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Invited Perspective

Strategic directions for mitigating cultivated soil acidification in China: Insights from global progress and local practice

Soil acidification is a global soil degradation issue that impairs soil quality and hinders the sustainable development of agricultural systems, posing a severe threat to national food security especially in populous countries like China. This perspective synthesizes the global research progress and practical experience in mitigating cultivated soil acidification. In the context of China's high-intensity land use and the demands for advancing agricultural science and technology, we propose three core strategic directions for future research and practice: i) formulating a national zoning plan for the prevention and control of cultivated soil acidification, ii) achieving breakthroughs in key core technologies for acidified soil management, and iii) implementing major action plans for large-scale technology promotion. These strategies aim to provide scientific and technological support for curbing soil acidification, safeguarding cultivated land quality, and ensuring national food security.

Soil acidification is a global soil degradation problem driven primarily by atmospheric nitrogen deposition and agricultural activities (Guo *et al*., 2010; Chen *et al*., 2023; Smith *et al*., 2024). Atmospheric nitrogen deposition has caused an average 0.16-unit decline in soil pH over the past four decades, with hotspots in the eastern United States, southern Brazil, Europe, and South and East Asia (Chen *et al*., 2023). In China, soil acidification in cultivated land is characterized by extensive spatial distribution, rapid temporal aggravation, and high potential for further acidification. It has become a major constraint on agricultural sustainability of the country, given its large population, limited arable land, and long-term high-intensity soil utilization.

Currently, the total area of acidic cultivated land (pH $<$ 6.5) in China is approximately 61.3×10^4 km^2; among this, 17.4×10^4 km^2 is classified as highly acidic (pH $<$ 5.5), with 11.07×10^4 km^2 distributed in the southern red-yellow soil region (unpublished data). Compared with the Second National Soil Survey (1980s), the total area of acidic soils in China has increased by 64.5×10^4 km^2 by the 2010s (Zhao *et al*., 2023). Specifically, the areas of pH $\leqslant$ 5.0, pH 5.0–5.5, and pH 5.5–6.5 increased by 3.1×10^4, 11.6×10^4, and 49.9×10^4 km^2, respectively. Spatially, the area of acidic soils has increased by 19.6×10^4 km^2 in the southern red-yellow soil region, 23.0×10^4 km^2 in the northeastern region, and 22.0×10^4 km^2 in other regions, reflecting the nationwide spread of soil acidification. Long-term excessive application of nitrogen fertilizer is the dominant anthropogenic driver, leading to soil pH declines of 0.42, 0.62, and 0.37 units in farmland, grassland, and forest, respectively (Guo *et al*., 2010; Yang *et al*., 2012; Zhu *et al*., 2016).

Soil acidification triggers a cascade of adverse ecological and agricultural effects: it exacerbates the degradation of soil fertility, impairs key soil ecological functions, and elevates the risk of heavy metal mobilization and contamination (Shen, 2008; Xu, 2013). These impacts directly deteriorate cultivated land quality, reduce crop yields, and threaten the stability of agro-ecosystems, posing a substantial challenge to food security especially in populous countries like China (Shen and Teng, 2015, 2023; Lehmann *et al*., 2020). Curbing the trend of soil acidification has thus become an urgent scientific and technological priority for agro-ecosystem health management and national food security guarantee.

Global progress in soil acidification mitigation

Developed countries have long focused on research and management of soil acidification, forming a series of mature technologies and management models tailored to their national conditions (Sharma *et al*., 2025). European and North American countries were the first to investigate acid deposition-driven soil acidification processes, prediction models, and associated ecological impacts (De Vries and Breeuwsma, 1987; Caputo *et al*., 2016; Goulding, 2016; Zeng *et al*., 2017). Since the 1970s, the United States has conducted systematic research on crop acid tolerance, defined acid damage thresholds for different crops in various acidic soils, and established zoned and classified management strategies, along with methods for lime application dosage estimation and precise application technologies. The use of industrial and agricultural byproducts (*e.g*., phosphogypsum) has also been validated to ameliorate subsurface soil acidity—technologies now widely promoted in Brazil, South Africa, and other countries (Zhao *et al*., 2023; Silva *et al*., 2025).

In Australia, research has focused on the mechanisms of agricultural practice-induced soil acidification, leading to the development of a targeted management model based on the different acid-causing processes (Dai *et al*., 2017). This model integrates the selection of acid-tolerant crop varieties, optimization of fertilizer management, and rational lime application. In recent years, developed countries in Europe and America have shifted their focus toward healthy soil cultivation and ecological function coordination. The European Union's Horizon Project has set multi-scale ecosystem construction, ecosystem value chain transformation, and innovative plant system development as core goals, aiming to improve soil health and ecological service functions while mitigating acidification. These global experiences provide important insights for China's soil acidification control. The key insights include the integration of targeted technical measures with regionalized management strategies and a shift from passive amelioration to active prevention and ecological improvement.

Research and practice of soil acidification mitigation in China

China has a long history of research on soil acidification, with significant breakthroughs achieved in basic research, technology development, and field demonstration (Xu *et al*., 2018; Zhao *et al*., 2023). These efforts have led to the formation of a technical system tailored to the characteristics of China's acidic cultivated land. As early as the 1950s, Chinese Academy of Sciences launched soil resource investigations and utilization research in the southern red-yellow soil region. Since then, the Institute of Soil Science, Chinese Academy of Sciences, has conducted in-depth research on red soil quality evolution, including formation processes, colloidal surface electrochemistry, and the quality degradation and reconstruction.

In response to the accelerated acidification of cultivated land, Chinese researchers, in collaboration with Wageningen University, have developed and applied an extended very simple dynamic (VSD) model VSD^+ for assessing farmland soil acidification (Zeng *et al*., 2017; Zhu *et al*., 2018). This model quantifies the contributions of acid deposition, nitrogen fertilizer input, and crop harvest to the acidification of intensive farmland soils. A series of national scientific and technological projects has been carried out to address the combined acidification and fertility degradation of southern cultivated land. As a result, a batch of core technologies for acid control and fertility improvement has been developed (Shi *et al*., 2017; Liu *et al*., 2023). These technologies include precise acid reduction for strongly acidic soils, targeted aluminum control to inhibit activation of mineral aluminum, long-term acid suppression *via* organic-inorganic combinations and proton source reduction, and soil biological fertility improvement based on the coupling of aggregates, organic matter, and biological functions. A technical specification for the zonal and classified governance of acidified soil compound degradation has also been formulated. Up to now, more than 30 demonstration zones (each over 0.6667 km^2) have been established in 17 southern provinces, realizing the integration of technology research, application, demonstration, and promotion. These achievements have formed a systematic solution for the sustainable utilization of southern cultivated land and laid a solid technical foundation for national soil acidification control, making important contributions to regional food security.

Strategic directions for mitigating cultivated soil acidification in China

Despite significant progress, China's efforts to control soil acidification still face challenges, including insufficient national unified planning, an incomplete core technology system, and inadequate large-scale technology promotion. In the next five years, research and practice should focus on basic research, key core technology breakthroughs, and technology promotion application. To comprehensively curb the trend of soil acidification, the following three strategic measures are proposed.

Strengthen basic research and formulate a national zoning plan for acidification prevention and control. A comprehensive characterization of the spatiotemporal evolution patterns and driving mechanisms of soil acidification in typical cultivated lands across China should be conducted. It is essential to reveal the molecular mechanisms of soil aluminum activation and key control factors, thereby clarifying the principles of targeted blocking technologies. A national soil acidification prediction model and an acid control decision-making system should be developed. Based on the response relationship between soil acidification and crop productivity, the acid damage thresholds of major crops should be defined, and an acidification risk early warning model should be developed. National key soil acidification risk areas should be identified, and breeding efforts for acid-tolerant and high-yielding crop varieties should be advanced. Furthermore, the synergetic mechanisms linking long-term acid suppression, soil fertility improvement, and regional grain production capacity should be clarified. On this basis, we should formulate a national zoning plan for cultivated soil acidification prevention and control to provide a macroframework for regionalized and classified governance.

Strengthen research and development to achieve breakthroughs in key core technologies for acidified farmland management. A rapid and accurate calculation method for soil conditioner dosage for acidic soil amelioration should be developed. Efficient acid-reducing conditioners tailored to the characteristics of soil acidification in different regions (southern red-yellow soil, northeastern black soil, and North China) need to be researched and developed. Core technologies—including precise acid reduction, targeted aluminum control, long-term acid suppression, and fertility improvement based on the coupling mechanisms of "soil aggregates-organic matter-biological functions"—should be advanced. A technical system for acid control, fertility improvement, and safe utilization of acidified paddy fields with mild to moderate heavy metal pollution should be established. Technical integration and model demonstration should be carried out in acidified cultivated land areas of South, Southwest, East, Central, Northeast, and North China. Thereby, an integrated technical pattern for regional soil acidification treatment will be formed to realize the efficient coordination of acidification control and agricultural production capacity improvement.

Accelerate technology promotion and implement major action plans for acidification control. The scope of the key county construction initiative for farmland acidification control (currently covering 50 counties across 16 provinces) should be further expanded to realize the full coverage of key risk areas. The popularization and application of new acidification control technologies and methods must be accelerated, with strengthened training for grassroots agricultural technicians and farmers to ensure the landing and implementation of advanced technologies at the rural household level. An innovative resource allocation mechanism should be established for guiding the diversified investment from central and local governments as well as social enterprises. This will form a joint force for soil acidification control and promote the establishment of a comprehensive and long-term mechanism for the coordinated development of soil acidification control and agricultural sustainability.

In conclusion, soil acidification poses a long-term and arduous challenge to the sustainable development of agriculture in China. Its governance is a systematic project involving basic research, technology development, industrial application, and policy support. Based on the global research progress and China's practical experience, future work must combine scientific research with practical application, regional governance with national planning, and technical measures with policy support. By formulating a unified national zone plan, breaking through core key technologies, and implementing large-scale promotion actions, we can comprehensively curb the trend of soil acidification in cultivated lands, continuously improve cultivated land quality and agro-ecosystem health, and provide a solid scientific and technological guarantee for China's food security and agricultural sustainable development.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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