Effects of Biogas Slurry Drip Irrigation on Growth Performance of *Brassica chinensis* L. and Soil Nutrient Dynamics

Dongxue Yin,[a,]* Jiajun Qin,[a] Dongdong Chen,[a] Baozhong Wang,[a] Wei Liu,[b] Yingxian Wang,[a] Weijuan Lan,[a] Zhihao Wang,[c] and Jiachen Wang [a]

The optimal amount of biogas slurry was determined to improve both the yield of *Brassica chinensis* L. (BL) and soil quality. An experiment was set up with six sets of drip irrigation gradients (1:3 mix of biogas and water) of 12 (BS-1), 15 (BS-2), 18 (BS-3), 21 (BS-4), 24 (BS-5), and 27 (BS-6) L. Each treatment was repeated three times and irrigated eight times. The radius of drip irrigation was 1.2 m, and the dripping speed was 2 L/h. The highest plant height, fresh weight, dry weight, soluble sugar content, and protein content of 25.2 cm, 16.7 g, 1.10 g, 0.61 g/100 g, and 1.90 mg/g, respectively, were obtained under the BS-5 treatment. Soil total nitrogen, available phosphorus, and organic matter content under the BS-4 treatment increased 5.29%, 230.75%, and 1.00%, respectively, compared with those before drip irrigation treatment. The soil available potassium content was highest under the BS-3 treatment and had increased 20.4% compared with that before drip irrigation treatment. The most remarkable influence on the yield and quality of BL was observed when the drip irrigation amount was 24 L. Drip irrigation with 21 L of biogas slurry is conducive to improving soil physical and chemical properties.

DOI: 10.15376/biores.20.1.2026-2037

Keywords: Biogas slurry; Brassica chinensis L.; Yield; Quality; Soil nutrient

*Contact information: a: College of Agricultural Equipment Engineering, Henan University of Science and Technology, Luoyang, PR China; b: College of Agriculture, Henan University of Science and Technology, Luoyang 471000, P. R. China; c: Henan Fengcai Agricultural Development Co. LTD., Sui County 476900, P. R. China; *Corresponding author: DongXueYin01@163.com*

INTRODUCTION

Climate change represents an important challenge to human society. Considering the intrinsic requirements for sustainable development, China proposed two objectives: carbon neutrality and carbon peak limitation. Greenhouse gas emissions in rural areas should not be underestimated. The vigorous development of the comprehensive use of biomass in rural areas represents an important measure for enhancing the ability of rural areas to reduce emissions and sequester carbon, optimizing the rural energy structure, and reducing greenhouse gas emissions. China is endowed with a plethora of agricultural biomass resources and has an estimated energy utilization of 461 million tons of standard coal, resulting in a carbon reduction of approximately 218 million tons (China Association for the Promotion of Industrial Development, Biomass Industry Branch *et al.* 2021). Therefore, the comprehensive utilization of agricultural biomass is an important measure to achieve the goal of carbon neutrality and carbon peak compliance.

In recent years, the comprehensive utilization of biomass has been actively advocated and supported by the state, and the promotion and utilization of biological natural gas have attracted considerable attention (Lv 2012; Song *et al.* 2014; Li *et al.* 2015; Wang *et al.* 2023). According to the 13th Five-Year Plan for National Rural Biogas Development, the number of large-scale biogas projects in China reached 10,122 in 2020 (National Development and Reform Commission and Ministry of Agriculture and Rural Affairs of the People's Republic of China 2017), and this number will increase dramatically during the 14th Five-Year Plan period. The Guidance on Promoting the Industrialization and Development of Biogas proposed that by 2030, the annual production of biogas should exceed 20 billion m^3 (NDRC *et al.* 2019). The 14th Five-Year Plan for Renewable Energy Development emphasizes that each county needs to promote 1 to 3 biological natural gas projects with an annual output of 10 million m^3 (NDRC *et al.* 2021). The utilization of biomass resources plays a vital role in achieving the goal of carbon neutrality and carbon peak (Li *et al.* 2015; Lönnqvist *et al.* 2015; Mardoyan and Braun 2015; Jelínek *et al.* 2021; Liang *et al.* 2023; Liu *et al.* 2023a).

Anaerobic digestion is key in the production of biogas, and large amounts of biogas slurry are produced with digestion (Gong *et al.* 2013; Jelínek *et al.* 2021). A 1,000 m^3 pig manure biogas project produces more than 20,000 tons of biogas slurry per year (Jiao 2018). The annual discharge of biogas slurry in China is estimated to exceed 200 million tons (Feng 2017), resulting in problems of biogas slurry storage and utilization. The direct application of untreated biogas slurry to farmland may cause environmental risks (Insam *et al.* 2015; Yin *et al.* 2019). Studies have shown that the application of biogas slurry to paddy fields can decrease dissolved oxygen content in water, increase sulfate in sediments, and reduce soil pH (Yin *et al.* 2019; Zhang *et al.* 2022). Therefore, the green and efficient use of biogas slurry is an important factor restricting the development of the biogas industry (Gong *et al.* 2013; Wu *et al.* 2016; Nabel *et al.* 2017).

Research has shown that biogas slurry is rich in nutrients (Wentzel *et al.* 2015; He and Zheng 2022) and can be used as organic fertilizer to improve soil fertility, reducing the use of chemical fertilizers (Garg *et al.* 2005; Alburquerque *et al.* 2012; Duan *et al.* 2012; Cheng *et al.* 2014; Chen *et al.* 2019; Xu *et al.* 2019; Zheng *et al.* 2019; Yin *et al.* 2019; Qiao and Zheng 2022). Moreover, biogas slurry irrigation can inhibit the occurrence of soil diseases and insect pests and improve the soil ecological environment (Zhang *et al.* 2017; Chen *et al.* 2020; Feng 2020). Wen *et al.* (2023) found that applying biogas slurry at appropriate concentrations in combination with chemical fertilizers can effectively improve Chinese onion yield and soil microbial content, microbial community structure, and nutrient status. Qiao and Zheng (2022) found that biogas slurry irrigation can improve tomato fruit quality, pulp flavor and yield, and soil aggregate structure. Du *et al.* (2023) found that the reasonable combination of biogas slurry and chemical fertilizer can improve soil fertility, thereby considerably improving the quality of peach fruit. Hence, it can be regarded as a feasible, green, and efficient biogas slurry consumption method (Insam *et al.* 2015; Wu *et al.* 2016; Ningsih *et al.* 2024).

Recently there has been a lot of research on the use of biogas slurry instead of chemical fertilizers, but research on the irrigation amount of biogas slurry is still limited. *Brassica chinensis* L. (BL), as a common organic vegetable in Henan Province, Shanghai. It requires a stable supply of organic fertilizers during its growth process. Therefore, this study applied a certain concentration of BS as fertilizer in farmland through drip irrigation to plant BL. After BL maturity, the quality, yield, and soil physicochemical indicators of BL were measured, and the effect of BS on BL quality was studied. In this preliminary study, the objective was to provide theoretical guidance for the agricultural application of BS.

EXPERIMENTAL

Pilot Area Profiles and Materials

The experimental area is located in the Kaiyuan Campus Farm of Henan University of Science and Technology, Luolong District, Luoyang City (34°35‘N, 112°25’E). The soil of the experimental area is clay loam with moderate fertility. The experimental area has a temperate continental climate with an average annual temperature of 14.5 °C, and average annual precipitation and evaporation of 578 mm and 1200 mm, respectively. Rainfall occurs mainly (> 70%) between June and September. The experimental area has approximately 223 frost-free days per year. The soil moisture content in the 0 to 20 cm soil layer is 7.3% (mass moisture content). The soil of the experimental area had the following characteristics before the experiment: pH 8.46, organic matter (OM) of 22.2 $g•kg^{-1}$, and average total nitrogen (TN), available phosphorus (AP), and available potassium (AK) contents of 1.27 $g•kg^{-1}$, 6.83 $mg•kg^{-1}$, and 225 $mg•kg^{-1}$, respectively.

The biogas slurry used in the experiment was collected from the biogas digester of Lankeshan Cooperative in Xin’an County, Luoyang City. The fermentation raw material mainly consisted of cow dung, pig manure, and crop residues. The biogas slurry was treated by standing for 10 days before application, and then filtered twice with a 100-mesh nylon net. The main properties of biogas slurry were a total solids concentration of 0.43%; volatile solids of 34.9%; pH of 8.35; and average TN, AP, and AK contents of 376 $mg•L^{-1}$, 18.1 $mg•L^{-1}$, and 0.84 $g•L^{-1}$, respectively.

Experimental Design and Agricultural Managements

The experiment used a mixture of water and biogas slurry for the drip irrigation of BL (Zheng *et al.* 2019) with three replicate plots arranged using random blocks (Wang 2014). Each plot was 1.2 m long and 1 m wide. The experimental design is shown in Fig. 1. The experimental biogas slurry ratio was 1:3 (volume ratio of biogas slurry to water). Irrigation was performed every 3 days, and irrigation eight times. The experiment was set up with six drip irrigation groups, namely, BS-1, BS-2, BS-3, BS-4, BS-5, and BS-6, with irrigation treatments of 12, 15, 18, 21, 24, and 27 L, respectively.

Soil Sampling and Physicochemical Analysis

Soil samples were collected from the 0 to 10 cm soil layer in the sample plots before the sowing and after harvesting of BL through the S-sampling method and used to determine soil moisture content and physicochemical properties. The samples were air dried and passed through a 100-mesh sieve.

Plant Parameters Analysis

Random samples were taken from each plot, and the plant height, fresh weight, and dry weight were measured, soluble sugar content was determined by anthrone colorimetry, and soluble protein content was determined by Coomassie brilliant blue method.

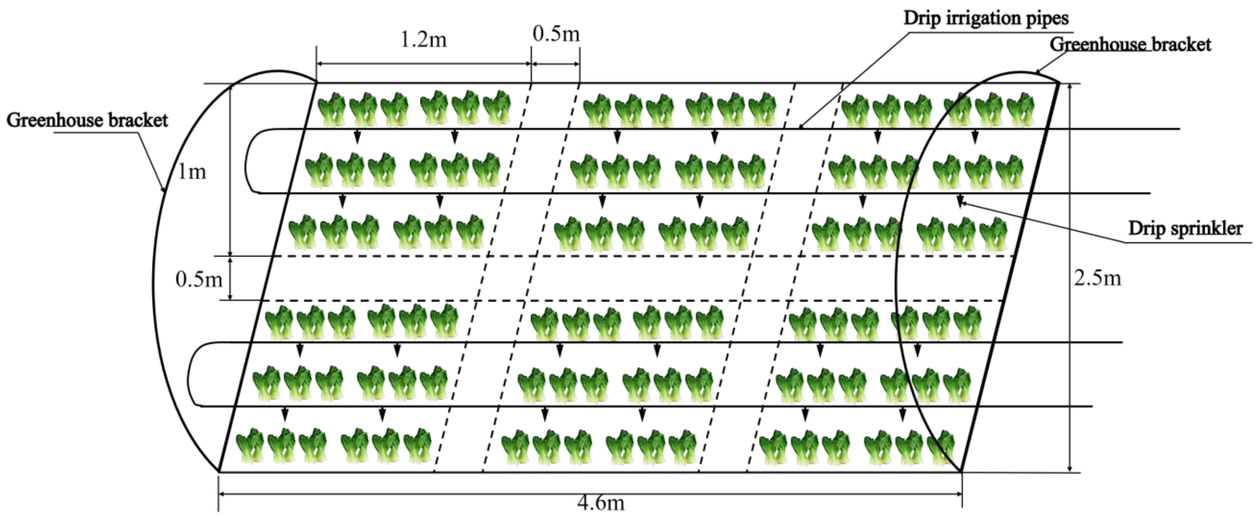

Fig. 1. Drip irrigation design plan for test sample plots

RESULTS AND DISCUSSION

Plant Yield and Quality

With the increase in drip irrigation amount, the plant height of BL showed a fluctuating rising–declining–rising–declining trend and did not exhibit a linear growth relationship (Fig. 2[a]). Among all treatments, BS-5 resulted in the highest plant height of 25.2 cm. The other treatments followed the order of BS-6, BS-2, BS-1, and BS-4 with corresponding plant heights of 22.8, 22.8, 22.7, and 22.2 cm, respectively. The BS-3 treatment resulted in the shortest plant height of 21 cm. Plant height under BS-5 increased 19.9% relative to that under BS-3, indicating that the drip irrigation of biogas slurry at the volume of 24 L was favorable for the growth of BL.

The trend of the dry weight of BL was similar to that of fresh weight. Both increased and then decreased with the increase in the amount of biogas drip irrigation. This finding was consistent with the results of the study by Jin *et al.* (2022). Figure 2(b) shows that fresh and dry weights were the highest under BS-5 and were 16.67 and 1.10 g, respectively, and were lowest under BS-1 and were 5.00 and 0.30 g, respectively.

Figure 2(c) shows that the amount of soluble sugar first increased and then decreased with the increase in the amount of biogas slurry drip irrigation. Among treatments, BS-5 resulted in the highest content of 0.61 g/100 g, whereas BS-1 resulted in the lowest content of 0.23 g/100 g. BS-5 increased the amount of soluble sugar by 165% compared with BS-1. Therefore, BS-5 remarkably contributed to the remarkable increase in the soluble sugar content of BL.

The change trends of the protein and soluble sugar contents of BL were consistent, first increasing and then decreasing with the increase in the drip irrigation volume of biogas, as shown in Fig. 2(d). BS-5 resulted in the highest protein content of 1.90 mg/g. BS-1 resulted in the lowest content of 1.25 mg/g. The protein content under each treatment followed the order of BS-5 > BS-6 > BS-4 > BS-3 > BS-2 > BS-1. BS-5 resulted in a 52.0% increase in protein content compared with BS-1.

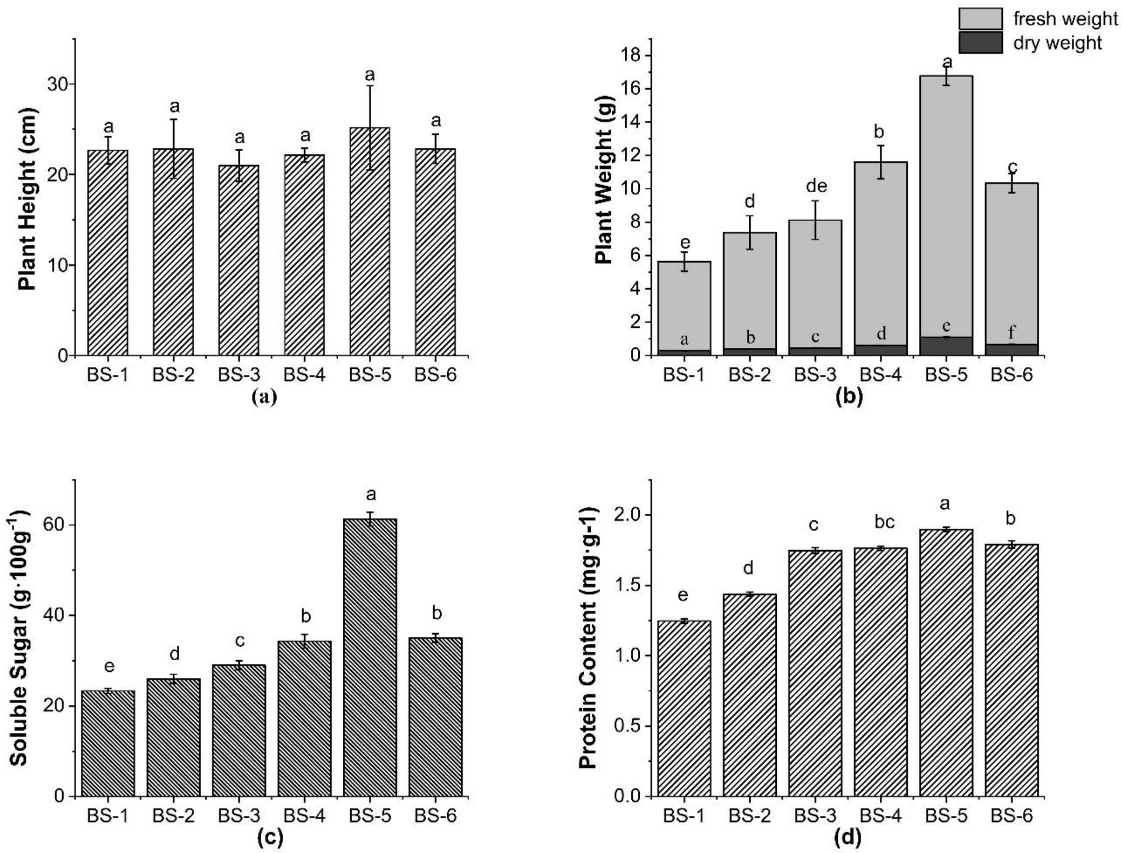

Fig. 2. Effects of biomass deficit irrigation treatments on individual plants: (a) plant height ($p < 0.5$), (b) plant fresh ($p < 0.01$) and dry weight ($p < 0.01$), (c) soluble sugar content ($p < 0.01$), and (d) protein content ($p < 0.01$)

Soil Physicochemical Properties

Soil nitrogen content has an important effect on photosynthesis and protein synthesis in plants. It showed an increasing–decreasing–increasing–decreasing trend with the increase in drip irrigation with biogas (Fig. 3[a]). The TN content was 1.27 g/kg before sowing and changed by −6.31%, 4.18%, −6.31%, 5.29%, 4.97%, and −12.08% in order of magnitude. The TN was highest under the BS-4 treatment (1.33 g/kg) but was lowest under the BS-6 treatment (1.11 g/kg). Therefore, the appropriate application of biogas will increase TN.

The trend of AP content was similar to that of TN and exhibited two peaks (Fig. 3 [b]). The AP was 6.83 mg/kg before sowing and changed by 31.7%, 228%, 25.9%, 231%, 16.1%, and −61.5% under the treatments after sowing. BS-4 resulted in the highest effective phosphorus content of 22.6 mg/kg, whereas BS-6 resulted in the lowest content of 2.63 mg/kg. The negative growth of AP under BS-6 indicated that biogas effectively replenished the AP in the soil that was consumed by crop uptake and utilization, further verifying the role of biogas in water and fertilizer conservation.

The AK contributes to plant dry matter accumulation and plays a major role in plant disease resistance. It showed fluctuating trends with the increase in the drip irrigation volume of the digestate (Fig. 3[c]). The AK was 225 mg/kg before sowing and changed by −8.89%, 2.67%, 20.4%, 4.0%, 18.2%, and −11.11% under treatments after sowing. BS-3 resulted in the highest AK of 271 mg/kg, whereas BS-6 resulted in the lowest AK of 200 mg/kg. All treatments, except for BS-1 and BS-6, increased AK. Therefore, the application of biogas can effectively promote the retention of AK in the soil and avoid nutrient loss, which has a good effect on potassium conservation.

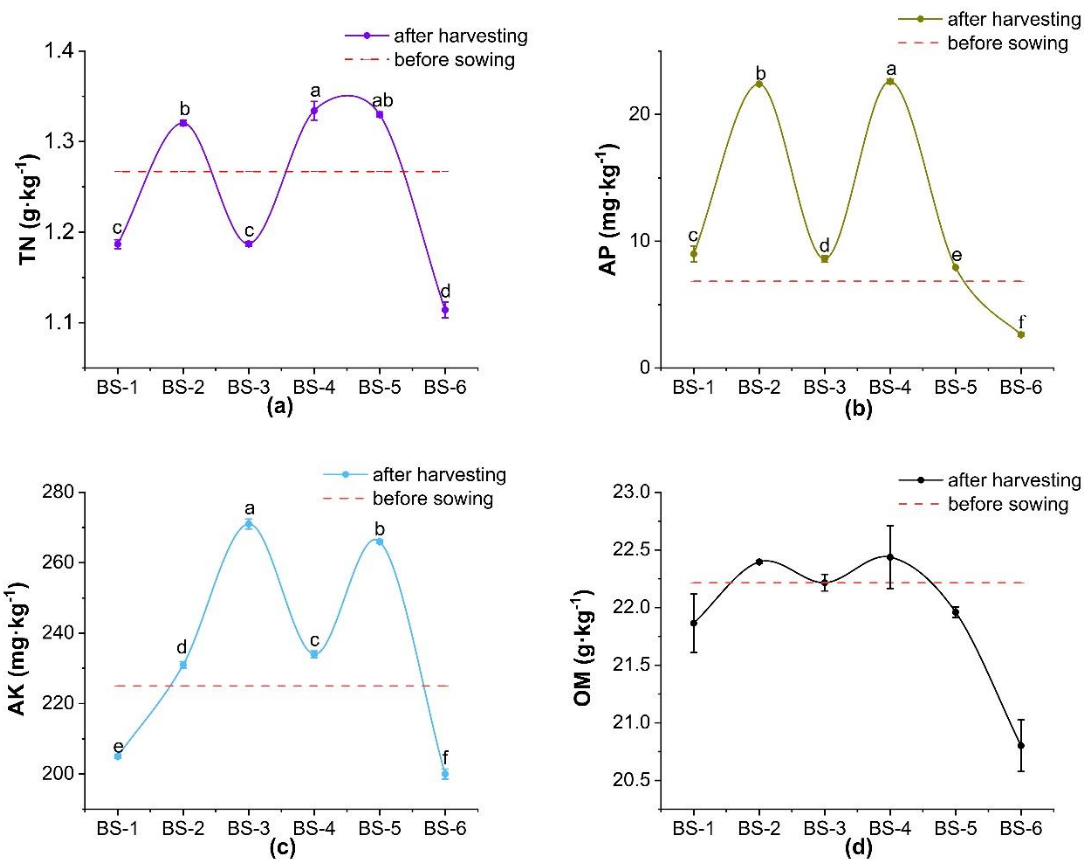

Fig. 3. Effect of biomass deficit irrigation treatments on soil nutrients: (a) total nitrogen content (TN) ($p < 0.01$), (b) available phosphorus content (AP) ($p < 0.01$), (c) available potassium contributed (AK) ($p < 0.01$), and (d) organic matter content (OM)($p < 0.01$)

The soil OM content showed a rising–decreasing–rising–decreasing trend with the increase in the amount of biomass drip irrigation (Fig. 3[d]). The OM was 22.2 g/kg before sowing and increased −1.58%, 0.81%, 0.01%, 1.01%, −1.15%, and −6.36% after sowing. The OM during treatment did not fluctuate considerably compared with that during the pre-irrigation period because the digestate had a low OM content. Only BS-6 resulted in a high reduction in OM, which was likely due to the leaching of soil OM caused by the high drip irrigation volume of the digestate.

Effect of Different Irrigation Amounts of BS Drip Irrigation on the Quality and Yield of BL

Drip irrigation with biogas slurry had a significant effect on plant height ($p < 0.5$) and weight ($p < 0.01$) of BL. However, the difference in plant height was not significant among the treatments, while there was a remarkable difference in weight, which is consistent with the results of Wang *et al*. (2016). This finding was attributed to the nutrients having a more direct impact on the weight of the plants rather than their height. The experimental results indicated that both the soluble sugar content ($p < 0.01$) and the protein content ($p < 0.01$) exhibited an overall trend of first increasing and then decreasing with the increase in the amount of biogas slurry drip irrigation, peaking at BS-5. Concurrently, BS-5 had the highest plant height, dry weight, and fresh weight, and this result is supported by published results (Yin *et al*. 2024; Jin *et al.* 2022). The results indicate that plants possess a certain degree of self-regulatory ability in the absorption and utilization of nutrients. Within a certain range, as the amount of biogas slurry drip irrigation increases, plants can enhance the synthesis of soluble sugars and proteins by strengthening root absorption and metabolic activities. When the irrigation volume is low, plants compete with soil microorganisms for limited nutrients, while also responding with a series of adaptive response mechanisms (Khapte *et al.* 2019; Wang *et al*. 2022). When drip irrigation was below 24 L, plants prioritized the use of limited water and nutrients to maintain their basic life activities. When drip irrigation exceeded 24L, plants were unable to obtain sufficient nutrients to synthesize proteins and soluble sugars, due to soil nutrients flowing into deeper soil layers. The 24 L biogas slurry drip irrigation met the nutritional needs of the plants while avoiding nutrient leaching. Adequate nitrogen and phosphorus significantly promoted protein synthesis, and phosphorus and potassium enhanced energy metabolism, leading to an increase in the amount of soluble sugars (Xue *et al.* 2019), which in turn increased the weight of the plants.

Effect of Different Irrigation Amounts of BS Drip Irrigation on Soil Physical and Chemical Properties

Nitrogen, phosphorus, and potassium in soil are important nutrients required for plant growth and can influence the synthesis of chlorophyll, proteins, and other important substances in plants (Xie *et al.* 2021). OM can increase the number of microorganisms and promote plant growth. The research results indicate that appropriate amounts of biogas slurry drip irrigation could increase the content of soil TN ($p < 0.01$), AP ($p < 0.01$), AK ($p < 0.01$), and OM ($p < 0.01$). This result is consistent with previous research (Xue *et al*. 2019; Yin *et al*. 2024; Gong *et al.* 2020). This is because the biogas slurry contains a large amount of nutrients, and microorganisms can convert the organic matter in the biogas slurry into inorganic nutrients absorbable by plants through the process of mineralization (Zhao *et al.* 2017; Wen *et al*. 2023). The results indicate that soil nutrient content exhibits a trend of first increasing and then decreasing with the increase in biogas slurry irrigation volume, which is different with the positive correlation found in Jin *et al.* (2022). This is because when the amount of biogas slurry drip irrigation is too large, a significant amount of nutrients leach into the deeper soil layers along with the slurry. The concentrations of TN and OM in the soil fluctuate little among different treatments, showing a relatively stable state. This indicates that the nitrogen and OM in the biogas slurry can be fully utilized by plants and soil microorganisms to maintain a suitable growth environment. BS-4 had the highest AP, and BS-3 had the highest AK. This is consistent with Zhao *et al.* (2023). This is because the plants did not fully utilize the AP and AK, and at BS-3 and BS-4, the rate at which soil microorganisms transformed AK and AP exceeded the absorption rate of plants and microorganisms. Although the soil nutrient content in BS-5 was not the highest, the BL quality of BS-5 was the best, which may be due to the fact that under 24L of drip irrigation, soil microorganisms were able to release growth hormones that promoted the absorption and growth of BL nutrients.

The results show that most soil nutrient contents were higher than before planting, indicating that long-term application of biogas slurry can effectively improve soil fertility. In addition, long-term application of biogas slurry can enhance the resilience and stability of the soil microbial community (Liu *et al.* 2023b). However, biogas slurry contains a significant amount of heavy metal elements, and long-term application of biogas slurry can lead to an increase in soil heavy metal content, which cannot be naturally degraded. This can inhibit the growth and development of plants and even pose a risk to human health.

CONCLUSIONS

1. The yield and nutritional quality of *Brassica chinensis* L. (BL) can be significantly enhanced by application of biogas slurry (BS) with drip irrigation. Among the six treatments, BS-5 (24 L) showed the most favorable therapeutic effect.
2. Different drip irrigation amounts of BS were shown to have varying effects on the soil. When the drip irrigation volume was between 15 L (BS-2) and 24 L (BS-5), the contents of total nitrogen (TN), available phosphorus (AP), available potassium (AK), and organic matter (OM) in the soil will increase. Especially in BS-3 and BS-4, the soil nutrient content is the highest, with the greatest increase compared to before planting. Therefore, an appropriate drip irrigation amount of BS can enhance soil fertility.

ACKNOWLEDGMENTS

This study was supported by the Project for National Natural Science Foundation of China (31902129), Henan Province Science and Technology Plan Joint Fund Project of China (232103810057), Henan Province Science and Technology Plan Project of China (222102110140).

REFERENCES CITED

Alburquerque, J. A., de la Fuente, C., and Bernal, M. P. (2012). "Chemical properties of anaerobic digestates affecting C and N dynamics in amended soils," *Agriculture, Ecosystems & Environment* 160, 15-22. DOI: 10.1016/j.agee.2011.03.007

Branch Committee of Bio-energy Industrial of Chinese Industrial Development Committee, Deutsche Gesellschaft für Internationale Zusammenarbeit, Environmental Engineering Assessment Centre of the Ministry of Ecology and Environment, and Beijing Songshan Institute of Low Carbon Technology. (2021). *3060 Blue Book on the Development Potential of Zero Carbon Biomass Energy*, Branch Committee of Bio-energy Industrial of Chinese Industrial Development Committee, Beijing, China.

Chen, Z., Chen, G., and Li, J. (2019). "Research progress on application of biogas slurry in China's agricultural production," *Jiangsu Agricultural Sciences* 47(08), 1-6. DOI: 10.15889/j.issn.1002-1302.2019.08.001

Chen, Z., Wang, Q., Ma, J., Chapman, S., Zou, P., Ye, J., Yu, Q., Sun, W., Lin, H., and Jiang, L. (2020). "Soil microbial activity and community composition as influenced by application of pig biogas slurry in paddy field in southeast China," *Paddy and Water Environment* 18(1), 15-25. DOI: 10.1007/s10333-019-00761-y

Cheng, S., Li, Z., Mang, H.-P., Neupane, K., Wauthelet, M., and Huba, E.-M. (2014). "Application of fault tree approach for technical assessment of small-sized biogas systems in Nepal," *Applied Energy* 113, 1372-1381. DOI: 10.1016/j.apenergy.2013.08.052

Du, C., Lu, H., Xiong, Y., Sun, X., Sun, X., Pu, J., and Zhang, N. (2023). "Effects of combined application of biogas slurry and chemical fertilizer on peach growth and soil physical and chemical properties for two consecutive years," *Journal of Agricultural Science and Technology* 25(08), 165-175. DOI: 10.13304/j.nykjdb.2022.0022

Duan, G., Zhang, H., Liu, Y., Jia, Y., Hu, Y., and Cheng, W. (2012). "Long-term fertilization with pig-biogas residues results in heavy metal accumulation in paddy field and rice grains in Jiaxing of China," *Soil Science and Plant Nutrition* 58(5), 637-646. DOI: 10.1080/00380768.2012.726597

Feng, L. (2017). "Resource utilisation of biogas and problems," *Agricultural Technology Service* 34(18), 123-126.

Feng, Z. J. (2020). *Study on the Suitable Model of Water / Biogas Slurry Integrated Irrigation Instead of Chemical Fertilizer in the Whole Growth Period of Tomato*, Master's Thesis, Lanzhou University of Technology, Lanzhou, China.

Garg, R. N., Pathak, H., Das, D. K., and Tomar, R. K. (2005). "Use of flyash and biogas slurry for improving wheat yield and physical properties of soil," *Environmental Monitoring and Assessment* 107(1–3), 1-9. DOI: 10.1007/s10661-005-2021-x

Gong, H., Yan, Z., Liang, K. Q., Jin, Z. Y., and Wang, K. J. (2013). "Concentrating process of liquid digestate by disk tube-reverse osmosis system," *Desalination* 326, 30-36. DOI: 10.1016/j.desal.2013.07.010

Gong, Y., Wang, W., Guan, N., and Liu, Y. (2020). "Research progress on the effect of irrigation on tomato growth, yield and quality," *China Cucurbits and Vegetables* 33(07), 7-13. DOI: 10.16861/j.cnki.zggc.2020.0155

He, S., and Zheng, J. (2022). "Effects of different water-biogas slurry integrate irrigation methods on the growth, yield and quality of tomato," *China Rural Water and Hydropower* 2022(01), 118-122, +129.

Insam, H., Gómez-Brandón, M., and Ascher, J. (2015). "Manure-based biogas fermentation residues – Friend or foe of soil fertility?," *Soil Biology and Biochemistry* 84, 1-14. DOI: 10.1016/j.soilbio.2015.02.006

Jelínek, M., Mazancová, J., Van Dung, D., Phung, L. D., Banout, J., and Roubík, H. (2021). "Quantification of the impact of partial replacement of traditional cooking fuels by biogas on global warming: Evidence from Vietnam," *Journal of Cleaner Production* 292, article ID 126007. DOI: 10.1016/j.jclepro.2021.126007

Jiao, P. (2018). *Based on the Theory of Circular Economy, the Industrial Chain of Biogas Residue and Biogas Slurry Treatment in Biogas Engineering is Studied*, Master's Thesis, North China Electric Power University, Beijing, China.

Jin, K., Wang, S., Hu, B., Jia, S., Wan, X., Wang, Y., Ai, P., and Wang, H. (2022). "Effects of biogas fertilizer application rate on shanghai cabbage yield and soil physicochemical properties," *China Biogas* 40(06), 50-56. DOI: 10.20022/j.cnki.1000-1166.2022060050

Khapte, P. S., Kumar, P., Burman, U., and Kumar, P. (2019). "Deficit irrigation in tomato: Agronomical and physio-biochemical implications," *Scientia Horticulturae* 248, 256-264. DOI: 10.1016/j.scienta.2019.01.006

Li, C., Liao, Y., Wen, X., Wang, Y., and Yang, F. (2015). "The development and countermeasures of household biogas in northwest grain for green project areas of

China," *Renewable and Sustainable Energy Reviews* 44, 835-846. DOI: 10.1016/j.rser.2015.01.027

Liang, Z., Lan, C., Jin, X., Li, S., Cai, J., Yang, S., Hou, G., Cheng, W., Shao, X., Jia, R., *et al*. (2023). "Spatial distribution and influencing factors of China's household biogas: Evidence from provincial-level data," *Environmental Science and Pollution Research* 30, 110119-110132. DOI: 10.1007/s11356-023-30069-8

Liu, T., Ferrari, G., Pezzuolo, A., Alengebawy, A., Jin, K., Yang, G., Li, Q., and Ai, P. (2023a). "Evaluation and analysis of biogas potential from agricultural waste in Hubei Province, China," *Agricultural Systems* 205, article ID 103577. DOI: 10.1016/J.AGSY.2022.103577

Liu, Y., Chi, Y., Dong, Y., Ye, B., Fan, Z., Nie, X., and Xing, J. (2023b). "Variation of nutrient content and microbial community in soils under different application years of biogas slurry," *Journal of Plant Nutrition and Fertilizers* 29(03), 483-495.

Lönnqvist, T., Sanches-Pereira, A., and Sandberg, T. (2015). "Biogas potential for sustainable transport – A Swedish regional case," *Journal of Cleaner Production* 108, 1105-1114. DOI: 10.1016/j.jclepro.2015.07.036

Lv, W. (2012). *Effect of the Agricultural Usage of Biogas Slurry on Wheat Yield, Quality and Environmental Quality of Soil*, Master's Thesis, Sichuan Agricultural University, Ya'an, China.

Mardoyan, A., and Braun, P. (2015). "Analysis of Czech Subsidies for solid biofuels," *International Journal of Green Energy* 12(4), 405-408. DOI: 10.1080/15435075.2013.841163

Nabel, M., Schrey, S. D., Poorter, H., Koller, R., and Jablonowski, N. D. (2017). "Effects of digestate fertilization on *Sida hermaphrodita*: Boosting biomass yields on marginal soils by increasing soil fertility," *Biomass and Bioenergy* 107, 207-213. DOI: 10.1016/j.biombioe.2017.10.009

National Development and Reform Commissiion, National Energy Administration, Ministry of Finance of the People's Republic of China, Ministry of Natural Resources of the People's Republic of China, and Ministry of Ecology and Environment of the People's Republic of China (2022). "The 14th Five-Year Renewable Energy Plan," (https://www.ndrc.gov.cn/xwdt/tzgg/202206/t20220601_1326720.html?code=&state=123), Accessed 01 June 2022.

National Development and Reform Commission, and Ministry of Agriculture and Rural Affairs of the People's Republic of China (2017). "The 13th Five-Year Plan for the Development of Rural Biogas in China," (https://www.gov.cn/xinwen/2017-02/10/content_5167076.htm), Accessed 02 July 2017.

National Development and Reform Commission, National Energy Administration, Ministry of Finance of the People's Republic of China, Ministry of Natural Resources of the People's Republic of China, and Ministry of Ecology and Environment of the People's Republic of China (2019). "Guiding Opinions on Promoting the Development of Biogas Industrialization," (https://www.gov.cn/zhengce/zhengceku/2019-12/26/content_5464147.htm), Accessed 04 Dec 2019.

Ningsih, L. M., Hasanudin, U., and Roubík, H. (2024). "The use of biofilter in anaerobic baffled reactor to improve quality of methane concentration and effluent as liquid organic fertiliser," *Journal of Ecological Engineering*. DOI: 10.12911/22998993/191261

Qiao, M., and Zheng, J. (2022). “Effects and evaluation of different water-biogas slurry integrated deficit irrigation modes on yield and quality of tomato,” *Water Saving Irrigation* 12, 15-23.

Song, Z., Zhang, C., Yang, G., Feng, Y., Ren, G., and Han, X. (2014). “Comparison of biogas development from households and medium and large-scale biogas plants in rural China,” *Renewable and Sustainable Energy Reviews* 33(204–213). DOI: 10.1016/j.rser.2014.01.084

Wang, H. (2014). *Study of Different Water Soluble Fertilizer Formula Effect on Chinese Cabbage and Soil Fertility in Fertigation*, Master’s Thesis, Guizhou Normal University, Guiyang, China.

Wang, X., Xing, Y., and Zhang, F. (2016). “Optimal amount of irrigation and fertilization under drip fertigation for tomato,” *Transactions of the Chinese Society for Agricultural Machinery* 47(01), 141-150.

Wang, S., Jia, X., He, L., Li, H., Wang, H., Li, D., He, J., Fang, Q., and Li, R. (2022). “Response mechanism of crops to drought stress and measures for improving drought resistance of crops: Research progress,” *Chinese Agricultural Science Bulletin* 38(29), 31-44.

Wang, Y., Zhi, B., Xiang, S., Ren, G., Feng, Y., Yang, G., and Wang, X. (2023). “China’s biogas industry’s sustainable transition to a low-carbon plan—A socio-technical perspective,” *Sustainability* 15(6), article 5299. DOI: 10.3390/su15065299

Wen, Y., Zhang, J., Li, L., Wang, Q., Diao, F., Gao, M., Wang, X., and Shi, X. (2023). “Effects of biogas slurry combined with chemical fertilizer on *Allium fistulosum* yields, soil nutrients, microorganisms, and enzymes activities,” *Chinese Journal of Eco-Agricultural* 4(01), 1-11. DOI:10.12357/cjea.20230401

Wentzel, S., Schmidt, R., Piepho, H.-P., Semmler-Busch, U., and Joergensen, R. G. (2015). “Response of soil fertility indices to long-term application of biogas and raw slurry under organic farming,” *Applied Soil Ecology* 96, 99-107. DOI: 10.1016/j.apsoil.2015.06.015

Wu, S., Ni, P., Li, J., Sun, H., Wang, Y., Luo, H., Jacek, D., and Dong, R. (2016). “Integrated approach to sustain biogas production in anaerobic digestion of chicken manure under recycled utilization of liquid digestate: Dynamics of ammonium accumulation and mitigation control,” *Bioresource Technology* 205, 75-81. DOI: 10.1016/j.biortech.2016.01.021

Xie, D., Zeng, H., To, J., Yu, X., Xu, L., Chen, H., and Wang, F. (2021). “Improvement effect of several recyclable substrates on water fern cultivation,” *Jiangsu Agricultural Sciences* 49(02), 97-103. DOI: 10.15889/j.issn.1002-1302.2021.02.018

Xu, M., Xian, Y., Wu, J., Gu, Y., Yang, G., Zhang, X., Peng, H., Yu, X., Xiao, Y., and Li, L. (2019). “Effect of biogas slurry addition on soil properties, yields, and bacterial composition in the rice-rape rotation ecosystem over 3 years,” *Journal of Soils and Sediments* 19(5), 2534-2542. DOI: 10.1007/s11368-019-02258-x

Xue, B., Xu, H., and Ruan, H. (2019). “A review on the effects of biogas slurry on agroforestry soil ecosystems,” *Journal of Nanjing Forestry University (Natural Sciences Edition)* 43(3), 175-182.

Yin, G., Wang, X., Du, H., Shen, S., Liu, C., Zhang, K., and Li, W. (2019). “N 2 O and CO_2 emissions, nitrogen use efficiency under biogas slurry irrigation: A field study of two consecutive wheat-maize rotation cycles in the North China Plain,” *Agricultural Water Management* 212, 232-240. DOI: 10.1016/j.agwat.2018.08.038

Yin, D., Chen, D., Qin, J., Liu, W., Wang, Y., Lan, W., Zhong, N., and Ma, P. (2024). "Effect of drip irrigation with biogas slurry on the yield and quality of Chinese cabbage," *BioResources* 9(3), 5717-5730. DOI: 10.15376/biores.19.3.5717-5730

Zhang, J., Wang, M., Cao, Y., Liang, P., Wu, S., Wah, L. A. O., and Peter, C. (2017). "Replacement of mineral fertilizers with anaerobically digested pig slurry in paddy fields: Assessment of plant growth and grain quality," *Environmental Science and Pollution Research* 24(10), 8916-8923. DOI: 10.1007/s11356-015-5125-z

Zhang, S., Shi, Z., Zhang, Q., Ye, S., and Li, Y. (2022). "Effects of microalgae-treated biogas slurry on seed germination and seedling growth of rice," *Jiangsu Journal of Agricultural Sciences* 38(04), 875-881.

Zhao, D., Wang, J., and Fu, X. (2017). "Effect of long-term fertilization on soil organic carbon and its fractions under dryland farming system," *Agricultural Research in the Arid Areas* 35(01), 97-102.

Zhao, T. (2023). "Effects of applying biogas slurry on tomato growth and soil bacterial community and function," Master's Thesis, Northwest A&F University, Yangling, China.

Zheng, J., Yan, F., Ma, B., Pan, Z., Feng, Z., and Ren, H. (2019). "Using biogas slurry to regulate growth, field and fruit quality of greenhouse tomato and nitrogen dynamics in root zone," *Journal of Irrigation and Drainage Engineering* 38(07), 23-31. DOI: 10.13522/j.cnki.ggps.20190137

Article submitted: August 5, 2024; Peer review completed: September 21, 2024; Revised version received: November 23, 2024; Accepted: December 29, 2024; Published: January 15, 2025.
DOI: 10.15376/biores.20.1.2026-2037