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Effects of applying different organic and inorganic soil amendments to improve the late stage of reclaimed soil from abandoned homesteads on soil nutrients and maize yield

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Abandoned homesteads in hollow villages are important reclamation resources, and how to improve the fertility of reclaimed soil is an important issue. In this paper, the effect of maturing agent (ferrous sulfate), organic fertilizer (well-composted chicken manure) and fly ash on the post-amelioration of soil maturation of the abandoned homesteads was investigated in different ratios using a field plot experiment by stripping topsoil, backfilling homesteads soil and adding clinker materials. The results of the study showed that the maturing agent + organic fertilizer (T1), fly ash + organic fertilizer (T2) and organic fertilizer (T3) treatments had a better effect on the improvement of organic matter, total nitrogen, total phosphorus, available phosphorus and available potassium of the reclaimed soil and were significantly higher than that of the inorganic treatments; and that the increase in soil nutrients showed a trend of increasing and then decreasing as the year lengthened in the period of 2019−2021. After 5 years of improvement, soil nutrient content increased from low level 5 to intermediate level 3. Maize yield under each treatment was also higher at T1, T2 and T3; comparing the time span, maize yield was highest in 2010 with an average of 7,724 kg/hm^2; significantly higher than in 2019 and 2021. Correlation heat map analysis showed that maize yield had negative highly significant correlation with soil bulk density and positive highly significant correlation with soil organic matter. Based on the results of this study, it is recommended that at the later stage of raw soil maturation and soil improvement, it can be considered to reduce the addition of inorganic amendments and focus on increasing the organic and inorganic matter rationing, which can provide technical support for the rapid improvement of nutrients in reclaimed arable land.

KEYWORDS

organic and inorganic soil conditioners, soil total nutrients, soil nutrient availability, maize yield, late soil improvement

1 Introduction

Food security is an important ballast for national prosperity and people's security, and an important guarantee for safeguarding national security, among which arable land resources are the most important key factor for safeguarding food security. With the rapid development of urbanization and industrialization, a lot of arable land resources are inevitably occupied. At the same time, as the rural population moves to cities, idle or abandoned rural residential land is relatively common. On the one hand, it occupies valuable land resources, and on the other hand, it has become a place or hiding place for some illegal activities in society (Liu, 2018; Liu et al., 2016; Tian et al., 2024). In order to increase the area of cultivated land and regulate idle land, local governments, in accordance with relevant laws and regulations, take the abandoned homesteads in hollow villages as the object of regulation and reclamation, which can not only revitalize the land stock, but also alleviate the contradiction of shortage of cultivated land resources (Liu et al., 2024; Liu and Zhou, 2017; Liu et al., 2018b). However, in the process of large-scale artificial land reclamation, it is inevitable that the topography and soil cultivation layer should be turned over and disturbed, which will bring about the mother layer of raw soil surface, raw and ripe and churning, how to see the effect of the mother soil in that year, how to make the interaction between the raw soil and the crop under the regulation of artificial fertilizer to make the inorganic mother soil into an inorganic cultivated soil, which inevitably involves the "root-soil-fertilizer" relationship problem. This inevitably involves the 'root-soil-fertilizer' relationship.

However, the key scientific problem in the reclamation and renovation of rural abandoned homesteads is to break through the soil conversion obstacles such as "raw, hard, solid and barren" of newly added cultivated land, improve the soil quality characteristics, and enhance the basic ability of soil to coordinate water, fertilizer, gas and heat, so as to meet the basic needs of plant growth (Liu et al., 2022a,b; Lei et al., 2019; Meng et al., 2024). In order to ensure the principle of "balance of occupation and compensation" and to meet the needs of agricultural production on cultivated land, it is necessary to improve the reclaimed homestead and screen out the economical and environmentally friendly reclamation soil amendment, which has important practical significance for the land regulation of homesteads.

Organic and inorganic amendments are often used to improve the quality of soil on reclaimed homesteads. With organic amendments generally including plant residues, animal manure and biochar; Inorganic amendments generally include lime-based, gypsum-based and mineral-based. Animal manure is an easily available organic fertilizer material, such as well-composted chicken manure, which is rich in a large number of beneficial substances, including a variety of organic acids, peptides, and nitrogen, phosphorus and potassium, among other nutrients. Not only can it provide nutrients for crops, but it also has a long fertilizer effect, increases soil organic matter content, promotes microbial reproduction, improves soil biological activity and physicochemical properties (Huang et al., 2020; Cai et al., 2019; Zhou et al., 2019), and is widely available and distributed, and has the potential to be widely used because of its simple and low-cost production technology. Inorganic amendment fly ash is mainly the fine ash material captured in the flue gas after coal combustion, mainly from the solid waste discharged from coal-fired power plants. When used to improve the soil, it can improve the stability of aggregates, reduce soil weight, and improve soil aeration and water permeability (Ou et al., 2021; Pham et al., 2022). In the northern region of China, there are many coal-fired power plants, fly ash resources are very rich, with cheap and stable sources. Ferrous sulfate is an inorganic compound, anhydrous ferrous sulfate is a white powder, soluble in water, the aqueous solution is light green, common its seven hydrate (green alum). Ferrous sulfate on the one hand has a certain neutralizing effect on alkaline soil, can reduce the pH of the soil, alkaline soil in the north of China has a certain role in the improvement (Majumder et al., 2021). The above three organic and inorganic amendments are commonly used economic and convenient materials for soil improvement.

Maize (*Zea mays L.*), an annual herbaceous plant in the family Gramineae, is a highly adaptable, high-yielding and high-quality food and feed crop. As a comprehensive crop that takes into account food, economic and feed needs, maize plays a pivotal role in guaranteeing national food security and effective supply of agricultural products. According to the China Statistical Yearbook (China Statistical Yearbook, 2023), the area under maize accounts for 25.3% of the total area under cereals and 40.4% of total cereal production. Maize is not very strict on soil requirements, loose soil, deep soil can be, to organic matter-rich black soil, black calcium soil, light black calcium soil, alluvial soil and thick layer of meadow soil is the best, but its seed yield on nitrogen demand is high (Wang et al., 2020).

Organic fertilizer (well-composted chicken manure), inorganic (fly ash) and maturing agent (ferrous sulfate) amendments are commonly used to improve soil structure, increase soil organic matter, improve soil quality and increase crop yields. However, the time required for organic and inorganic amendments to improve soils varies with soil conditions, amendment practices and management levels, with significant improvements in soil quality usually taking 3–5 years. Most researchers have studied the effects of soil amendments over a 3–5 year period (Jaufmann et al., 2024; Kang et al., 2022), with fewer studies continuing to track soil nutrients and crop yields at later stages.

Therefore, based on the lack of late research on soil improvement effects, this study screened various organic and inorganic substances to improve reclaimed soil by simulating house site reclamation, and investigated and analyzed the effects of various amendments on soil nutrient contents and crop yields in the late stage (years 5, 6, and 7). The aim was to find ways to restore the basic functions of the soil in the process of house site reclamation and to rapidly improve the productivity of the land, and to effectively save costs and provide technical support for the rapid improvement of nutrients in reclaimed farmland.

2 Materials and methods

2.1 Overview of the study area

The long-term positioning test plot for soil reclamation and soil improvement of abandoned residential bases was established on 15 June 2015 at the pilot base in Fuping County, Weinan City, Shaanxi Province (34°42′N, 109°12′E). It is mainly used for experimental research and technical demonstration of key technologies for comprehensive rehabilitation of hollow villages.

The study area is located on the north side of the Loess Plateau, north of Wei'an, with a warm temperate semi-humid continental monsoon climate zone, an average annual evaporation of 1154.2 mm, an average annual air temperature of 13.3°C, and an average annual rainfall of 513.5 mm.

The backfill soil of the test plot was obtained from the old wall soil (raw soil) that was backfilled to a depth of 30 cm from the abandoned homestead. After removal of gravel and other impurities, the reclaimed soil was consolidated and structurally improved by the addition of various amendments to meet the new requirements for the growth of food crops. Before the experiment, the pH of the topsoil was 8.5, the organic matter content was 4.5 g kg^{-1}, the total nitrogen content was 0.16 g kg^{-1}, the available phosphorus content was 3.1 mg kg^{-1}, the available potassium content was 61.4 mg kg^{-1} and the soil bulk density was 1.40 g cm^{-3}. The soil quality was relatively poor.

2.2 Experimental plot setting

In this study, fly ash, organic fertilizer (well-composted chicken manure) and maturing agent (ferrous sulfate) were selected as amendment materials for reclaimed soil. The experiment was designed as a randomized block field trial with seven treatments, namely, maturing agent (T5), fly ash (T6), organic fertilizer (T3), maturing agent + organic fertilizer (T1), fly ash + organic fertilizer (T2), maturing agent + fly ash (T4) and no amendment added (CK) treatment. Each treatment had three replications with a total of 21 experimental plots with an 80 cm separation zone between each treatment group. The cropping system was a two-year, three-crop system in a winter wheat-summer maize rotation. The experimental summer maize was sown in the first 20 days of June at a density of 6.5 × 104 plants/ha and harvested in the first 10 days of October. The variety used was 'Xianyu 958'. Before sowing, all maize treatments were fertilized with 1,500 kg ha^{-1} of compound fertilizer containing 15, 10, and 20% of N, P and K, respectively. Soil amendments from the different treatments were then evenly mixed into the reclaimed raw soil and soil amendments were applied to each treatment at the same time. Daily management indices such as irrigation rate and fertilizer treatment were the same for the six treatments. The specific experimental treatments and application rates of soil amendments are shown in Table 1.

TABLE 1 Test treatment.

Number	Treatments	Application amount
1	Maturing agent + Organic fertilizer (T1)	(30 + 0.6)t · hm^{-2}
2	Fly ash + Organic fertilizer (T2)	(22.5 + 15)t · hm^{-2}
3	Organic fertilizer (T3)	30 t · hm^{-2}
4	Maturing agent + fly ash (T4)	(45 + 0.6)t · hm^{-2}
5	Maturing agent (T5)	0.6 t · hm^{-2}
6	Fly ash (T6)	45 t · hm^{-2}
7	No soil amendments (CK)	0

2.3 Experimental treatment

Soil samples were collected from the 0–30 cm tillage layer in each plot after the harvest of summer maize in 2019, 2020 and 2021, and three soil samples were collected diagonally from each plot. The collected soil samples were partially packed in aluminum boxes for determination of soil moisture content (Gao et al., 2011) and partially packed in self-sealing bags to be taken back to the laboratory for backup. The samples were air-dried for 7 days and passed through sieves of 2, 1, and 0.25 mm.

The laser particle analyzer (Mastersizer 2000, Malvern Company, UK) was used to measure the percent volume of soil particles in the range 0.02–2000 μm. According to the US classification standards, soil particles are divided into three classes: clay particles<0.002 mm, silt particles 0.002–0.05 mm and sand 0.05–2.000 mm. Soil bulk density (BD) were measured using a gravimetric method (Gao et al., 2011). The soil organic matter (SOM) content was determined by potassium dichromate oxidation - oil bath heating method (Nelson and Sommers, 1982); the soil total nitrogen (STN) content was determined by Kjeldahl nitrogen fixation (Bremner and Mulvaney, 1982); the soil total phosphorus (STP) content was determined by H_2SO_4-$HCLO_4$ digestion-molybdenum antimony blue colorimetric method (Murphy and Riley, 1962); the soil available phosphorus (SAP) content was measured using the molybdate ascorbic acid method following a 0.5 mol/L $NaHCO_3$, extraction (Zhang et al., 2022); the soil available potassium (SQP) content was determined by 1 mol/L ammonium acetate leaching-flame photometry method (Chen et al., 2021).

2.4 Data analysis

Microsoft Excel 2010 software was used for basic data statistics and processing; the software IBM Statistics SPSS 22 software was used for one-way analysis of variance and LSD method was for significance test. The software Origin 2018 software was used to draw correlation heatmaps, bar charts and line graphs.

3 Results

3.1 Soil bulk density and particle composition under different treatments

From Table 2, it can be concluded that the soil bulk density under the different applications of organic inorganic amendments ranged from 1.16 g cm^{-3} to 1.38 g cm^{-3}, with the lowest BD being 1.16 g cm^{-3} for the T1 treatment and the highest being 1.38 g cm^{-3} for the CK treatment. From 2019 to 2021, there was little change in the BD under the different treatments as the number of years increased. Over a three-year period, the basic trend of BD under the different treatments was CK > T6 > T5 > T4 > T3 > T2 > T1.

From Table 2, it can be seen that the content of soil clay and silt particles was higher and sand particles was lower under T1 and T2 treatments. This indicates that organic and inorganic application can increase the content of soil clay particles and decrease the content of sand particles. The content of clay particles was lower and the content of sand particles was higher under the T3 treatment. The rest of the inorganic treatments were basically no difference in soil clay, silt and sand content (Table 2).

3.2 Soil total nutrient content under different treatments

From Figure 1a it can be concluded that the soil organic matter content under different organic–inorganic treatments and the blank treatment (conventional fertilizer) was higher than the baseline value of 4.5 g/kg of reclaimed soil. In 2019–2021, there was no significant difference in soil organic matter content under the same treatment among different years ($p < 0.05$). In 2019, the magnitude of soil organic matter content under different treatments was T1 > T2 > T3 > T4 > T5 > T6 > CK, and there was no significant difference among treatments except for CK treatment ($p < 0.05$). In 2020, soil organic matter content under T1 treatment was significantly higher ($p < 0.05$) than other treatments. In 2021, soil organic matter content under T1 treatment was significantly higher ($p < 0.05$) than other treatments except T2 treatment. The increase in soil organic matter under T1, T2, T3, T4, T5 and T6 treatments was 107.68, 84.69, 49.70, 33.05, 27.02 and 8.54% in 2019 compared to CK treatments; the increase was 146.19, 83.07, 65.28, 46.64, 21.20 and 16.76% in 2020; in 20,201 the increase was 102.99, 79.54, 38.28, 30.19, 7.96 and 6.53%, respectively. The increase in soil organic matter under the treatments showed an increasing and then decreasing trend with increasing years.

TABLE 2 Soil bulk density and particle composition under different amendments.

Year	Test treatment	BD (g/ cm^3)	Silt (%)	Clay (%)	Sand (%)
2019	T1	1.18	84.18	12.67	3.16
	T2	1.19	83.19	12.25	4.56
	T3	1.21	81.26	11.99	6.74
	T4	1.24	84	11.53	4.46
	T5	1.26	83.98	11.04	4.98
	T6	1.29	83.63	11.48	4.89
	CK	1.38	82.56	10.78	6.66
2020	T1	1.16	84.13	13.06	2.81
	T2	1.19	83.5	12.44	4.06
	T3	1.2	81.81	12.21	5.98
	T4	1.24	84.21	11.56	4.23
	T5	1.26	84.33	11.23	4.44
	T6	1.28	84.02	11.66	4.32
	CK	1.36	84.12	11.22	4.66
2021	T1	1.16	83.97	13.32	2.71
	T2	1.18	82.49	13.25	4.26
	T3	1.2	83	11.89	5.11
	T4	1.22	84.19	11.77	4.04
	T5	1.27	83.3	12.03	4.67
	T6	1.26	83.68	11.54	4.78
	CK	1.36	83.68	11.56	4.76

From Figure 1b it can be concluded that the total soil nitrogen content under the different organic–inorganic treatments and the blank treatment (conventional fertilizer) was higher than the baseline value of the reclaimed soil by 0.16 g/kg. From 2019 to 2021, there was no significant difference in soil total nitrogen content under T1, T2, T3, T4 treatments among different years ($p < 0.05$); soil total nitrogen under T5, T6 and CK treatments in 2021 showed significantly higher ($p < 0.05$) than in 2020 and 2019. soil total nitrogen content under T1, T2, T3 treatments was significantly higher ($p < 0.05$). In 2020, soil total nitrogen content under T1, T2, T3 treatments was significantly higher ($p < 0.05$) than inorganic treatments T4, T5, T6 and CK; in 2021, there was no significant difference ($p < 0.05$) in soil total nitrogen content under each treatment. Compared to CK treatment, T1, T2, T3, T4, T5 and T6 treatments increased soil total nitrogen content by 9.65, 4.68, 2.81, 2.53, 1.59% and − 0.06%, respectively, in 2019; and in 2020, soil total nitrogen content increased by 66.21, 66.42, 65.68, 29.35, 28.41 and 20.80%, respectively, in 2019; and in 2021, total soil nitrogen content increased by 52.72, 51.10, 51.10, 21.85, 22.38 and 13.07%, respectively. Similar to soil organic matter, the increase in soil total nitrogen content under each treatment showed a tendency to increase and then decrease with increasing years.

From Figure 1c it can be concluded that the soil total phosphorus content of the different organic–inorganic treatments and the blank treatment (conventional fertilizer) was higher than the baseline value (0.06 g/kg) of the reclaimed soil. Among different years of the same treatment, the soil total phosphorus content was significantly higher in 2021 than in 2020 and 2019 ($p < 0.05$), and there was no significant difference between 2019 and 2020. In 2019, soil total phosphorus content T1 > T2 > T3was significantly different ($p < 0.05$), in 2020, soil total phosphorus content T1 was significantly higher than CK treatment ($p < 0.05$) and there was no significant difference between the other treatments; in 2021, there was no significant difference in soil total phosphorus among the different treatments. Compared with CK treatment, T1, T2, T3, T4, T5 and T6 treatments increased soil total phosphorus content by 420.66, 263.56, 101.59, −79.34%, 24.49% and − 61.94%, respectively, in 2019; and in 2020, the increase in soil total phosphorus content was 764.07, 652.37, 636.93, 468.09, 329.91 and 255.85%, respectively; and in 2021 the increase in soil total phosphorus content was 36.25, 25.35, 19.69, 20.95, 15.20% and − 0.21%, respectively. Similar to soil organic matter and total nitrogen, the increase in soil total phosphorus content under each treatment showed an increasing and then decreasing trend with increasing years.

3.3 Soil nutrient availability under different treatments

From Figure 2a it can be concluded that the soil available phosphorus content of the different organic–inorganic treatments and the blank treatment (conventional fertilizer) were all higher than the basal value of the reclaimed soil of 3.1 mg/kg. Among different years of the same treatment, there was no significant difference in soil available phosphorus content of the other treatments except T4 treatment ($p < 0.05$). There was no significant difference in soil available phosphorus content among treatments in 2019 and 2020; in 2021, soil available phosphorus content of T1 treatment was

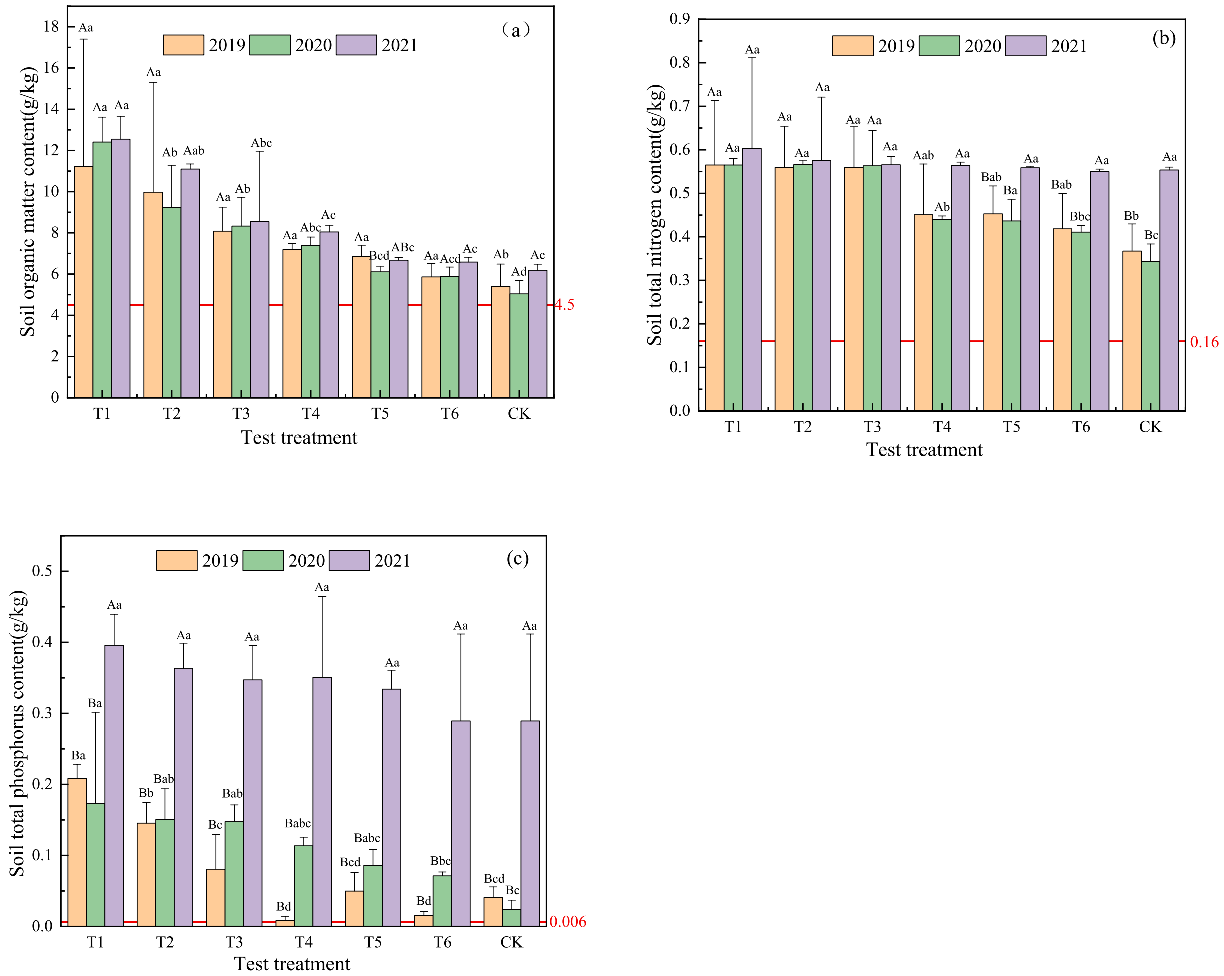

FIGURE 1
Soil total nutrient content under different amendments. **(a)** Soil organic matter content (g/kg), **(b)** Soil total nitrogen content (g/kg), **(c)** Soil total phosphorus content (g/kg). Upper case letters in the graphs indicate differences between different years of the same treatment and lower case letters indicate differences between different treatments in the same year ($p < 0.05$), as in the lower graph.

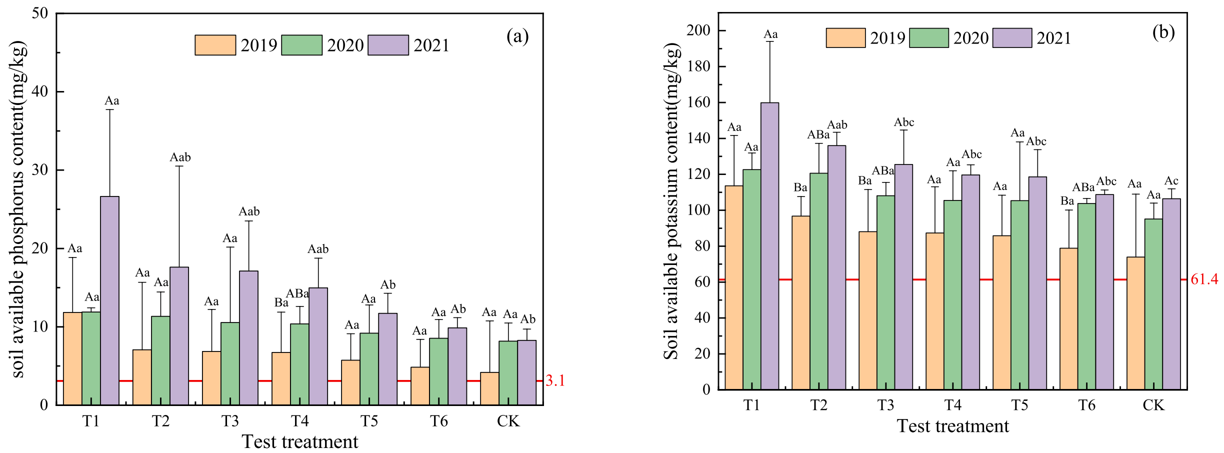

FIGURE 2
Soil nutrient availability content under different amendments. **(a)** Soil available phosphorus content (mg/kg), **(b)** Soil available potassium content (mg/kg).

significantly higher ($p < 0.05$) than T5, T6 and CK treatments. Compared with CK treatment, T1, T2, T3, T4, T5 and T6 treatments increased soil available phosphorus content by 182.50, 68.75, 63.74, 60.63, 37.12 and 15.64% in 2019; and in 2020, soil available phosphorus content increased by 45.40, 38.69, 28.91, 26.82, 12.39, 28.91, 26.82 and 12.39%, respectively. 26.82, 12.39 and 4.33%, and in 2021 the available soil phosphorus content will increase by 222.11, 113.10, 107.09, 81.02, 41.72 and 19.29%, respectively. With increasing years, the increase in soil available phosphorus content under each treatment also showed the trend of decreasing and then increasing.

From Figure 2b it can be concluded that the soil available potassium content of the different organic–inorganic treatments and the blank treatment (conventional fertilizer) were all higher than the basal value of the reclaimed soil, 61.4 mg/kg. There was no significant difference in soil available potassium content between the same treatments in different years under T1, T4, T5 and CK treatments; soil available potassium content of T2, T3 and T6 treatments showed that it was significantly higher in 2021 than in 2019 ($p < 0.05$). In 2019 and 2020, there was no significant difference in soil available potassium content between treatments; in 2021, soil quick potassium content of T1 treatment was significantly higher than the other treatments except T2 treatment ($p < 0.05$). Compared to CK treatments, T1, T2, T3, T4, T5 and T6 treatments increased soil available potassium content by 53.73, 30.87, 19.18, 18.16, 16.13 and 6.73% in 2019; and in 2020, soil available potassium content increased by 28.91, 26.76, 13.61%, 10.86%, 10.71 and 9.02% in 2020; and 50.20, 27.78, 17.91, 12.42, 11.45 and 2.19% in 2021.

3.4 Maize production and its components

As shown in Table 3, the number of ears and yield of maize in each treatment were significantly higher in 2020 than in 2019 and 2021 ($p < 0.05$), while there was no significant difference between 2019 and 2021. The mean values of maize yield, number of ears, number of grains in ears and 100 kernel weight in 2019, 2020 and 201 were 6,487 kg hm^{-2}, 54,056, 487 and 28 g, 7,288 kg hm^{-2}, 56,094, 511, 29 g and 6,624 kg hm^{-2}, 53,974, 500, 28 g, respectively. In 2019, the magnitude of maize yield among treatments was T1 > T2 > T3 > T4 > T5 > CK > T6, and T1, T2, and T3 treatments were significantly higher than T4, T5, CK, and T6 treatments ($p < 0.05$). In 2020, maize yield, number of ears, and 100 kernel weight were significantly higher under T1, T2, and T3 treatments than under T4, T5, T6, and CK treatments ($p < 0.05$); In 2021, maize yield and number of ears were significantly higher in T1, T2 and T3 treatments than in T4, T5, T6 and CK treatments ($p < 0.05$); there was no significant difference in number of ears between treatments.

TABLE 3 Maize production and composition production composition.

Year	Experimental treatment	Spike number/ hm^{-2}	Spike grain number	Hundred-kernel weight/g	Yield/kg hm^{-2}
2019	T1	55,501 ± 331Ba	520 ± 1Aa	28.82 ± 0.47Ba	7,319 ± 79Ba
	T2	55,598 ± 507Ba	518 ± 3Aa	28.03 ± 0.41Bb	7,109 ± 138Bb
	T3	54,500 ± 118Bb	515 ± 4Aa	28.25 ± 0.56Bab	6,973 ± 184Bb
	T4	54,103 ± 164Bbc	496 ± 4Bb	27.84 ± 0.19ABb	6,580 ± 72Bc
	T5	54,148 ± 75Bbc	492 ± 2Bbc	27.97 ± 0.28Ab	6,552 ± 68Bc
	T6	53,883 ± 132Bc	489 ± 2Bbc	27.72 ± 0.34Ab	6,432 ± 75Bc
	CK	54,056 ± 170Bbc	487 ± 9Bc	28 ± 0.28Ab	6,487 ± 131Bc
2020	T1	56,733 ± 280Aa	515 ± 6Aa	30.28 ± 0.39Aa	7,786 ± 151Aa
	T2	56,794 ± 98Aa	515 ± 3ABa	29.59 ± 0.17Ab	7,617 ± 15Aab
	T3	56,814 ± 72Aa	508 ± 9Aa	29.58 ± 0.53Ab	7,516 ± 156Ab
	T4	55,675 ± 388Ab	513 ± 8Aa	28.46 ± 0.38Ac	7,155 ± 220Ac
	T5	55,731 ± 220Ab	508 ± 12Aa	28.28 ± 0.29Ac	7,040 ± 143Ac
	T6	55,661 ± 555Ab	510 ± 8Aa	27.91 ± 0.36Ac	6,971 ± 80Ac
	CK	55,253 ± 132Ab	511 ± 4Aa	27.9 ± 0.39Ac	6,928 ± 102Ac
2021	T1	54,734 ± 176Ca	518 ± 6Aa	28.59 ± 0.57Ba	7,128 ± 77Ba
	T2	54,500 ± 256Ca	512 ± 2Ba	28.28 ± 0.39Bab	6,940 ± 75Ba
	T3	54,280 ± 247Ba	516 ± 3Aa	27.83 ± 0.79Bab	6,864 ± 203Ba
	T4	53,435 ± 255Ca	492 ± 10Bb	27.73 ± 0.44Bab	6,418 ± 247Bb
	T5	53,386 ± 310Ca	488 ± 3Bb	27.75 ± 0.23Aab	6,361 ± 56Bb
	T6	53,362 ± 85Ba	486 ± 1Bb	27.49 ± 0.61Aab	6,269 ± 141Bb
	CK	54,120 ± 763Ba	485 ± 12Bb	27.67 ± 0.68Ab	6,391 ± 232Bb

In the table, upper case letters indicate differences in maize yield and yield components between years under the same treatment, while lower case letters indicate differences in maize yield and yield components between treatments in the same year ($p < 0.05$).

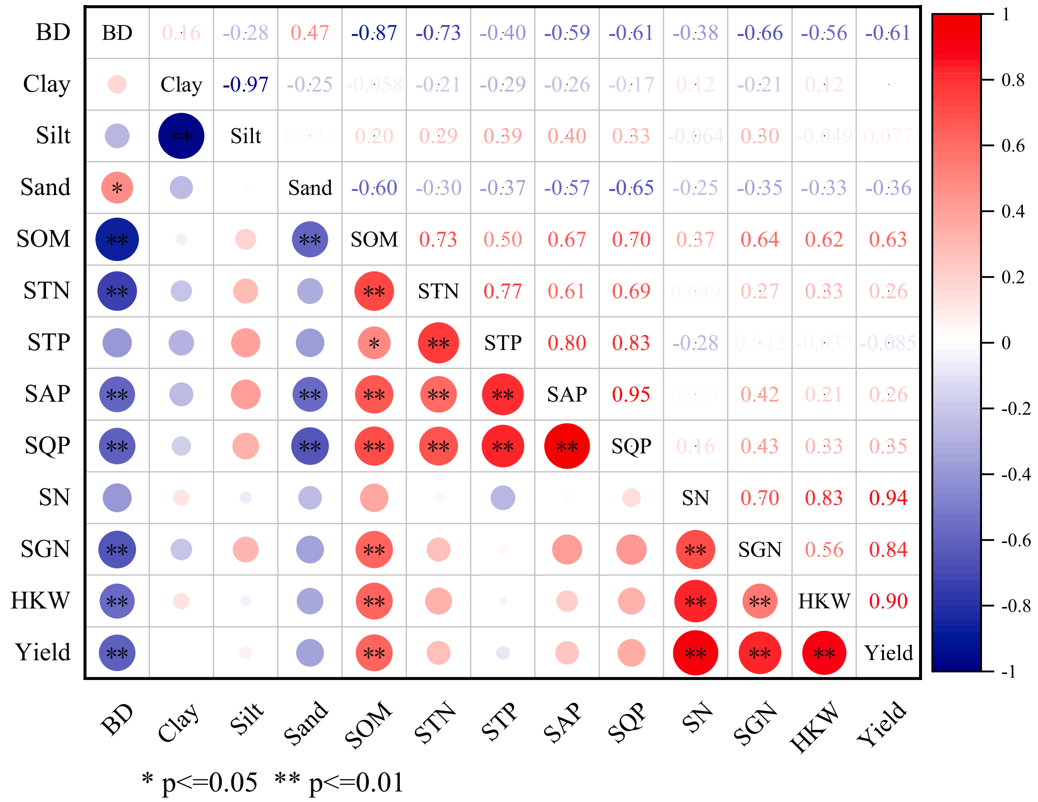

FIGURE 3
Heat map of correlation between maize yield and soil nutrients, etc.

3.5 Correlation heat map analysis

From the correlation heat map analysis in Figure 3 shows that maize yield showed a negative and highly significant correlation with soil capacity and a positive and highly significant correlation with organic matter content, number of ear, number of grains in ear and 100 grain weight; soil organic matter, total nitrogen, available phosphorus and available potassium showed a negative and highly significant correlation with soil capacity; Available phosphorus and available potassium showed a positive and highly significant correlation with total soil nutrients, and a positive and highly significant correlation was found between them; total soil nutrients also showed a positive and significant correlation with each other. Phosphorus and available potassium showed a positive and highly significant correlation with total soil nutrients, and a positive and significant correlation between the two; total soil nutrients also showed a positive and significant correlation.

4 Discussion

4.1 Effect of amendments on the bulk weight and particle composition of homestead reclaimed soils

Soil bulk density was lower in all six treatments compared to CK, but the application of fly ash, ferrous sulfate alone or a mixture of the two (T3, T4 and T5) was not as effective as the T1, T2 and T3 treatments, which had lower soil bulk density and better soil structure improvement. This is related to the application of organic fertilizer (well-composted chicken manure), although the porous structure and large specific surface area of fly ash can increase soil porosity and facilitate air and water circulation (Li et al., 2024; Le et al., 2021), and iron in ferrous sulfate can react chemically with certain components of the soil, which can help to disperse and loosen soil particles, thus reducing soil weight (Manzano et al., 2014), but both contain less organic matter and do not provide more nutrients needed by the soil. Organic fertilizers are rich in organic matter, which decomposes in the soil to form humus, which improves soil structure, increases soil porosity, loosens the soil and helps to reduce the compact accumulation of soil particles, thus reducing soil weight. In addition, organic fertilizer provides a rich food source and a good living environment for soil microorganisms, and microbial activity can further improve soil structure, promote the release and use of soil nutrients, and indirectly reduce soil weight capacity (Bebber and Richards, 2022; Zhao et al., 2016). This is consistent with the findings of Zhai et al. (2022) that organic manure application can better reduce the soil capacity of planted maize soils.

The clay particle content of the soil in this study increased relatively high under T1, T2 and T3 treatments compared to CK. This is due to the fact that humus in organic fertilizer is an important cementing agent for the formation of soil aggregates, humus contains a large number of functional groups such as carboxyl groups, phenolic hydroxyl groups, etc., which are able to form chemical bonds with metal ions on the surface of soil particles, thus binding soil particles together to form stable soil aggregates, thus increasing soil sticky particles (Hafez et al., 2021). In addition, the soil particle composition did not differ much under the inorganic treatments, which may be related to the late stage of soil amendment.

4.2 Effect of amendments on the nutrient composition of soil reclaimed from homesteads

In the later stages of soil improvement (years 5, 6, and 7), the application of different amendments was effective in improving and increasing the nutrient content of the reclaimed soil on the homestead compared to the baseline nutrient levels in the reclaimed soil. Except for total phosphorus and available potassium, there were no significant differences in soil organic matter, total nitrogen and available phosphorus contents between years, mainly because the time of amendment was more than 5 years, the soil had matured and some of the nutrient indices had reached the soil limit values. The results of all the experiments showed that the significant differences in the effect on the nutrient content of the soil were between the T1, T2 and T3 treatments with the addition of organic fertilizers, while the differences between fly ash and soil maturing agent (ferrous sulfate) were not significant, mainly because the soil was mature after more than 5 years of improvement and the effect of fly ash and maturing agent on the total nutrients of the soil was not significant at the later stage of the experiment. With the increase of years, the increase of soil organic matter, total nitrogen and total phosphorus content showed the trend of increasing and then decreasing, which also reflected the gradual maturation of the soil, and the exogenous organic matter and other amendments had less and less effect on soil nutrient accumulation. This is consistent with the findings of Ma et al. (2023) and Morra et al. (2021) that the rate of improvement in soil quality decreased with increasing duration of application of organic and inorganic amendments. According to Table 4 of the Cultivated Land Quality Classification Index of Shaanxi Province, the soil nutrient content in the study area increased from a low level of Class 5 at the base value to an intermediate level of Class 3 after 5 years of improvement.

In this study it was found that soil nutrients were higher in T1, T2 and T3 treatments, mainly because organic manure (poultry manure) increases the soil organic matter content. The increase in organic matter content will promote the growth and development of plant roots, and the metabolites secreted by the metabolism of plant rhizobacteria can activate the stabilized phosphorus and potassium in the soil, releasing more available phosphorus and potassium to meet the needs of plants and microorganisms (Liu et al., 2021). Due to the different organic and inorganic soil amendments T1-T6 and CK, the metabolic activity of the plant root system will be significantly different, and the ability to activate and stabilize the elements of phosphorus and potassium will be different, and therefore the improvement effect on soil available phosphorus and available potassium will be significantly different. The results of this study showed that the organic–inorganic mixed application treatment can effectively use the fertilizing effect of organic fertilizer on the soil, and can well achieve the comprehensive effect of soil improvement and fertilization. Mixed application can not only meet the requirements of the investment cost of land preparation, but also quickly and effectively improve soil fertility (Abrahao et al., 2021; Glaser et al., 2015; Wei et al., 2016). It can also turn waste into treasure, protect the ecological environment, and find a suitable reuse site for solid waste.

4.3 Effects of amendments on maize yield

As with soil bulk density, maize yield was higher in the T1, T2 and T3 treatments in all years. This indicates that the application of appropriate amounts of organic fertilizer and inorganic amendments facilitates plant growth and development and further increases grain yield. This is mainly due to the fact that the energy generated from the hydrolysis of fly ash accelerates and enhances the mineralization of organic matter, crop and soil respiration processes, which ultimately leads to a significant increase in the content of nitrogen, phosphorus, potassium and other nutrients in the soil, thereby promoting crop growth (An et al., 2024). The humification process of organic manure in the soil promotes crop growth and yield by increasing soil enzyme activity and nutrients, and regulating soil fertility, resulting in a more pronounced fertilizer effect and ultimately achieving the goal of increased crop yield (Hu et al., 2023; Liu and Zhou, 2017; Wei et al., 2016). Maize yield in this study was highest in 2020 and significantly different from 2019 and 2021, which is an issue that deserves our attention. Maize yield over time is not only influenced by soil nutrients, but also by multiple factors such as annual temperature, rainfall and disasters. Maize yield in this paper is informative on different treatments, but multiple references are recommended on the time series.

4.4 Correlation between maize yield and soil physico-chemical properties

From the correlation heat map analysis in Figure 3, it was found that maize yield, yield components and soil organic matter,

TABLE 4 Grading criteria for biochemical indicators of arable land quality in Shaanxi Province.

Mark	A unit	Criteria for classification				
		Level 1 (high)	Level 2 (relatively high)	Level 3 (middle)	Level 4 (relatively high)	Level 5 (low)
SOM	g/kg	≥25	25–18	18–10	10–5	<5
STN	g/kg	≥1.6	1.6–1.2	1.2–0.8	0.8–0.5	<0.5
STP	g/kg	≥1.5	1.5–1.0	1.0–0.5	0.5–0.2	<0.2
SAP	mg/kg	≥35	35–25	25–15	15–8	<8
SQP	mg/kg	≥300	300–220	220–150	150–80	<80

total nitrogen, available phosphorus and available potassium were all negatively correlated with soil bulk density. That is to say, maize prefers loose soil, and loose soil has good air and water permeability, which helps the growth and development of maize root system. Both maize yield and yield components had highly significant relationship with soil organic matter, which is in line with Previous studies (Yu et al., 2019; Hafez et al., 2021; Jaufmann et al., 2024) that maize yield is closely related to soil organic matter yield. However, in this study, maize yield was only significantly related to soil total nitrogen, available phosphorus and available potassium, and the relationship was not significant, which differed from the study of Wang et al. (2020), in which maize kernel yield was strongly influenced by nitrogen in the previous study, whereas there was no significant correlation between maize yield and soil total nitrogen in the present study, which may be related to the fact that the present study was in the late maturity stage of the soil, and that there was not much difference in the yield of different maize under different treatments, the yield was also affected by other external factors (natural disasters, rainfall, etc.).

5 Conclusion

In the later stages of soil amendment on reclaimed abandoned homesteads (years 5, 6 and 7), we found that application of the inorganic amendments fly ash and maturing agent (ferrous sulfate) alone had little effect on increasing soil nutrients and improving soil bulk density. Mixed applications of organic and inorganic amendments still increased soil nutrient content and improved soil bulk density, but the nutrient increases became smaller over time. Maize yields were significantly higher with the organic–inorganic amendment pair than with the inorganic treatment, but based on the 2019–2021 maize yield analysis, factors affecting maize yields were not only related to soil amendments, but also to natural factors such as climate, including precipitation and temperature. Although the organic–inorganic amendment dosed treatment achieved better results in this study, there are some limitations as it is a plot study, so it needs to be further verified by continuing field trials.

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

RZ: Formal analysis, Supervision, Writing – original draft. TM: Writing – original draft. ZS: Formal analysis, Supervision, Writing – original draft. ZL: Formal analysis, Supervision, Writing – original draft.

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Conflict of interest

RZ is employed by Shaanxi Agricultural Development Group Co., Ltd. TM, ZS, and ZL were employed by the Institute of Land Engineering and Technology, Shaanxi Provincial Land Engineering Construction Group Co. RZ was employed by the Shaanxi Agriculture Development Oils & Fats Group Co., Ltd. TM, ZS, and ZL were employed by the Shaanxi Agricultural Development Group Co., Ltd.

Generative AI statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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