.* 14, 246–256. doi: 10.2174/18744331502014010246
- Hong, S., Gan, P., and Chen, A. (2019). Environmental controls on soil pH in planted forest and its response to nitrogen deposition. *Environ. Res.* 172, 159–165. doi: 10.1016/j.envres.2019.02.020
- Junior, E. C., Gonçalves, A., Seidel, E. P., Ziemer, G. L., Zimmermann, J., de Oliveira, V. H. D., et al. (2020). Effects of liming on soil physical attributes: A review. *J. Agric. Sci.* 12, 278. doi: 10.5539/jas.v12n10p278
- Kalembasa, S. J., and Jenkinson, D. S. (2006). A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. *J. Sci. Food Agric.* 24, 1085–1090. doi: 10.1002/jsfa.2740240910
- Latifah, O., Ahmed, O. H., and Majid, N. M. A. (2017). Soil pH buffering capacity and nitrogen availability following compost application in a tropical acid soil. *Compost Sci. Utilization* 26, 1–15. doi: 10.1080/1065657x.2017.1329039
- Leghari, S. J., Han, W., Soomro, A. A., Shoukat, M. R., Zain, M., Wei, Y., et al. (2024). Navigating water and nitrogen practices for sustainable wheat production by model-based optimization management systems: A case study of China and Pakistan. *Agric. Water Manage.* 300, 108917. doi: 10.1016/j.agwat.2024.108917
- Li, Y., Sun, J., Tian, D., Wang, J., Ha, D., Qu, Y., et al. (2018). Soil acid cations induced reduction in soil respiration under nitrogen enrichment and soil acidification. *Sci. Total Environ.* 615, 1535–1546. doi: 10.1016/j.scitotenv.2017.09.131
- Liang, H., Tan, Y., Yin, J., Peng, Y., Wei, M., Chen, H., et al. (2024). Phosphate fertilizers' Dual role in cadmium-polluted acidic agricultural soils: dosage dependency and passivation potential. *Agronomy* 14, 2201. doi: 10.3390/agronomy14102201
- Liu, D., Tian, R., Liu, X., and Li, H. (2023). Polarization induced covalent/hydrogen bonding adsorption of NH_4^+ and K^+ in soils: comparison study on permanently and variably charged soils. *J. Soils Sediments* 24, 722–731. doi: 10.1007/s11368-023-03669-7
- Long, M., Wu, H.-H., Smith, M. D., La Pierre, K. J., Lü, X.-T., Zhang, H.-Y., et al. (2016). Nitrogen deposition promotes phosphorus uptake of plants in a semi-arid temperate grassland. *Plant Soil* 408, 475–484. doi: 10.1007/s11104-016-3022-y
- Lv, H., Zhao, Y., Wang, Y., Wan, L., Wang, J., Butterbach-Bahl, K., et al. (2020). Conventional flooding irrigation and over fertilization drives soil pH decrease not only in the top- but also in subsoil layers in solar greenhouse vegetable production systems. *Geoderma* 363, 114156. doi: 10.1016/j.geoderma.2019.114156
- Mielcarek, A., Józwiak, T., Rodziejewicz, J., Bryszewski, K., Janczukowicz, W., Kalisz, B., et al. (2023). Recovery of phosphorus and other minerals from greenhouse wastewater generated during soilless tomato cultivation by means of alkalizing agents. *Sci. Total Environ.* 892, 164757. doi: 10.1016/j.scitotenv.2023.164757
- Mosley, L. M., Rengasamy, P., and Fitzpatrick, R. (2024). Soil pH: Techniques, challenges and insights from a global dataset. *Eur. J. Soil Sci.* 75, e70021. doi: 10.1111/ejss.70021
- Munyanza, V., Zhang, W., Haider, S., Xu, F., Wang, C., and Ding, G. (2024). Strategies for alleviating aluminum toxicity in soils and plants. *Plant Soil* 504, 167–190. doi: 10.1007/s11104-024-06617-7
- National Bureau of Statistics of China (2020). *China Statistical Yearbook*, In Chinese.
- Nobile, C. M., Bravin, M. N., Becquer, T., and Paillat, J. M. (2020). Phosphorus sorption and availability in an andosol after a decade of organic or mineral fertilizer applications: Importance of pH and organic carbon modifications in soil as compared to phosphorus accumulation. *Chemosphere* 239, 124709. doi: 10.1016/j.chemosphere.2019.124709
- Puissant, J., Jones, B., Goodall, T., Mang, D., Bland, A., Gweon, H. S., et al. (2019). The pH optimum of soil exoenzymes adapt to long term changes in soil pH. *Soil Biol. Biochem.* 138, 107601. doi: 10.1016/j.soilbio.2019.107601
- Raza, S., Miao, N., Wang, P., Ju, X., Chen, Z., Zhou, J., et al. (2020). Dramatic loss of inorganic carbon by nitrogen-induced soil acidification in Chinese croplands. *Global Change Biol.* 26, 3738–3751. doi: 10.1111/gcb.15101
- Sánchez-Moreno, S., and Curiel Yuste, J. (2022). Forest dieback switches the relationships between microfaunal bacterivore guilds and soil nutrients. *Soil Biol. Biochem.* 172, 108763. doi: 10.1016/j.soilbio.2022.108763
- Shen, Y., Zhang, Z., and Xue, Y. (2021). Study on the new dynamics and driving factors of soil pH in the red soil, hilly region of South China. *Environ. Monit. Assess.* 193, 304. doi: 10.1007/s10661-021-09080-4
- Shi, R.-y., Hong, Z.-N., Li, J.-Y., Jiang, J., Kamran, M. A., Xu, R.-K., et al. (2018). Peanut straw biochar increases the resistance of two Ultisols derived from different parent materials to acidification: A mechanism study. *J. Environ. Manage.* 210, 171–179. doi: 10.1016/j.jenvman.2018.01.028
- Shoghi Kalkhoran, S., Pannell, D., Polyakov, M., White, B., Chalak Haghighi, M., William Muger, A., et al. (2021). A dynamic model of optimal lime application for wheat production in Australia. *Aust. J. Agric. Resource Economics* 65, 472–490. doi: 10.1111/1467-8489.12424
- Vogels, J. J., Verberk, W. C. E. P., Kuper, J. T., Weijters, M. J., Verbaarschot, E., Lamers, L. P. M., et al. (2024). Nitrogen deposition and heathland management cause multi-element stoichiometric mismatches, reducing insect fitness. *Funct. Ecol.* 38, 2537–2552. doi: 10.1111/1365-2435.14671

- Wan, W., Tan, J., Wang, Y., Qin, Y., He, H., Wu, H., et al. (2020). Responses of the rhizosphere bacterial community in acidic crop soil to pH: Changes in diversity, composition, interaction, and function. *Sci. Total Environ.* 700, 134418. doi: 10.1016/j.scitotenv.2019.134418
- Wang, X., Ai, S., and Liao, H. (2023a). Deciphering interactions between phosphorus status and toxic metal exposure in plants and rhizospheres to improve crops reared on acid soil. *Cells* 12, 441. doi: 10.3390/cells12030441
- Wang, P., Guo, J., Xu, X., Yan, X., Zhang, K., Qiu, Y., et al. (2020b). Soil acidification alters root morphology, increases root biomass but reduces root decomposition in an alpine grassland. *Environ. pollut.* 265, 115016. doi: 10.1016/j.envpol.2020.115016
- Wang, Z., Li, T., Lu, C., Wang, C., Wu, H., Li, X., et al. (2024). Mowing aggravates the adverse effects of nitrogen addition on soil acid neutralizing capacity in a meadow steppe. *J. Environ. Manage.* 362, 121293. doi: 10.1016/j.jenvman.2024.121293
- Wang, Z., Tao, T., Wang, H., Chen, J., Small, G. E., Johnson, D., et al. (2023b). Forms of nitrogen inputs regulate the intensity of soil acidification. *Global Change Biol.* 29, 4044–4055. doi: 10.1111/gcb.16746
- Wang, Z., Wang, S., Bian, T., Song, Q., Wu, G., Awais, M., et al. (2022). Effects of nitrogen addition on soil microbial functional diversity and extracellular enzyme activities in greenhouse cucumber cultivation. *Agriculture* 12, 1366. doi: 10.3390/agriculture12091366
- Wang, L., Zou, R., Li, Y. C., Tong, Z., You, M., Huo, W., et al. (2020a). Effect of Wheat-Solanum nigrum L. intercropping on Cd accumulation by plants and soil bacterial community under Cd contaminated soil. *Ecotoxicol. Environ. Saf.* 206, 111383. doi: 10.1016/j.ecoenv.2020.111383
- Xie, W., Yang, J., Gao, S., Yao, R., and Wang, X. (2022). The effect and influence mechanism of soil salinity on phosphorus availability in coastal salt-affected soils. *Water* 14, 2804. doi: 10.3390/w14182804
- Yang, T.-Y., Cai, L.-Y., Qi, Y.-P., Yang, L.-T., Lai, N.-W., Chen, L.-S., et al. (2019). Increasing nutrient solution pH alleviated aluminum-induced inhibition of growth and impairment of photosynthetic electron transport chain in citrus sinensis seedlings. *BioMed Res Int.* 1–17. doi: 10.1155/2019/9058715
- Yang, W., Cui, H., Liu, Q., Wang, F., Liao, H., Lu, P., et al. (2024). Effect of nitrogen reduction by chemical fertilization with green manure (*Vicia sativa* L.) on soil microbial community, nitrogen metabolism and and yield of *Uncaria rhynchophylla* by metagenomics. *Arch. Microbiol.* 206, 106. doi: 10.1007/s00203-024-03839-2
- Yao, F., Chen, Y., Chen, Q., Qin, Z., Liu, X., Shi, Z., et al. (2024). Addition of organic amendments derived from invasive apple snails alleviated soil acidification, improved soil nitrogen and phosphorus effectiveness, microbial growth and maize yield in South China. *Environ. Technol. Innovation* 33, 103475. doi: 10.1016/j.eti.2023.103475
- Yuan, X., Ma, S., Geng, H., Cao, M., Chen, H., Zhou, B., et al. (2024). Joint effect of black carbon deriving from wheat straw burning and plastic mulch film debris on the soil biochemical properties, bacterial and fungal communities. *Sci. Total Environ.* 947, 174522. doi: 10.1016/j.scitotenv.2024.174522
- Zhang, S., Chen, X., Ji, Z., Yan, X., Kong, K., Cai, Y., et al. (2022a). Reducing aluminum is the key nutrient management strategy for ameliorating soil acidification and improving root growth in an acidic citrus orchard. *Land Degradation Dev.* 34, 1681–1693. doi: 10.1002/ldr.4561
- Zhang, J., Liu, Y., Sun, Y., Wang, H., Cao, X., and Li, X. (2020). Effect of soil type on heavy metals removal in bioelectrochemical system. *Bioelectrochemistry* 136, 107596. doi: 10.1016/j.bioelechem.2020.107596
- Zhang, X., Shan, X., Fu, H., and Sun, Z. (2022b). Effects of artificially-simulated acidification on potential soil nitrification activity and ammonia oxidizing microbial communities in greenhouse conditions. *PeerJ* 10, e14088. doi: 10.7717/peerj.14088
- Zhang, K., Wei, H., Chai, Q., Li, L., Wang, Y., and Sun, J. (2024). Biological soil conditioner with reduced rates of chemical fertilization improves soil functionality and enhances rice production in vegetable-rice rotation. *Appl. Soil Ecol.* 195, 105242. doi: 10.1016/j.apsoil.2023.105242
- Zhang, S., Yang, X., Hsu, L.-C., Liu, Y.-T., Wang, S.-L., White, J. R., et al. (2021). Soil acidification enhances the mobilization of phosphorus under anoxic conditions in an agricultural soil: Investigating the potential for loss of phosphorus to water and the associated environmental risk. *Sci. Total Environ.* 793, 148531. doi: 10.1016/j.scitotenv.2021.148531
- Zhang, Y., Zhang, S., Wang, R., Cai, J., Zhang, Y., Li, H., et al. (2016). Impacts of fertilization practices on pH and the pH buffering capacity of calcareous soil. *Soil Sci. Plant Nutr.* 62, 432–439. doi: 10.1080/00380768.2016.1226685
- Zhou, D., Meinke, H., Wilson, M., Marcelis, L. F. M., and Heuvelink, E. (2021). Towards delivering on the sustainable development goals in greenhouse production systems. *Resources Conserv. Recycling* 169, 105379. doi: 10.1016/j.resconrec.2020.105379
- Zhou, C., Yuan, H., Ning, C., Li, S., Xia, Z., Zhu, M., et al. (2020). Evaluation of different types and amounts of amendments on soil cd immobilization and its uptake to wheat. *Environ. Manage.* 65, 818–828. doi: 10.1007/s00267-020-01287-4