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Application of oyster shell powder for five consecutive years effectively controlled soil acidification and reduced cadmium accumulation in rice grains

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Oyster shell powder enhances soil quality by mitigating acidification and improving fertility, boosting crop yields. However, its efficacy in immobilizing cadmium (Cd) in paddy soils remains uncertain. We performed a field experiment from 2014 to 2018 and assessed four treatments of oyster shell powder: 0 kg/ha (L0), 750 kg/ha (L750), 1,500 kg/ha (L1500), and 2,250 kg/ha (L2250). From 2014 to 2018, grain yield among all treatments was assessed at maturity, and Cd of grain, soil pH, and available Cd content were measured. Our results revealed that oyster shell powder significantly increased rice yields compared to L0, with L750, L1500, and L2250 treatments enhancing yields by 0.53–3.07% (average value of 1.80%), 3.20–7.61% (average value of 5.41%), and 4.19–10.96% (average value of 7.58%), respectively. Simultaneously, the Cd concentration in rice grains decreased by 3.57–5.51%, 7.14–16.34%, and 9.91–19.84% for L750, L1500, and L2250, respectively, with L2250 demonstrating the most effective Cd reduction. Additionally, soil pH increased by 0.12–0.39, 0.20–0.60, and 0.38–0.79 units, while soil bioavailable Cd decreased by 5.71–13.04%, 10.39–15.46%, and 14.73–18.84% for L750, L1500, and L2250, respectively. Further analysis indicated that over five years of continuous application, a 0.1-unit increase in soil pH correlated with a reduction of 0.42–0.82 mg/kg in Cd levels in rice grains, while a 0.1 mg/kg reduction in bioavailable Cd in the soil corresponded to a 0.07–0.16 mg/kg decrease in Cd in rice grains. In conclusion, five years of continuous application of oyster shell powder effectively mitigated soil acidification and reduced Cd bioavailability, increasing rice yields and diminishing Cd accumulation in rice grains. Higher application rates of oyster shell powder (up to 2,250 kg/ha) resulted in more pronounced acid control, Cd immobilization, and yield enhancements.

Keywords Acidification, Cd accumulation, Oyster shell powder, Paddy soil

Soil is the foundational material for agricultural development and is one of the most vital, extensive, and irreplaceable natural resources for human survival. Recently, issues related to soil quality have become increasingly prevalent, particularly concerning soil acidification and heavy metal contamination, critical research topics. Human activities, including acid deposition, improper fertilization, and intensive land use, have intensified soil acidification trends, especially in red soil[1–2]. Soil acidification negatively impacts soil biological activity and reduces nutrient availability while promoting the solubilization of free manganese, aluminum, and heavy metal ions into soil solutions[3–5]. This elevates the risk of toxic heavy metal levels exceeding acceptable crop limits, adversely affecting yield and quality[6]. Consequently, this issue has emerged as a major barrier to sustainable agricultural development in China[7].

Approximately 16.7% of agricultural soil in China is polluted by various heavy metals, with over 40% of these soils contaminated with cadmium (Cd)[6]. Cd-contaminated cereal crops reach up to 1.46×10^8 kg[7]. Soil

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Cd contamination occurs through two primary pathways: natural factors and anthropogenic sources. Human activities–such as agricultural practices, mining, smelting industries, and atmospheric deposition–are the main contributors to Cd pollution[8–9]. Soil acidification activates the fixed-state Cd in the soil, increasing the bioavailable Cd content and causing rice Cd contamination. As bioavailable Cd concentrations increase, plants exhibit symptoms such as chlorosis of leaves and stems, leaf shedding, and reductions in biomass, including plant height, leaf length, leaf width, stem thickness, and dry mass[10]. When Cd stress exceeds a threshold, it disrupts plant growth and physiological and biochemical processes, causing stunted growth, damaged cell structures, impaired photosynthesis, and hindered transpiration, affecting crop quality and yield[11]. During rice development, Cd negatively impacts seed germination, seedling growth, and maturation[12–13]. Soil conditioners offer an economical, efficient, and straightforward approach to addressing soil Cd pollution[14]. They enhance soil structure, mitigate salinity and alkalinity risks, adjust pH, and optimize moisture conditions, ultimately reducing the bioavailability of soil Cd. This, in turn, lowers Cd uptake by crops, ensuring the safety of agricultural products[15]. Oyster shell powder, a slow-release calcium-rich soil conditioner produced through protective roasting, enriches the soil with calcium, raises pH, immobilizes Cd, and improves the soil's physical and chemical properties[16–18]. Previous studies have demonstrated that applying oyster shell powder can enhance the yields of crops while controlling soil acidity and immobilizing Cd[19–22]. It has also been shown to increase microbial metabolic diversity in tobacco rhizosphere soil, effectively preventing bacterial wilt in tobacco[23]. However, most research has been limited to single-year experiments, leaving the long-term effects of oyster shell powder on soil productivity and crop yield unclear. The impact of varying application rates over extended periods also remains underexplored.

Jiangxi Province, situated on the southern bank of the Yangtze River's middle and lower reaches, has a subtropical, humid climate characterized by abundant sunlight, heat, and water resources. This typical red soil region is vital for food security and the sustainable supply of key agricultural products. Since 1979, the acidification trend of paddy soil in the area has continuously deteriorated. According to statistics, the average pH of paddy soil in Jiangxi Province from 2018 to 2020 was 5.4[4,5]. The average cadmium concentration in paddy fields in the red soil region of Jiangxi is 0.25 mg/kg, slightly higher than the national median (0.23 mg/kg)[24]. To investigate the long-term effects of oyster shell powder on typical acidic paddy soils, a five-year field experiment was conducted from 2014 to 2018 in Majia Village, Zhanggong Town, Jinxian County, Nanchang City, Jiangxi Province. The experiment assessed rice yield, soil pH, and Cd content under different oyster shell powder treatments, providing essential data for restoring acidic farmland soils.

Materials and methods

Experimental time and location

The experiment was conducted continuously for five years, from 2014 to 2018, at Majia Village, Zhanggong Town, Jinxian County, Nanchang City, Jiangxi Province (116°17'60"E, 28°35'24"N). This central subtropical zone has an average annual temperature of 18.1 °C, an accumulated temperature ≥ 10 °C of 6,480 °C, annual rainfall of 1,537 mm, and annual evaporation of 1,150 mm. The frost-free period lasts about 289 days, with annual sunshine totaling 1,950 h. The soil is a loam and classified as a Stagnic Anthrosols (IUSS working group) and a red paddy soil in the Chinese classification system, derived initially from Quaternary Red Clays[25]. Soil properties before the experiment included: pH 5.61, exchangeable hydrogen 4.55 mmol/kg, exchangeable aluminum 38.65 mmol/kg, organic matter 27.96 g/kg, total nitrogen 0.95 g/kg, total phosphorus 0.89 g/kg, total potassium 12.23 g/kg, available nitrogen 97.44 mg/kg, available phosphorus 10.33 mg/kg, available potassium 95.10 mg/kg, total Cd content 0.49 mg/kg, and bioavailable Cd content 0.22 mg/kg[26].

Experimental materials

The rice variety used was 'Y Liangyou 1928,' planted as a mid-season rice crop with a spacing of 20 cm × 20 cm, planted on May 13th and harvested on September 25th. The paddy field was flooded, tilled, and puddled to a depth of approximately 20 cm with a small machine before transplanting every season. Then, the rice seedlings were manually transplanted with a spacing of 20 cm × 20 cm. In addition, herbicide (i.e., propisochlor) and pesticides (i.e., avermectins, emamectin benzoate, and pymetrozine) were applied during the growth period when needed. The oyster shell powder, produced by Fujian Mata Agricultural Co., Ltd. (China), was in powder form, with a CaO content of ≥ 45.0% and a pH range of 8.5–10.5.

Experimental design

The experiment included four treatments:

Control (L0): conventional fertilization, with a basal application of 750 kg/ha of compound fertilizer (N, P2O5, and K2O at 15%, 15% and 15%) and a topdressing of 225 kg/ha of urea after seedlings recovery.

Treatment 1 (L750): conventional fertilization + 750 kg/ha of oyster shell powder.

Treatment 2 (L1500): conventional fertilization + 1,500 kg/ha of oyster shell powder.

Treatment 3 (L2250): conventional fertilization + 2,250 kg/ha of oyster shell powder.

Each treatment was replicated three times, resulting in 12 plots measuring 60 m² (6 m × 10 m) and arranged in a randomized block design. Table 1 summarizes the specific amounts of oyster shell powder and fertilizers applied. The oyster shell powder was applied once as a basal fertilizer, and water management during the rice growing season followed standard practices, with traditional local planting and cultivation methods.

Every season, a small machine flooded, tilled, and puddled the paddy field to a depth of approximately 20 cm before transplanting. Then, the rice seedlings were manually transplanted with a spacing of 20 cm × 20 cm. In addition, herbicides (e.g., propisochlor) and pesticides (e.g., avermectins, emamectin benzoate, and pymetrozine) were applied during the growth period when needed.

Treatment	Oyster Shell Powder (kg/ha)	Nitrogen (N, kg/ha)	Phosphorus (P_2O_5, kg/ha)	Potassium (K_2O, kg/ha)
L0	0	146.25	146.25	146.25
L750	750	146.25	146.25	146.25
L1500	1500	146.25	146.25	146.25
L2250	2250	146.25	146.25	146.25

Table 1. Application rates of oyster shell powder and fertilizers.

Measurement indicators

Rice Yield: At maturity, rice was harvested from each plot, threshed, dried, and weighed to calculate yield. **Soil pH**: After harvest, soil samples were collected, and pH was measured using a pH meter with a water-to-soil ratio of 2.5:1. **Available Cd content in soil**: Using the five-points method, 200 g soil samples were taken from each neighborhood at 0–20 cm depth, air dried, and sieved (20-mesh sieve) to determine available Cd. Available Cd was determined using the 0.01 mL^{-1} $CaCl_2$ method. The soil/water (1:5) was shaken at 160 r min^{-1} for 2 h at 25 °C, and filtered with a quantitative filter paper. The Cd content of the filtered samples was determined by inductively coupled plasma mass spectrometry (Agilent ICP-OES 5110, USA)[27]. **Cd content in rice grains**: At maturity, rice samples were taken from three points in each plot, dried, ground, and analyzed for Cd content using atomic absorption spectrophotometry. The plant shoots were separately harvested and washed with 5 mM $CaCl_2$ solution three times and rinsed with deionized water before being dried at 70 °C for 5 days. Tissues were digested completely in 1 mL of 70% (v/v) nitric acid at 80 °C for 1 h, 100 °C for 1 h, and 120 °C for 2 h. After dilution to 20 mL with ultrapure water, the total Cd content from samples was quantified using inductively coupled plasma-atomic emission spectrometry (Agilent ICP-OES 5110, USA)[27]. In terms of quality control, we set up standard samples, blind samples, and parallel samples to ensure the accuracy of the cadmium results. The standard material number of soil samples was GBW-07410, and the recovery rate of Cd was 99.9%.

Statistical analysis

All data were organized using Excel 2003. Variance analysis was performed using SPSS 16.0. One-way analysis of variance (ANOVA) was performed to test the significant differences in all treatments for the same year. The difference was statistically significant at the 0.05 level, $F > 0.05$, and $P < 0.05$. It also indicated significant positive relationships between oyster shell powder rates with rice yield, Cd content of rice grains, soil pH, and available Cd, at the 0.05 level, $R^2 > 0.5$, $P < 0.05$. Graphs were created using Origin (version 8.1).

Results

Effect of oyster shell powder on rice yield

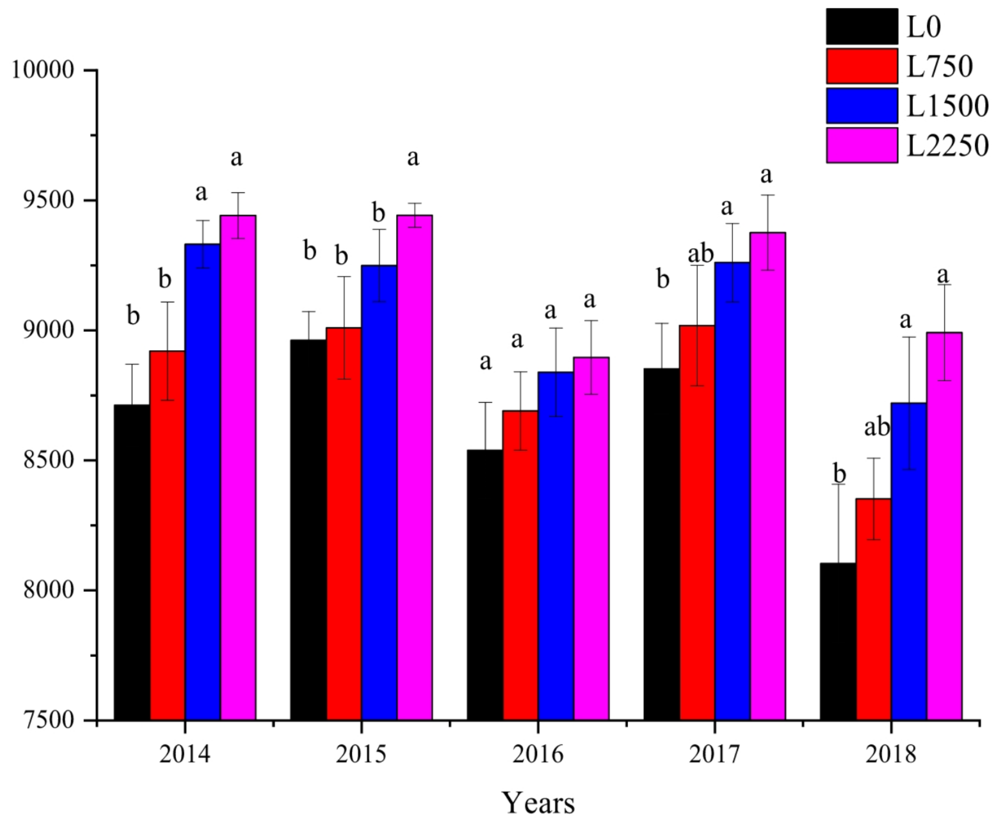
Rice yields fluctuated from 2014 to 2018 due to variations in temperature, sunlight, and precipitation, which were significantly lower in 2018 than in other years, primarily due to high temperatures and low rainfall during the middle of rice planting in mid-May. However, the yield of oyster shell powder has increased in the last five years (Fig. 1). Yields increased from 0.53 to 3.07%, 3.20–7.61%, and 4.19-10.96% for the L750, L1500, and L2250 treatments, respectively, compared to the L0 treatment. Notably, higher application of oyster shell powder resulted in higher yields, with L2250 treatment reaching a significant level compared to L0. The fitted equation (Table 2) showed that the application rate was significantly and positively correlated ($P < 0.05$) with rice yield. Yield increased by 0.35 kg/ha for every 1 kg/ha increase in oyster shell meal in the first year, and then increased to 0.40 kg/ha after 5 years of continuous.

Effect of oyster shell powder on cd content in rice grains

As shown in Fig. 2, Cd accumulation in rice fluctuated due to different external environments, such as temperature, sunlight, and rainfall, from 2014 to 2018. However, the application of oyster shell powder reduced Cd content in rice grains. Compared to the L0 treatment, Cd levels in rice from the L750, L1500, and L2250 treatments decreased by 3.57–5.51%, 7.14–16.34%, and 9.91–19.84%, respectively, over five years. The L2250 treatment demonstrated the most substantial reduction. The fitted equations (Table 3) indicated a significant negative correlation between oyster shell powder application rate and Cd content ($P < 0.05$). Continuous application of oyster shell powder reduced Cd content by 0.11×10^{-4} to 0.24×10^{-4} mg/kg for each additional 1 kg/ha.

Effect of oyster shell powder on soil acidification

Oyster shell powder application effectively improved soil acidification (Fig. 3). Compared to the L0 treatment, soil pH in the L750, L1500, and L2250 treatments increased by 0.12–0.39, 0.20–0.60, and 0.38–0.79 units, respectively, over the five years. The longer the application, the more significant the improvement. In the L0 treatment, soil pH decreased from 5.53 to 5.38 after five years, while pH increased in plots receiving oyster shell powder annually. In particular, soil pH was slightly reduced in 2018, probably due to the lower yield of rice in 2018, which had a weaker capacity to fix Cd in the soil. The fitted equations (Table 4) indicated a significant positive correlation between application rate and soil pH. For each additional 1 kg/ha, soil pH increased by 0.16×10^{-2} to 0.35×10^{-2} units over the 2014–2018 period.



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Changes in rice yield under oyster shell powder application over different years.

Fig. 1. Changes in rice yield under oyster shell powder application over different years.

Year	Equation	R^2	*P*
2014	y = 8711.85 + 0.3463x	0.95754	0.02146
2015	y = 8913.90 + 0.2240x	0.94512	0.02783
2016	y = 8557.67 + 0.1628x	0.96622	0.01704
2017	y = 8854.79 + 0.2418x	0.98374	0.00816
2018	y = 8086.71 + 0.4044x	0.99462	0.00269

Table 2. Linear relationship between oyster shell powder rates and rice yield.

Effect of oyster shell powder on cd immobilization in soil

The effective cadmium in the soil of each treatment gradually decreased from 2014 to 2018, probably because rice cultivation also has a phytoremediation function on cadmium-contaminated soil, and the total cadmium content of the soil decreased with the increase in the number of years of cultivation. Oyster shell powder significantly reduced the bioavailable Cd content in the soil (Fig. 4). Compared to the L0 treatment, bioavailable Cd levels in the L750, L1500, and L2250 treatments decreased by 5.71-13.04%, 10.39-15.46%, and 14.73-18.84%, respectively, over the five years. Higher application rates resulted in more pronounced reductions. The fitted equations (Table 5) revealed a significant negative correlation between application rate and bioavailable Cd content ($P < 0.05$). Each additional 1 kg/ha of oyster shell powder decreased bioavailable Cd content by 0.14×10^{-4} to 0.16×10^{-4} mg/kg over the 2014–2018 period.

Correlation between soil pH, available cd, and cd content in rice grains

Data from five years of rice planting revealed a negative correlation between soil pH and Cd content in rice grains, alongside a positive correlation between bioavailable Cd content in soil and Cd content in rice (Table 6). Significant negative correlations between soil pH and rice grain Cd content in 2014, 2016, and 2017 (R^2 = 0.99, 0.91, 0.98, respectively, $P < 0.05$). From 2015 to 2017, there were significant positive correlations between soil bioavailable Cd content and rice grain Cd content (R^2 = 0.92, 0.95, 0.96, respectively, $P < 0.05$). The linear equation slope indicated that for every 0.1 unit increase in soil pH, the Cd content in rice grains decreased by

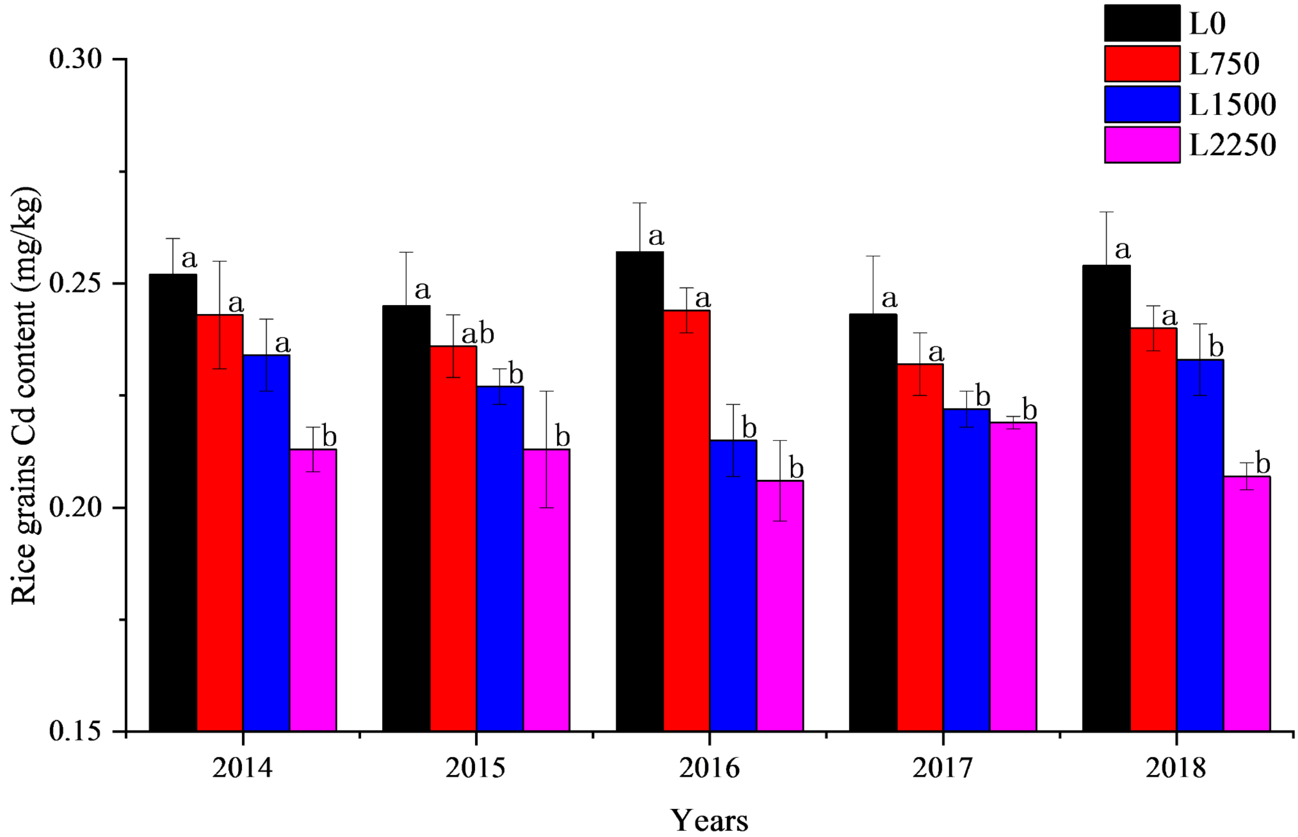

Fig. 2. Changes of Cd content in rice grains under oyster shell powder application in different years. In general, increased oyster shell powder reduced Cd levels over time.

Year	Equation	R^2	*P*
2014	y = 0.2544–0.000017x	0.94839	0.02615
2015	y = 0.2460–0.000014x	0.98658	0.00673
2016	y = 0.2578–0.000024x	0.96012	0.02014
2017	y = 0.2414–0.000011x	0.94915	0.02576
2018	y = 0.2557–0.000020x	0.94009	0.03042

Table 3. Linear relationship between oyster shell powder rates and cd content in rice grains.

0.42–0.82 mg/kg. Similarly, for every 0.1 mg/kg decrease in bioavailable Cd content, the Cd content in rice grains decreased by 0.07–0.16 mg/kg. In 2018, the correlation between soil pH and rice grain Cd content, soil bioeffective Cd content, and rice Cd content was not significant, probably due to the external environment in 2018, which severely affected the growth and development of the crop and reduced the crop yield and the accumulation of Cd.

Discussion

Response of rice yield and its cd content in the application of oyster shell powder

Rice is the second-largest grain crop globally and China's most important food crop, playing a critical role in food security. Previous studies indicate that short-term applications of oyster shell powder can enhance rice yields, with higher application rates yielding greater increases[20]. In this study, five consecutive years of oyster shell powder application yielded increases of 0.16–0.40 kg/ha for every 1 kg/ha applied. Cd is not an essential element for plant growth; when its levels reach a threshold, it disrupts metabolic processes, impairs chlorophyll function, and reduces photosynthesis[28], leading to yellowing leaves and stunted growth[29]. Rice can accumulate Cd, posing health risks as it moves up the food chain. Applying oyster shell powder effectively mitigates Cd accumulation in rice[30,31]. This study demonstrated that with five years of continuous application, the Cd content in rice grains decreased by 0.11×10^{-4} to 0.24×10^{-4} mg/kg for each 1 kg/ha increase in oyster shell powder. Furthermore, as rice grows gradually, this may decrease effective Cd content through conversion to non-absorbable Cd or absorption by grains. Increasing crop yield may dilute Cd concentration to a certain extent. However, due to

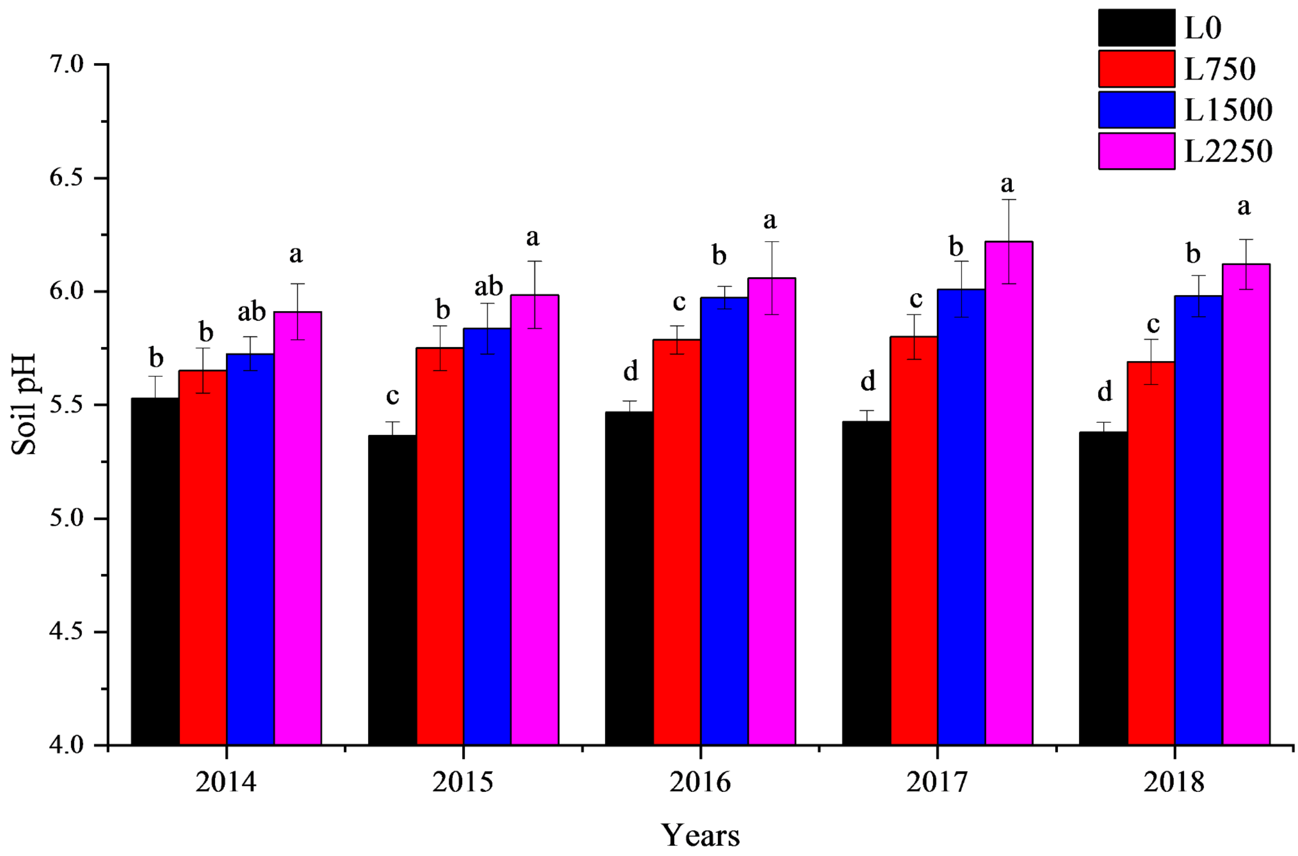

Fig. 3. Changes in soil pH under oyster shell powder application over different years. The pH increased with increased oyster shell powder application over time.

Year	Equation	R^2	*P*
2014	y = 5.5209 + 0.00016x	0.97088	0.01467
2015	y = 5.4417 + 0.00026x	0.90153	0.05051
2016	y = 5.5288 + 0.00026x	0.93390	0.03362
2017	y = 5.4752 + 0.00035x	0.97650	0.01182
2018	y = 5.4160 + 0.00033x	0.97502	0.01257

Table 4. Linear relationship between oyster shell powder rates and soil pH.

objective reasons such as research platform and funding, this study did not analyze the impact of biomass or yield increase on Cd concentration dilution. In the discussion, however, we added a perspective on this idea.

Response of soil pH and available cd content in the application of oyster shell powder

Soil acidification, exacerbated by soil properties and human-induced land degradation, is a significant issue in red paddy soils of southern China, leading to resource wastage, and negative impacts on agricultural productivity. Zhou et al.[32] reported that oyster shell powder application can increase soil pH by 1.36 units compared to controls. In this study, the application of 750–2,250 kg/ha of oyster shell powder effectively mitigated soil acidification, increasing soil pH by 0.12–0.38 units in the first year compared to the untreated control. After five years, soil pH reached 6.12 in the L2250 treatment. The calcined oyster shells, rich in calcium carbonate, convert to calcium oxide, enhancing alkalinity and facilitating strong adsorption and immobilization of Cd[33]. The main reason is that oyster shell powder, which is deeply processed and mainly contains nutrients such as CO_3^{2-} and exchangable calcium, is easy to neutralize and react with H^+ in soil solution and produce CO_2. By reducing the concentration of H^+ and Al^{3+} in soil, soil acidity can be improved, and acidification of red soil dryland can be controlled[34]. Secondly, after applying oyster shell powder, more cation exchange sites, such as Ca^{2+}, were provided, and Ca^{2+} occupied the original Al^{3+} position. Al^{3+} lost its charge, and Al^{3+} and H^+ in the soil were reduced, increasing the soil's pH. This was consistent with the findings of Zhang et al.[35]. It showed that base ions adsorbed on colloids of acidic soil, such as NH_4^+, K^+, Ca^{2+}, and Mg^{2+}, were mostly replaced by H^+ and Al^{3+} into the soil solution, and leaching was lost.

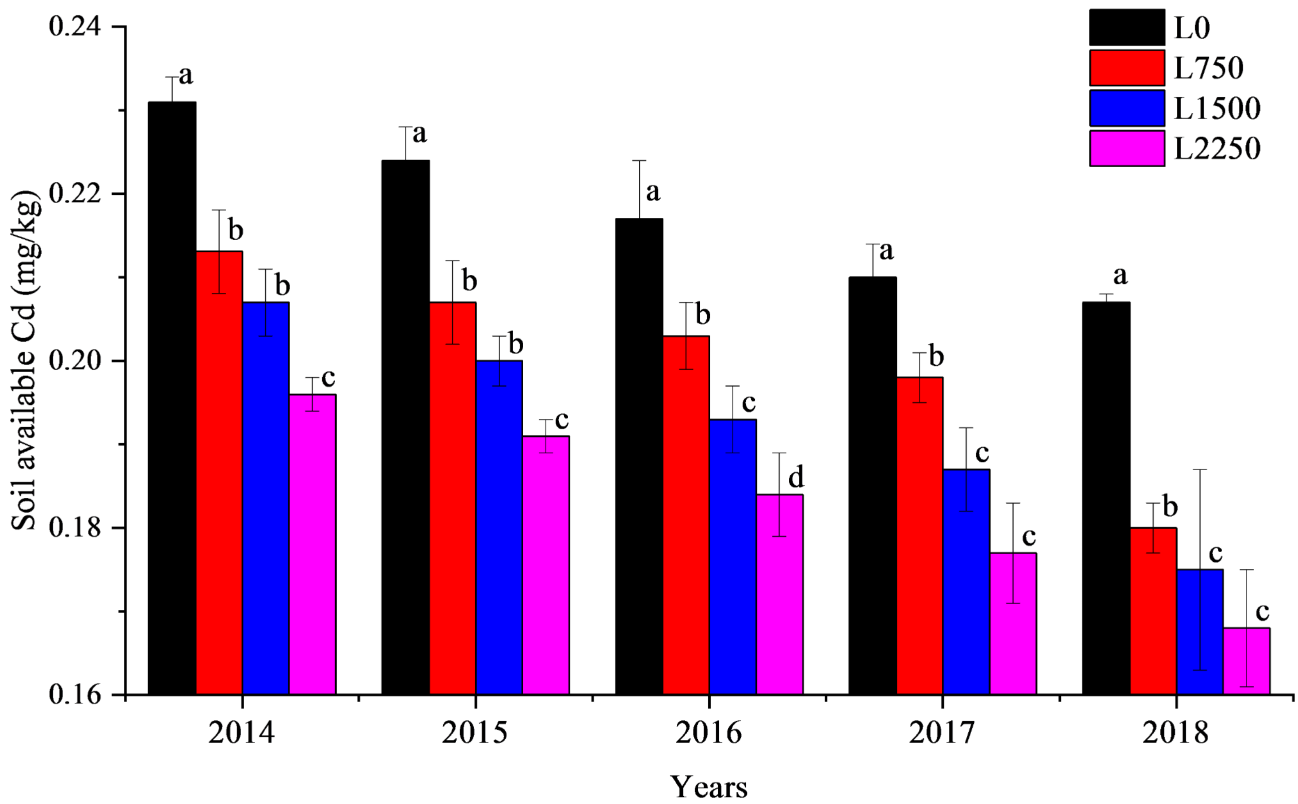

Fig. 4. Changes in available Cd levels in the soil under oyster shell powder application in different years. Generally, the amount of available Cd decreased with increased oyster powder application over time.

Year	Equation	R^2	*p*
2014	y = 0.2284–0.000015x	0.95980	0.02030
2015	y = 0.2214–0.000014x	0.96034	0.02003
2016	y = 0.2156–0.000015x	0.98885	0.00559
2017	y = 0.2095–0.000015x	0.99835	0.00825
2018	y = 0.2008–0.000016x	0.85246	0.07671

Table 5. Linear relationship between oyster shell powder rates and soil available cd content.

Year	Equation	R^2	*P*
2014	y = 0.2284–0.000015x	0.95980	0.02030
2015	y = 0.2214–0.000014x	0.96034	0.02003
2016	y = 0.2156–0.000015x	0.98885	0.00559
2017	y = 0.2095–0.000015x	0.99835	0.00825
2018	y = 0.2008–0.000016x	0.85246	0.07671

Table 6. Linear relationship between oyster shell powder rates and available soil cd content.

Research indicates that a one-unit decrease in soil pH can increase soil Cd activity by 100-fold. Thus, increased Cd uptake by crops often results from soil contamination and heightened Cd activity due to soil acidification[36]. This study demonstrated that the application of 2,250 kg/ha of oyster shell powder significantly raised soil pH and reduced bioavailable Cd content, aligning with findings from other studies that recommend similar application rates for oyster shell powder as a soil conditioner[37–39].

Indexes	Year	Equation	R^2	*P*
Soil pH	2014	y = 0.8276–0.1038x	0.98932	0.00536
	2015	y = 0.5031–0.0476x	0.85372	0.07603
	2016	y = 0.7415–0.0878x	0.91384	0.04405
	2017	y = 0.4158–0.0319x	0.97686	0.01164
	2018	y = 0.5543–0.0554x	0.85081	0.07760
Soil available Cd	2014	y = 0.0085 + 1.0719x	0.88270	0.06048
	2015	y = 0.0372 + 0.9393x	0.92377	0.03887
	2016	y = -0.09835 + 1.6504x	0.94864	0.02602
	2017	y = 0.0836 + 0.7536x	0.96462	0.01785
	2018	y = 0.0508 + 1.0012x	0.75107	0.13335

Table 7. Linear relationship between soil pH, available cd, and cd content in rice grains.

Interaction between soil pH, available Cd, and Cd content of rice grains in the application of oyster shell powder

After five years of continuous oyster shell powder application, a significant negative correlation emerged between soil pH and Cd content in rice grains, alongside a significant positive correlation between bioavailable Cd content in the soil and Cd content in rice grains. These findings are consistent with those of Ni et al.[40]. Specifically, in acidic paddy soils, for every 1-unit increase in soil pH, the bioavailable Cd content in the soil decreased by 0.40–0.63 mg/kg, while Cd content in rice grains decreased by 0.03–0.10 mg/kg. Applying oyster shell powder was instrumental in raising soil pH, which directly influenced bioavailable Cd levels and reduced Cd accumulation in rice grains. In addition, studies have shown that adding oyster shells can significantly increase the concentrations of dissolved organic carbon, calcium, and magnesium in soil pore water, reduce the levels of glutathione and plant chelators in roots, all of which can lower the levels of biologically available cadmium, minimize the accumulation of cadmium in rice grains, and improve rice growth[30].

The excessive use of chemical fertilizers and pesticides has led to soil acidification and compaction, severely impacting soil quality and agricultural productivity globally[41]. Utilizing oyster shell powder as a soil conditioner can improve soil water retention, nutrient retention, and aeration, thereby promoting microbial activity and enhancing nutrient uptake in crops, resulting in increased yields and better crop quality[42]. Kwo et al.[43] demonstrated that mixing finely ground oyster shell powder with sewage sludge improved soil quality and supported earthworm reproduction. Long-term reliance on chemical fertilizers often leads to soil compaction and acidification; however, applying alkaline oyster shell powder as a calcium fertilizer effectively boosts crop yields and mitigates soil acidification[44]. With the expansion of oyster farming and the rising demand for oysters driven by improving living standards and health awareness, the consumption of oysters is projected to increase. As a readily available, inexpensive, and renewable resource, oyster shells can be transformed from waste into a valuable asset. Advances in ultrafine grinding and modification have highlighted the potential applications of oyster shells, suggesting that further research will translate into practical uses in agriculture and daily life[45].

Conclusion

A five-year field experiment demonstrated that oyster shell powder application significantly enhanced rice yields and improved soil acidification trends. Compared to the untreated control, applying 750–2,250 kg/ha of oyster shell powder increased rice yields by 0.53–10.96% and raised soil pH by 0.12–0.79 units. Additionally, continuous application of oyster shell powder significantly reduced bioavailable Cd levels in the soil, reducing Cd absorption by rice grains. However, the response of Cd migration and transformation in paddy soil when oyster shell powder is applied may be influenced by initial soil pH levels and rice variety. So, further research on the long-term effects of oyster shell application is essential, as potential improvements to soil quality could address the challenges of farmland degradation. In addition, it was known that soil microorganisms would be changed under long-term oyster shell powder applications, and key microbial communities may be involved in the migration and transformation of soil Cd. In the future, the changes of soil microbial communities in the long-term application of oyster shell powder rates should be analyzed.

Data availability

The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Received: 15 November 2024; Accepted: 31 March 2025
Published online: 08 April 2025

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Acknowledgements
This research was supported by the "One Hundred Agricultural Technicians to Tackle Key Problems" project of Jiangxi Province, China (No. 202401), the National Natural Science Foundation of China (No. 42367051), and the Jiangxi Province Key Laboratory of Arable Land Improvement and Quality Enhancement, China (No. 2024SSY04221). We are grateful to the staff that helped with field planting.

Author contributions
ZM and SM performed data collection and analysis, as well as writing. SH and LK were responsible for experimental design, project management, and manuscript review. WY, HT, HD, XJ, and SH contributed to data analysis and manuscript preparation. All authors read and approved the final submitted version.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
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