Effects of biogas slurry on crop yield, physicochemical properties and aggregation characteristics of lime concretion soil in wheat-maize rotation in the North China Plain

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Abstract

Purpose: Biogas slurry is a potential sustainable substitute for chemical fertilizers and a soil amendment to restore soil organic matter depletion and structural deterioration. The effects of substituting biogas slurry for chemical fertilizer on a lime concretion soil in the North China Plain were investigated.

Methods: A field experiment examined the consequences of applying different proportions (0, 25, 50, 75 and 100%) of biogas slurry, while maintaining the same total nitrogen supply, over a period of 5 years. We determined effects on crop yield (winter wheat/summer maize rotation), soil physiochemical properties and aggregation characteristics (using dry- and wet-sieving) in the last experimental year.

Results: All fertilizer treatments increased crop yield relative to a control. 50% substitution by biogas slurry gave the highest yield of wheat and maize. Increasing substitution progressively increased soil pH, water holding capacity, organic matter content, total nitrogen content, available phosphorus and potassium contents and C/N ratio; conversely, bulk density declined. Soil aggregate size distribution and stability were improved to varying degrees by biogas slurry substitution, in comparison with chemical fertilizer application alone and unamended control; optimal values for macro-aggregate mass proportion, fractal dimension and percentage of aggregate destruction were achieved with 50% substitution, coinciding with the highest crop yield.

Conclusions: Lime concretion black soil was readily amenable to improvement by biogas slurry application, while maintaining optimal crop yields. Its use should be a priority for environmentally coordinated crop production and animal husbandry in this region.

Keywords: crop yield, physiochemical properties, aggregation stability, biogas slurry, lime concretion black soil, North China Plain

1 Introduction

Long-term, continuous application of chemical fertilizers, as part of agricultural management for intensive cropping, can intensify land degradation. The resulting problems, including depletion of soil organic matter, deteriorating soil structure, nutrient imbalances and loss of soil biodiversity, can hinder the development of sustainable of agricultural ecosystems (Chen et al. 2019; Bansal et al. 2020; Fan et al. 2020; Kamran et al. 2021). Such degradation is the case in the North China Plain (NCP), the major crop production area of China, which is mainly cultivated using an intensive annual crop rotation of wheat and maize (Wang et al. 2019; Zhu et al. 2021).

The deep soils, gently sloping terrain and equable climate of the NCP are conducive to large-scale agricultural production and great significance is attached to improving the soil structure and chemical nutrient retention (Chen et al. 2019). There are nearly 3.7 million ha of lime concretion black soil, which supports low to medium farm yields (Chen et al. 2019; Kan et al. 2020). This clay-rich, heavy soil is characterized by a poor structure, swelling-shrinkage with wetting/drying cycles and difficult workability (Wei et al. 2018). Low organic matter content and transient soil fertility may severely limit crop yields and the development of sustainable agriculture (Zheng et al. 2017). Chemical fertilizers have become the ubiquitous choice of growers, who lack sources of organic fertilizer and face constraints on labor costs (Dai et al. 2019). Therefore, it is desirable to seek a sustainable organic substitute for chemical fertilizer.

In China, more than 400 million tons of nitrogen-rich manure are produced annually by livestock and poultry husbandry (Yang et al. 2018). In the absence of appropriate treatments to prevent the discharge of raw manure, disposal causes environmental problems, particularly from soil pollution and water eutrophication (Cavalcante et al. 2019; Rahaman et al. 2021; Wang et al. 2021). Biogas engineering, using an anaerobic digestion process, provides both a suitable treatment and a valuable energy resource, and has been widely adopted around the world (Badagliacca et al. 2020). The residual liquid fraction from anaerobic digestion (biogas slurry) is rich in organic matter and plant nutrients, and represents a valuable resource for arable agriculture (Wang et al. 2021). Apart from addressing environmental problems, such recycling alleviates an increasing disconnection between large-scale animal husbandry and arable production (Du et al. 2018; Badagliacca et al. 2020; Chen et al. 2020). Although benefits of using biogas slurry have been widely reported, few long-term quantitative field studies have investigated the effects of biogas slurry on crop yield and soil structure, particularly in lime concretion black soil (Zheng et al. 2016; Bosch-Serra et al. 2017; Zheng et al.

2017).

Soil structure depends on the aggregation of soil particles into larger units, with pore spaces between them that allow the passage and storage of water and air (Bosch-Serra et al. 2017). These aggregates constitute the basic unit of soil structure and regulate physicochemical properties and biological processes, thereby affecting soil slaking and erosion, aeration and infiltration, and nutrient release and accumulation, as well as biodiversity (Kemper and Rosenau 1986; Dai et al. 2019; Grant et al. 2020). Thus, aggregate formation and stability play a vital role in soil fertility and rehabilitation in agricultural ecosystem (Six et al. 2004; Abbott and Murphy 2007; Diacono and Montemurro 2010; Zhu et al. 2021). The addition of organic materials is an economically viable and effective way to promote aggregate formation and they are widely applied in traditional agricultural production (Badagliacca et al. 2020; Garcia-Franco et al. 2021; Kamran et al. 2021). However, previous work has focused on the effects of soil ameliorations with solid organic amendments such as livestock manure, compost or green manure, rather than liquid organic amendments (Bosch-Serra et al. 2017; Chen et al. 2019; Dai et al. 2019).

The aims of the research described here were to investigate the effects of the application of biogas slurry, as a replacement for chemical fertilizer, on the crop yield, soil physicochemical properties and aggregate characteristics of lime concretion black soil. Different combinations of biogas slurry and chemical fertilizer were applied in a field experiment over five consecutive years. We hypothesized that: (1) fertilizer substitution with biogas slurry could maintain or even increase the crop yield in this type of soil; (2) fertilizer substitution with biogas slurry would modify soil physicochemical properties and soil aggregation, improving its stability; (3) crop yield increases would be associated with improved nutrient and water retention and aggregate characteristics. An optimal proportion of biogas slurry substitution was sought to provide a theoretical and practical basis for coordinated arable farming, animal husbandry and sustainable land use in this region.

2 Materials and methods

2.1 Study site

A field experiment was established in the village of Shangji (Zhangming Town, Shangshui County) in the Henan province of China (33°63′N, 114°28′E, 33.72 m a.s.l). It is located in the southern part of the North China Plain in an area with a long cultivation history. The region experiences a warm-temperate continental climate, with a mean annual temperature of 14.5 °C and mean annual precipitation of 785 mm (averages from 1975 to 2019). Most of the rainfall (>70%) is concentrated between June and September. Average annual sunshine duration is 2095 h, and the average annual frost-free period lasts for 223 days.

The terrain is relatively flat, favoring agricultural production. Summer maize and winter wheat have been cultivated in long-term rotation. Maize is generally sown in early June and harvested in late September, whereas wheat is seeded in the middle of October and reaped in the following June. The soil is classified as a Lime Concretion Black Soil according to the soil taxonomy system of China and as a Vertisol in the Soil Taxonomy of the USDA. Increasing use of chemical fertilizers since privatization in 1990 had led to soil degradation and surface crusting. The topsoil (surface 15 cm) contained 17.8 g kg^{-1} organic matter, 0.9 g kg^{-1} total Kjeldahl nitrogen, 24.7 mg kg^{-1} available phosphorus and 226.0 mg kg^{-1} available potassium, with a pH of 5.8, before the field experiment.

Near to the experimental area, a medium-sized fattening pig farm was established in March 2015, with an annual production capacity of about 3.0×10^5 pigs. Appropriate biogas plant and storage facilities were installed at the start of production. The main raw materials for the biogas plant reactor were pig excreta, as well as pigsty flushing water. Microbial anaerobic digestion was carried out at temperature of 30-40 degrees centigrade with a retention time of 7-10 days according to season. After passing through solid-liquid filter separators, biogas slurry from digestate was transferred to a storage pool covered with black high-polyester film. Standardized production schedules and processing guaranteed relative consistent component of slurry over the experimental period. The main properties of biogas slurry are: dry matter is 1.5-2.4%, pH is 7.6-7.7 with total nitrogen contents (TN), ammonia-N, total phosphorus (TP) and total potassium (AK) contents of 1150.0-1250.0 mg L^{-1}, 810.0-880.0 mg L^{-1}, 275.1-320.5 mg L^{-1}, 350.0-610.0 mg L^{-1}, respectively.

2.2 Experimental design

A series of six biogas slurry application treatments with five replicates were randomly established on 5 June 2015. These fertilization treatments comprised different substitution proportions of biogas slurry, while maintaining the same total nitrogen supply, including: complete chemical fertilizer with no biogas slurry (CF); 25% chemical fertilizer substituted by biogas slurry (BS25); 50% chemical fertilizer substituted by biogas slurry (BS50); 75% chemical fertilizer substituted by biogas slurry (BS75) and 100% biogas slurry applied with no chemical fertilizer (BS100,). In addition, an unamended control was designed without biogas slurry or chemical fertilizer application. Each replicate plot had an area of 134 m^2 (20 m long × 6.7 m wide).

Zhoumai 18 and Xuke 328 were the wheat and maize varieties chosen. The seed sowing rates were 225 kg ha^{-1} and 75000 plants ha^{-1}, respectively according to local recommendation. Crop seeds were sown in rows oriented in an east-west direction at a depth of 40 mm using a mechanical drill. The CF treatment was designed to provide 225 kg ha^{-1} of nitrogen as urea, with 90 kg ha^{-1} P_2O_5 and 90 kg ha^{-1} K_2O applied using superphosphate and potassium sulfate, respectively, for each of the two crops. Seventy percent of the urea was applied at planting (for maize in early June and for wheat in early October), and the remainder as top-dressing applied at the elongation stage (for maize in mid-July and for wheat in following March, respectively). Both superphosphate and potassium sulfate were applied concurrently with wheat and maize seed planting. For each treatment, all the amounts of total nitrogen, phosphorus and potassium provided by biogas slurry and chemical fertilizer are shown in Table 1.

Residue mulching was carried out before biogas slurry and chemical fertilizer application. The remaining maize stalks were incorporated by rotary tillage with an offset disc harrow with depth of 15 cm after maize harvesting at the beginning of October. All wheat straw was smashed with a straw crusher and spread on the soil surface. No tillage was applied before maize seed planting at the beginning of June (Pu et al. 2019). Because of no tillage, corn seeds were planted in rows exactly between the previously harvested wheat rows. A modified micro-spraying hose called "Small White Dragon" was connected to biogas slurry transmission network and used to apply biogas slurry. Biogas slurry was thus directly applied to the soil surface quantitatively, using an electromagnetic flowmeter after crop harvest. Two hoses connected to the same biogas slurry outlet were arranged in parallel to cover an area of 66 m^2（20 m long and 3.3 m wide）with the help of a booster pump. Sprayed biogas slurry was infiltrated into soil via gravity. In order to maintain consistent water supply for all of treatments, pumped ground water supplied at the same time was adjusted to complement the volume of water in the biogas slurry, using the same modified micro-spraying equipment. Other field management measures including herbicides and insecticides application were carried out according to local agricultural practices.

2.3 Sampling and analysis

For crop yield, wheat was harvested and measured by selecting a 1 m^2 area at maturity at the beginning of June, 2020. Maize yield was measured by random collecting 20 corn plants in each of the replicate plots before soil sampling. Finally, the yield per hectare is calculated based on the grain moisture content of 13%. Following 5 years of consecutive wheat-maize rotation, the main cropping system in this area, soil samples were collected after the maize harvest in early October 2020. From each plot, five randomly selected soil samples were taken from the upper 15 cm, using a cylindrical corer (50 mm height × 50 mm diameter) and combined. These samples were air-dried, mixed and passed through a 2-mm sieve to remove debris and litter for determining soil chemical properties. Additional, undisturbed, bulk soil samples (150 mm × 80 mm × 50 mm) from a similar depth were obtained by spade at the same sample points. Visible roots and crop residues were be removed before breaking up these soil clods along their natural cracks into pieces <10 mm in diameter (Kan et al. 2020). Then these samples were air-dried in the shade for determining aggregation characteristics.

Soil bulk density (BD) and soil water-holding capacity (WHC) were obtained using the cutting ring method for the undisturbed soil from the upper 15 cm in the field (Lu 1999). Soil pH was measured in a soil-water aqueous extract (1:2.5 by mass) after 30 min shaking at low speed (Orion Star 310p, Thermo, USA). Soil organic matter content (SOM) was determined by the potassium dichromate oxidation method and conversion coefficient (1.724) (Bao, 2008). The total N was estimated by titration of distillations after Kjeldahl digestion. Soil available phosphorus (AP) and potassium (AK) were measured using the Olsen and Dean method and flame atomic absorption spectrophotometry, respectively (Bao 2008).

Soil aggregate size fractions were estimated using the dry and wet sieving techniques, to obtain mechanical-stable and water-stable aggregates, respectively (Kemper and Rosenau 1986). 200 g air-dried bulk soil were distributed evenly on the top of a 5 mm sieve stacked over a nest of 30-cm diameter sieves with successive mesh sizes of 2, 1, 0.5, 0.25 and 0.053 mm, and spaced about 5 cm apart. Different aggregate size fractions were weighed immediately after sieving for 2 min at one oscillation per second. For wet sieving, 100 g air-dry soil from each dry sieving fraction was placed on the top of the same set sieves with the soil in the topmost sieve just submerged with deionized water for 5 min. The sieves were programmed move up and down by 3 cm at one oscillation per second for 2 min. Soil retained on each sieve was collected and weighed after drying at 40 °C for 48 h. Size fractions smaller than 0.053 mm in diameter were determined by a sequence of procedures including sedimentation, decanting and drying.

2.4 Calculation of aggregation characteristic parameters

Mean weight diameter (MWD) and geometric mean diameter (GMD) were calculated based on the percentage weight of soil in each range to the total soil sample, which could be used as an index reflecting the aggregate size distribution (Kemper and Rosenau 1986). MWD and GMD were estimated:

$$\text{MWD} = \sum_{i=1}^{n} w_i * x_i;$$

$$\text{GMD}=\exp\left(\sum_{i=1}^{n} w_i Inx_i \Big/ \sum_{i=1}^{n} w_i\right)$$

where w_i is the mass proportion of corresponding size fraction to the total dry sample weight, x_i is the mean diameter of any adjacent aggregates particle size range separated by sieving.

Percentage of aggregates destruction (PAD) was also determined as a structure stability index after wet sieving estimated (Zhang and Horn 2001):

$$\text{PAD}= \left(\frac{MR_{0.25}-WR_{0.25}}{MR_{0.25}}\right)*100\%;$$

where $\text{MR}_{0.25}$ and $\text{WR}_{0.25}$ are equal to the mass proportion of > 0.25mm mechanical-stable aggregate and water-stable soil aggregate (%), respectively.

A mass-based model for fractal dimension (D) was represented quantitatively using the structure characteristics of soil aggregates and reflected the uniformity of soil texture (Tyler and Wheatcraft 1992).

$$(3\text{-D}) \ln\frac{x_i}{x_{max}} = \ln\frac{M(r<x_i)}{M_t};$$

where M is the sum aggregate mass from sieves less than x_i; M_t is the total mass of aggregates; x_{max} is maximum value for the aggregate size. Linear regression was used to calculate fractal dimension by the least-squares method.

2.5 Statistical analysis

All data were tested for normality and homoscedasticity prior to analysis. Crop yield, soil physiochemical properties and aggregation indexes were compared for significant differences by one-way ANOVA followed by a Fisher's least significant difference (LSD) post hoc test at $p < 0.05$. Mantel tests were adopted to test the linear correlation between pairs of proximity matrices. These tests have been widely applied to explore the relationship between a group of environmental factors and microbial composition. In order to apply them to soil aggregate indexes, soil physiochemical properties and crop yield, the package Vegan in the statistical software R 3.6.1 was used. Other statistical analyses were performed with SPSS 22.0 (SPSS Inc., Chicago, USA) and graphs were plotted with Origin Pro 2019b (Origin Lab Corp, USA).

3 Results

3.1 Crop production

There were significant differences in wheat and corn yield, as well as the total yield, after 5 years of experimental treatment (Table 2). Compared with unamended control (CK), fertilization treatments all dramatically increased crop yield. For wheat, the yield changed with increasing substitution proportion. The largest yield was obtained with 50% substitution by biogas slurry (BS50), reaching 6775 kg ha^{-1}, which was slightly larger than 25% substitution (BS25) but much higher than other fertilization treatments. For maize, there was a similar trend with the greatest yield (12690 kg ha^{-1}) also in BS50. No significant difference was found between BS25 and chemical fertilizer alone (CF) or BS75. Total crop yield, in comparison with CK, was increased by 55% for CF, 63% for BS25, 76% for BS50, 65% for BS75 and 48% for BS100.

3.2 Soil physicochemical properties

Substantial differences in mean soil pH among treatments were seen (Fig. 1A). Continued application of chemical fertilizer alone (CF) significantly increased soil acidity, relative to the CK. All biogas slurry treatments significantly increased pH in comparison to the CK and CF. The highest pH was recorded in BS50 treatment, although that was not significantly higher than BS25; higher rates of substitution with slurry (BS75 and BS100) resulted in slightly lower pH.

Soil bulk density was highest in CK and not significantly different between CK and CF (Fig. 1B). Increasing substitution proportions of slurry progressively lowered bulk density, although it was not until BS50 that effect became significant. Soil water-holding capacity (Fig. 1C) and organic matter content (Fig. 2A) both showed the opposite trend – being lowest in the CK and CF, and then significantly higher with increasing slurry substitution, to a maximum in BS100. Water-holding capacity in BS100 was 41% higher than the CK and 63% higher than the CF.

Soil total nitrogen content, available phosphorus and available potassium all showed similar trends (Fig. 2B-D). These were significantly lower in the control than in all the biogas slurry substitution treatments. Few significant differences were found among substitution treatments: none for available P (Fig. 2C), only one for total N (BS50 was anomalously higher than other treatments; Fig. 2B) and there was considerable variation in available K (Fig. 2D). The soil C/N ratio was significantly enhanced by substitution by slurry only once its substitution proportion exceeded 50% (Fig.2E).

3.3 Soil aggregate mass proportions

The distributions of mechanically stable aggregates were dominated by the fractions of 2-5 mm and 0.5-1.0 mm (24.3-47.4% and 27.3-39.2%, respectively, across treatments) with micro-aggregates (<0.25 mm) representing less than 6.5% (Table 3). Differences in aggregate mass proportion were observed among the treatments. The total proportion of macro-aggregate particles (＞0.25 mm) was similar in the CK and CF but significantly greater in all treatments that had received biogas slurry substitution. Chemical fertilizer application alone significantly decreased the proportion of larger aggregates (>5 mm and 2-5 mm) and those in the 0.053-0.25 mm size range, but increased aggregate particles in the range of 0.25-0.5 mm, when compared with unamended control. Application of biogas slurry noticeably reduced the largest aggregate fraction (>5mm), as well as the 0.053-0.25 mm and <0.053 mm fractions, relative to the unamended control. Conversely, it significantly increased representation in the 0.5-1 mm aggregate fraction (Table 3).

In contrast to the mechanically stable aggregates, the water-stable aggregates were dominated by smaller size fractions (0.25-0.5, 0.053-0.25 and <0.053 mm) and micro-aggregates (<0.25 mm) represented 42-68% of the totals across treatments (Table 4). Chemical fertilizer application alone resulted in significantly lower representation of larger aggregates (particularly the >5 mm and 1-2 mm fractions) and concomitantly greater representation of some smaller aggregates (0.5-1 mm and 0.25-0.5 mm), relative to the unamended control. Moderate applications of biogas slurry (BS25 and BS50) were extremely effective in maintaining higher fractions of macro-aggregates (>0.25 mm) relative to both unamended control and chemical fertilizer alone, but this effect was not seen at the higher application rates (BS75 and BS100).

3.4 Soil aggregation stability characteristics

Mean weight diameter (MWD) and geometric weight diameter (GMD) of aggregates showed very similar patterns among treatments, although the water-stable values were consistently much lower than the mechanical-stable values (Fig. 3A, B). The MWD of mechanical-stable aggregates was largest in unamended control and lowest with chemical fertilizer application alone. However, increasing application of biogas slurry had a significant positive effect on the GMD of mechanical-stable and water-stable aggregate, up to maximum at 50% substitution with slurry, with diminishing returns thereafter. The mechanical-stable and water-stable values of GMD were smallest with chemical fertilizer application alone, and significantly lower than other treatments.

Increasing substitutions with biogas slurry increased values to a maximum at 50% substitution. Beyond that, these values declined again, such that 100% substitution was not significantly different from the unamended control for water-stable values of GMD.

Determinations of fractal dimension (D) reflected the smaller aggregate sizes after wet-sieving, with water-stable fractal dimensions being consistently higher than their mechanical counterparts. The differences between treatments were generally small, although 50% substitution with slurry yielded significantly the lowest values (Fig. 3C). This treatment also resulted in clearly the lowest percentage aggregate destruction (PAD) values observed the experiment (Fig. 3D). Unamended control, chemical fertilizer application alone and 100% slurry substitution produced the highest values of PAD, although these were not significantly different.

3.5 Correlations among crop yield and soil properties

Mantel test correlations among soil aggregation characteristics, physicochemical properties and crop yield confirmed that the distance of soil aggregate indexes was extremely significant positively correlated with soil physiochemical properties (Fig. 4A). Crop yield distance was similarly significant positively correlated with physiochemical properties (Figure 4B) and soil aggregate indexes (Fig. 4C).

4 Discussion

Fertilization is a key element of modern agricultural production (Abbott and Murphy 2007, Chen et al. 2020). Five years of continuous treatment in our experiment have shown that substituting biogas slurry for chemical fertilizer can maintain productivity under intensive crop production in a wheat-maize annual rotation. Indeed, a combination of slurry and chemical fertilizer gave the highest yields of both crops, suggesting a synergistic effect beyond simple replacement of nutrient supply. Consequently, the results of the present study supported the first hypothesis that appropriate biogas slurry utilization could maintain or even increase the crop yield in a lime concretion black soil. Much of previous work on biogas slurry application has implicated the roles of soil texture, underlying fertility, tillage management and crop species as factors in increased yield, in crops such as rice, wheat, peanut and maize (Galvez et al. 2012; Zheng et al. 2016; Zheng et al. 2017; Rahaman et al. 2021). It is important therefore to examine its effects on the soil itself.

Soil fertility depends on a range of physiochemical conditions that are related to its organic matter content (Abbott and Murphy 2007; Diacono and Montemurro 2010;

Badagliacca et al. 2020). A common approach to fertility maintenance involves amendment with allochthonous organic matter, such as livestock manure, green manure, composts and biochar (Du et al. 2018; Greenberg et al. 2019; Li et al. 2020). Our experiment confirmed that biogas slurry application was also effective in this respect when applied to a lime concretion black soil. The findings supported our second hypothesis that biogas slurry applicant would have physicochemical effects relative to both conventional chemical fertilizer treatment and unamended control. Soil pH is an important determinant of nutrient availability to plants and is used as an indicator of fertility (Yang et al. 2018; Shi et al. 2019). Because of its carbonate content, lime concretion black soil has a high buffering capacity (Luo et al. 2015; Bosch-Serra et al. 2017). Nevertheless, untreated control and chemical fertilizer treatments had become distinctly acidic, whereas substitution with biogas slurry significantly increased pH to near neutral (6.4-7.2) and the greatest buffering was obtained with moderate biogas slurry applications (25% and 50% substitution). These results are consistent with findings that biogas slurry application improved buffering capacity on a fluvio-aquic soil of the NCP due to the abundance of polysaccharides, humic acids and basic cations in digestate (Du et al. 2018). The less effective mitigation of acidification at higher substitution fractions might be explained by acid inputs exceeding the capacity of soil aggregation processes and microbial consumption to deal with them (Shi et al. 2019). However, whether this acidification continues to intensify or mitigate after prolonged biogas slurry application time (>5 years) still requires investigation.

Biogas slurry application clearly reduced soil bulk density and increased water-holding capacity in proportion to the amount of slurry added. Previous studies have also shown a decrease in bulk density with increasing slurry substitution application in the Indo-Gangetic alluvial tract and Southern China (Garg et al. 2005; Zheng et al. 2017). The driver of these effects would have been soil organic matter, which also increased in proportion to the amounts of biogas slurry added (Diacono and Montemurro 2010; Fan et al. 2020; Li et al. 2020). The increase could be directly from the biogas slurry and indirectly by enhanced decomposition of crop residues and stubbles (Galvez et al. 2012; Grant et al. 2020). The highest soil organic matter content recorded in the experiment (27.4 g kg^{-1}) is toward the upper end of the range for intensive agricultural production in this area (30-year average, 12.5-17.5 g kg^{-1}, unpublished data).

Organic matter is also a source of nutritional elements for plants; it provides the energy source for microbial metabolism and its associated mineralization yields available elements (Abbott and Murphy 2007; Mondini and Sequi 2008). Our results demonstrated that biogas slurry was a more than adequate substitute to maintain soil total nitrogen, available phosphorus and available potassium concentrations. Similar results were reported by Xu et al (2019) in Southwest China. Lime concretion black soils are generally characterized by nitrogen deficiency but have adequate phosphorus and potassium. Therefore, biogas slurry application would have contributed to balancing this nutritional maladjustment and to facilitating nitrogen transformations. Only the 50% substitution with biogas slurry gave slightly higher residual nitrogen content than the chemical fertilizer alone. However, there could have been losses ascribable to volatilization of ammonium-nitrogen, as about 70% of the nitrogen in biogas slurry presents in the form of NH_4^+ in our research (Wang et al. 2021), or leaching of poorly adsorbed nitrate-nitrogen. Both could ultimately have negative environmental impacts by contributing to climate warming and water eutrophication (Gericke et al. 2012). Although greater than in the control, available phosphorus was not significantly different in any of the other treatments, even though previous work suggested that phosphorus availability was enhanced by labile phosphorus from biogas slurry, as well as by stimulation of native soil phosphorus release (Grant et al. 2020; Niyungeko et al. 2020). Some of the available phosphorus could have been fixed by Ca^{2+} and Mg^{2+} in lime concretion black soils. Available potassium in the slurry substitution treatments was similar to that in the chemical fertilizer, although interpretation is complicated by potentially large amounts mineralized from straw mulches and their reserves (Luo et al. 2020). Biogas slurry application would promote mineralization by stimulating decomposer activity (Chen et al. 2020). The observed changes of soil C/N ratio would also be likely to affect the soil microbial biomass and nutrient fixation or release (Jiang et al. 2017). In comparison with complete chemical fertilizer application, biogas slurry substitution increased the soil C/N ratio proportionately, suggesting that its influence on the concentration of soil organic matter was greater than that on total nitrogen.

Organic matter also affects soil aggregate structure, the physical foundation of soil fertility (Kemper and Rosenau 1986; Abiven et al. 2009). Aggregates and the pore spaces between them determine soil aeration, drainage and permeability, influencing the activities of soil biota (Ceotto and Spallacci 2006; Du et al. 2016). After 5 years, biogas slurry application had substantial effects in promoting soil aggregation and stabilization, in comparison with exclusive use of chemical fertilizers. In general, macro-aggregates with a diameter of 0.25-10 mm are important indicators of soil physical, chemical and biological properties, and have been called ideal aggregates (Shi et al., 2019), although micro-aggregates with of diameter < 0.25 mm also would affect soil aeration and microbial activities (Pan et al. 2021). All biogas slurry substitution proportions contributed to macro-aggregate formation and aggregate stability, whether mechanical- or water-stable aggregates. Although organic matter has an important role in improving soil aggregate structure, the effects we observed were not linear (Diacono and Montemurro 2010; Shahbaz et al. 2017). Macro-aggregate mass proportions ($MR_{0.25}$ and $WR_{0.25}$), widely accepted as another important indicator of good structure (Liu et al., 2020), peaked at 50% substitution and then declined again, such that values at 100% were similar to those in the untreated controls although still significantly higher than for chemical fertilizer.

Differences between mechanical- and water-stable parameters, particularly expressed as percentage aggregates destruction (PAD) reinforced the finding that slurry substitution increased stability, with an optimum stability at 50% substitution. Aggregate distribution, rather than being lognormal as previously assumed, has fractal characteristics and so fractal dimension (D) represents a theoretically improved index of soil structural distribution (Tyler and Wheatcraft 1992, Six et al. 2004). The lower value of D at 50% substitution again indicated greater aggregate stability and macro-aggregate composition (Tyler and Wheatcraft 1992). Similar results were obtained by Zheng et al (2016) from biogas slurry application to upland red soil in southern China. As a Vertisol, lime concretion black soil is characterized by high clay content, dominated by smectite, which favors macro-aggregation formation and swelling-shrinkage (Okolo et al. 2020). Increasing application with biogas slurry might mask the effects of smectite, and slightly aggravate aggregate slaking because of exchangeable cations (Bosch-Serra et al. 2017).

Correlations among crop yield, soil aggregation indexes and physiochemical properties across different treatments provide insights into coordinated change involving crop production and soil fertility parameters, and thus support the third hypothesis. It is likely that these correlations devolve from a complex of factors associated with organic matter and arising from biogas slurry application. Organic matter, especially humus, is one of the main cementing materials in aggregate formation (Plaza-Bonilla et al. 2010). Compared with solid materials, biogas slurry had high flow characteristics, thus increasing contact area between soil particle and organic material (Bosch-Serra et al. 2017). Polysaccharides could also act as transitory binding agents to initiate aggregate formation (Tisdall and Oades 1982; Ceotto and Spallacci 2006; Abiven et al. 2009). Exogenous organic materials could bind to soil particles to increase intra-particle cohesion within aggregates and inter-aggregate hydrophobicity (Okolo et al. 2020). On the other hand, salinity could induce soil aggregate slaking and dispersion, as Na^+ could replace Ca^{2+} in clay mineral particles and Mg^{2+} adsorbed on the surface of soil (Abiven et al. 2009; Meng et al. 2014). Organically enriched soils might also have more exchange sites as was found by Yang et al. (2019) and Badagliacca et al. (2020).

Overall, substitution of biogas slurry for chemical fertilizers on lime concretion black soil of NCP had beneficial effects on its physicochemical properties and aggregation characteristics that were correlated with crop yield, with optimal values occurred at 50% substitution. Clearly, this approach deserves wider application in this region. Nevertheless, local conditions and resources need to be taken into account (Garcia-Franco et al. 2020). In particular, the economic effectiveness of a piping layout for biogas slurry transportation and application depends on proximity to animal breeding enterprises and farmers might need to adjust the timing of application according to the degree of drought and local crop nutritional requirements (Wang et al. 2021). Furthermore, the potential disadvantages of biogas slurry application should not be ignored: secondary salinization of the soil derived from its considerable salt content, heavy metal accumulation originating from feed additives (Cavalcante et al. 2019), and groundwater pollution (e.g. excessive nitrate content and antibiotic contamination) and ammonia volatilization (Rahaman et al. 2020). Further, long-term, work on the improvement of lime concretion black soil should encompass ecological safety and economic feasibility, as well as the relationships between soil aggregates, nutrients and crop yield.

5 Conclusions

Substitution of biogas slurry for fertilizer application on the lime concretion black soil in North China Plain represents a promising approach to sustaining crop yield and improving soil characteristics. A field experiment demonstrated the utility of biogas slurry application in reducing soil bulk density, while enhancing its water-holding capacity, organic matter, available phosphorus, available potassium and C/N ratio. All biogas slurry substitution proportions contributed to macro-aggregate formation and stability, relative to chemical fertilizer alone. Furthermore, the 50% substitution with biogas slurry gave optimal crop yield, soil aggregate structure and stability, and pH and total nitrogen content. This proportion of substitution with biogas slurry is recommended for more sustainable land and fertilizer use on lime concretion black soils in this region, where crop production can be integrated with intensive animal husbandry.

Acknowledgements

This research was supported by the Key Laboratory of High-efficient and Safe Utilization of Agriculture Water Resources of CAAS (2019AA02), Applied Research Program of Key Scientific Research Projects in Henan Province (20B210004), Postdoctoral Research Grant in Henan Province, China (201903042) and Plant Protection of Key Discipline Project of Henan Province. Special thanks are due here to Fei Wang and Yongpeng Xu from Muyuan Husbandry Company and all members from 513 scientific group for their valuable assistance during the 5-year experimental period. Finally, this manuscript was dedicated to my newborn baby named Yuxin in 2021.

Declarations

The authors declare that they have no conflict of interest.

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Table 1 Amounts of total nitrogen, phosphorus and potassium provided by different biogas slurry and chemical fertilizer applications for each crop

Treatment	Biogas Slurry				Chemical Fertilizer		
	Application Amount	N	P_2O_5	K_2O	N	P_2O_5	K_2O
	m^3 ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
CK	0.0	0.0	0.0	0.0	0.0	0.0	0.0
CF	0.0	0.0	0.0	0.0	225.0	90.0	90.0
BS25	46.9	56.3	14.1	22.5	168.7	75.9	67.5
BS50	93.8	112.6	28.2	45.0	112.4	61.8	45.0
BS75	140.7	168.9	42.3	67.5	56.1	47.7	22.5
BS100	187.6	225.0	56.4	90.0	0.0	33.6	0.0

Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer.

Table 2 Wheat yield, maize yield and total yield of the last crops in response to biogas slurry and chemical fertilizer application to lime concretion black soil

Treatment	Wheat yield kg ha^{-1}	Maize yield kg ha^{-1}	Total yield kg ha^{-1}
CK	4361 ±268e	6708 ±262e	11069 ±304e
CF	6045 ±471cd	11100 ±765c	17145 ±692c
BS25	6461 ±289ab	11545 ±352bc	18006 ±228b
BS50	6775 ±231a	12690 ±305a	19465 ±328a
BS75	6351 ±201bc	11935 ±369b	18286 ±440b
BS100	5903 ±214d	10510 ±297d	16413 ±422d

Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Values sharing same lowercase letters in the same column are not significantly different at $p < 0.05$.

Table 3 Mass proportions of mechanical-stable aggregates in response to biogas slurry and chemical fertilizer application to lime concretion black soil

Aggregate size class mm	Treatment					
	CK %	CF %	BS25 %	BS50 %	BS75 %	BS100 %
>5	12.1 ±1.0a	5.3 ±0.7d	8.8 ±0.8b	6.5 ±1.0c	4.1 ±0.6e	9.3 ±0.8b
2-5	39.4 ±3.5b	31.9 ±2.3c	38.7 ±3.2b	47.4 ±3.7a	41.7 ±3.6b	24.3 ±2.8d
1-2	7.3 ±1.1b	8.1 ±1.0b	6.7 ±1.0b	6.7 ±0.8b	7.3 ±0.7b	19.0 ±2.5a
0.5-1	27.3 ±1.6c	32.9 ±2.6b	35.9 ±2.2ab	32.4 ±3.3b	37.7 ±3.0a	39.2 ±3.8a
0.25-0.5	7.4 ±1.1b	16.1 ±1.5a	6.8 ±0.9b	5.0 ±0.6c	6.4 ±0.6b	5.1 ±0.8c
0.053-0.25	4.7 ±0.6a	3.9 ±1.0b	2.0 ±0.5c	1.5 ±0.1c	2.0 ±0.5c	2.2 ±0.4c
<0.053	1.7 ±0.2a	1.9 ±0.5a	1.0 ±0.1b	0.5 ±0.2c	0.9 ±0.2b	1.1 ±0.3b
$MR_{0.25}$	93.5 ±6.8d	94.2 ±1.4d	97.0 ±5.8b	99.0 ±2.6a	95.6 ±8.6c	96.7 ±1.5b

Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Values sharing same lowercase letters in the same column are not significantly different at $p < 0.05$.

Table 4 Mass proportions of water-stable aggregates in response to biogas slurry and chemical fertilizer application to lime concretion black soil

Aggregate size class mm	Treatment					
	CK %	CF %	BS25 %	BS50 %	BS75 %	BS100 %
>5	0.7 ±0.1c	0.2 ±0.0d	2.3 ±0.3a	1.1 ±0.0b	1.1 ±0.1b	0.8 ±0.1c
2-5	1.8 ±0.2c	1.5 ±0.2c	0.7 ±0.2d	5.6 ±0.9a	2.5 ±0.3b	1.6 ±0.3c
1-2	3.2 ±0.4c	1.6 ±0.2d	9.2 ±1.5b	10.8 ±1.0a	1.6 ±0.2d	2.4 ±0.2cd
0.5-1	9.7 ±1.4c	10.8 ±2.5c	14.5 ±2.5b	27.0 ±2.2a	11.5 ±1.5c	10.3 ±1.8c
0.25-0.5	17.9 ±1.7bc	18.3 ±1.8bc	15.5 ±1.3cd	13.8 ±2.5d	25.2 ±2.3a	20.4 ±2.3b
0.053-0.25	20.3 ±3.5b	13.6 ±2.1c	21.7 ±2.3b	10.9 ±1.9c	29.0 ±2.5a	20.3 ±3.0b
<0.053	46.4 ±2.6b	54.1 ±3.0a	36.2 ±4.9c	30.8 ±1.7d	29.1 ±2.8d	44.3 ±2.3b
$WR_{0.25}$	33.3 ±2.4cd	32.3 ±1.7d	42.2 ±3.7b	58.2 ±1.5a	41.9 ±1.6b	35.4 ±1.5c

Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Values sharing same lowercase letters in the same column are not significantly different at $p < 0.05$.

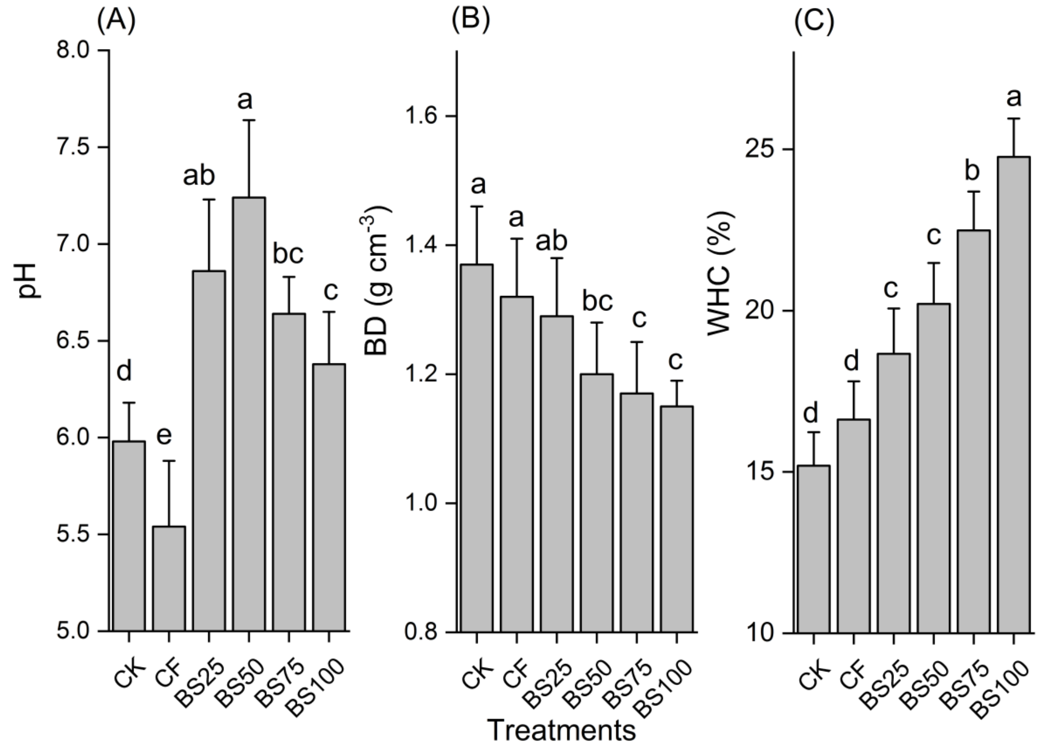

Figure. 1 Effects of combinations of chemical fertilizer and biogas slurry application on properties of lime concretion black soil: (A) pH; (B) Bulk density (BD); (C) Water-holding capacity (WHC). Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Bars sharing lower-case letters are not significantly different at $p < 0.05$.

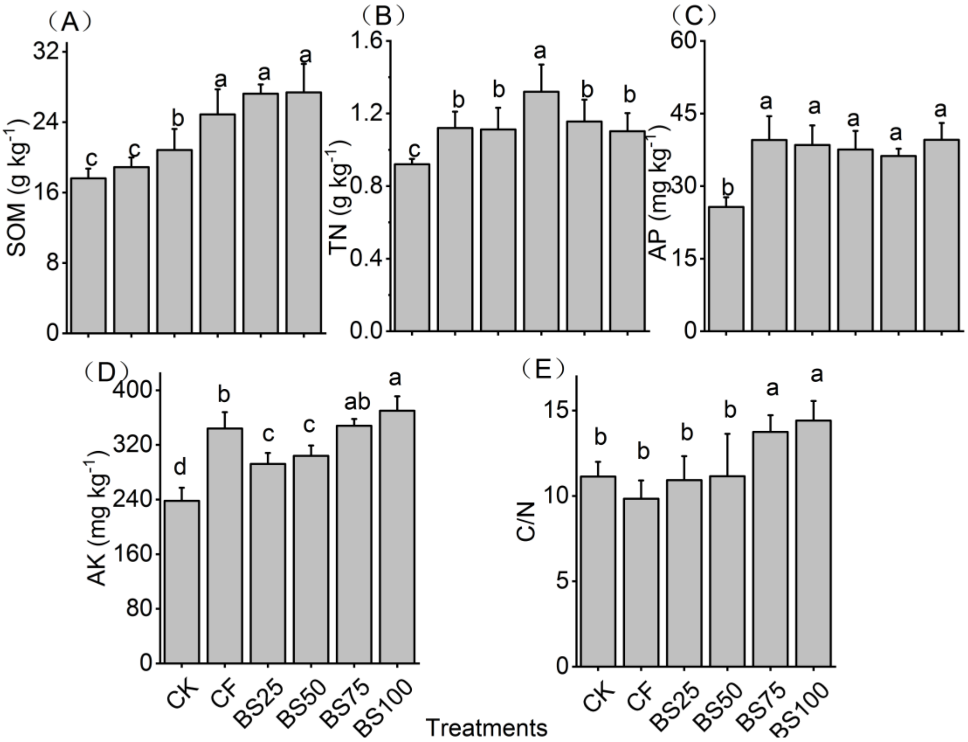

Figure. 2 Effects of combinations of chemical fertilizer and biogas slurry application on soil nutrient concentrations and C/N in lime concretion black soil: (A) Soil organic matter content (SOM); (B) Total nitrogen, (TN); (C) Available phosphorus (AP); (D) Available potassium (AK); (E) Carbon/nitrogen ratio (C/N). Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Bars sharing lower case letters are not significantly different at $p < 0.05$.

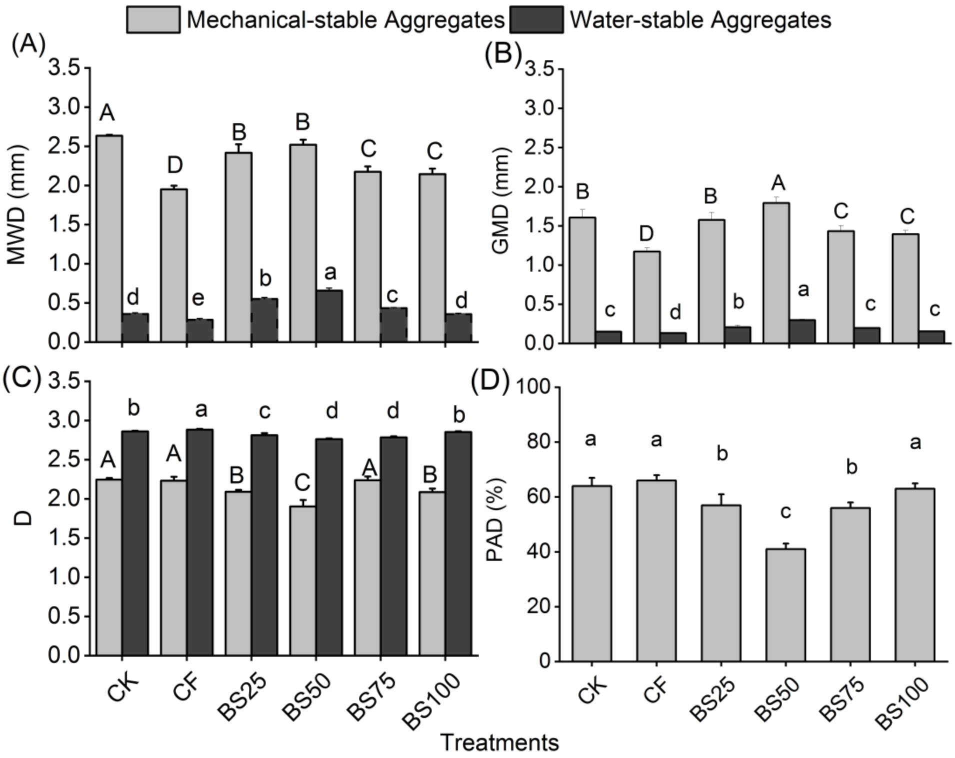

Figure. 3 Mechanical-stable and water-stable aggregation stability characteristics of the lime concretion black soil in response to biogas slurry application treatments: (A) Mean Weight Diameter (MWD); (B) Geometric Mean Diameter (GMD); (C) Fractal Dimension (D); (D) Percentage of Aggregates Destruction (PAD). Treatments: CK, unamended control; CF, chemical fertilizer alone; BS25, 25% biogas slurry substitution; BS50, 50% biogas slurry substitution; BS75, 75% biogas slurry substitution; BS100, 100% biogas slurry with no chemical fertilizer. Bars sharing same uppercase or lowercase letters were not significantly different at $p < 0.05$ for mechanical-stable and water-stable aggregates, respectively.

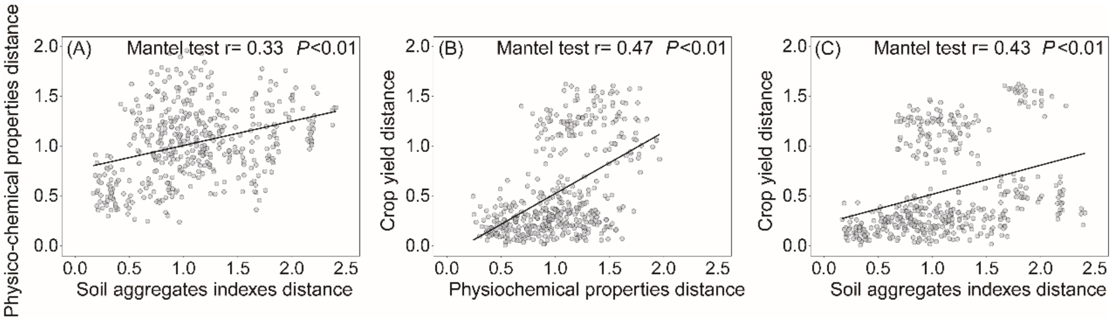

Figure. 4 Linear correlations between pairs of proximity matrices, using the Mantel test among soil aggregate indexes, soil physiochemical properties and crop yield: (A) Physicochemical properties v. Soil aggregates indexes; (B) Crop yield v. Physicochemical properties; (C) Crop yield v. Soil aggregates indexes.