Digested Slurry Analysis for Utilization Based on Irrigated Crop Water Demand

Jingpin Ren,[a,b] Yalei Wang,[a,b] Xufeng Sun,[a,b] Liang Liu,[a,b] Xinxin Liu,[a,b] and Gang Li [a,b,*]

To rationally utilize digested slurry, and thereby promote the integrated development of planting and breeding in breeding industry, the water-fertilizer requirement analysis of typical winter wheat-summer corn rotation tillage model in Zhengzhou was completed based on the water/nutrient requirement of crops. The results showed that the water demand and effective rainfall of winter wheat during the whole growth period were 492 and 190 mm, and the application amount of digested slurry was 3090 m^3. The N, P, and K provided were 3600, 197, and 1310 kg, respectively, which exceeded the normal nutrient requirement of wheat. During the whole growth period of summer corn, the water demand was 354 mm, the effective rainfall was 290 mm, and the application amount of digested slurry was 763 m^3. The amount of N, P, and K provided was 890, 48.6, and 324 kg, respectively. The amount of N and K exceeded the normal nutrient demand of corn, while the P was insufficient. Therefore, digested slurry can provide full nutrient requirements in winter wheat planting season in Zhengzhou, and P fertilizer should be added when applying digested slurry in corn planting season. If long-term application, excessive nutrient loss may cause non-point source pollution.

DOI: 10.15376/biores.18.4.7098-7108

Keywords: Crop water demand; Digested slurry; Water-fertilizer; Nutrients

Contact information: a: College of Mechanical and Electrical Engineering, Henan Agricultural University, Zhengzhou 450002, China; b: Key Laboratory of New Materials and Facilities for Rural Renewable Energy, Ministry of Agriculture & Rural Affairs, Zhengzhou 450002, China;
** Corresponding author: ligang@henau.edu.cn*

INTRODUCTION

In recent years, with the increase of people's demand for meat, eggs, and milk, the number of livestock and poultry breeding enterprises is gradually increasing, and the scale of breeding is gradually expanding. The rapid development of large-scale and intensive farming mode has realized the maximum utilization of confined space, but a large breeding density will produce a large amount of fecal contamination, which may cause the rapid spread of fungi and viruses if not treated in time. At present, the resource utilization of livestock and poultry manure mainly includes aerobic compost, processed feed, anaerobic fermentation, and so on (Li *et al*. 2020; Liu *et al*. 2021a). Anaerobic fermentation can decompose organic matter in manure, and the biogas, digested slurry, and digested sludge produced can also be used, so it is widely used in aquaculture as an effective way to treat manure.

As the main way to treat aquaculture sewage and reduce agricultural pollution, biogas fermentation can effectively remove organic matter in aquaculture sewage (Köthe *et al*. 2020; Zhu *et al*. 2021; Qu *et al*. 2022; Zhu *et al*. 2022), but the content of organic matter in discharged digested slurry is still high (Deng *et al*. 2014; Yan *et al*. 2019; Wang *et al*. 2020; Liu *et al*. 2021b), and direct discharge can easily cause secondary pollution (Li *et al*. 2017a). Digested slurry is rich in nutrient elements, including nitrogen, phosphorus, potassium, zinc, iron, as well as trace elements and organic matter (Li *et al*. 2017b; Ke *et al*. 2022). These substances can be used by plants for growth and development, the application can be quick and efficient, and the nutrients can easily be absorbed (Cao *et al*. 2016; Liu *et al*. 2022; Zhang *et al*. 2022). Also, the nutrients have a high utilization efficiency (Wu *et al*. 2013). Thus, digested slurry fertilizer is currently the main way to use the slurry.

Digested slurry can be used as a kind of high-quality organic fertilizer for crop planting after treatment. Reasonable application not only can improve the rural environment, but it also can realize the purpose of turning waste into value. Studies have found that applying digested slurry water and fertilizer can effectively increase the content of soil organic matter (Yan *et al*. 2019; Tang *et al*. 2022) and available nutrients (You *et al*. 2019; Yu *et al*. 2022). Some studies suggest that application of digested slurry fertilizer can increase the number of bacteria, fungi, and actinomyces in soil (Wentzel and Joergensen 2016; Tang *et al*. 2021) and thereby improve the soil's micro-ecological environment (Wang *et al*. 2023). Studies have also shown that the application of digested slurry water and fertilizer has significant effects on improving crop quality and increasing yield (Tang *et al*. 2019; Ai *et al*. 2020; de França *et al*. 2021; Tang *et al*. 2022), improving soil structure (Du *et al*. 2016; Xu *et al*. 2019), and reducing pests and diseases (Westphal *et al*. 2016).

At present, the application of digested slurry as water and fertilizer usually follows the principle of nutrient balance. Studies have shown that applying digested slurry according to the nutrient requirements of rice at different growth stages can increase crop yield 3.2% to 8.7% (Luo *et al*. 2022). However, for dryland crops, although this digested slurry application model can meet the nutritional requirements of crops, its water supply is often less than the crop water demand, so additional irrigation may be needed to meet the crop water demand. Combined with the distribution of rainfall time and the water/nutrient requirements at different growth stages of crops, a scientific application model of digested slurry water and fertilizer based on water balance and supplemented by nutrient balance was established, which could better solve the problem of insufficient water supply to crops in the application process of digested slurry. To provide scientific reference for rational utilization of digested slurry to promote the combined development of breeding industry, this study analyzed the water and fertilizer requirements of typical winter wheat-summer corn rotation tillage mode in Zhengzhou, using the water/nutrient requirements of crops as indexes.

MATERIAL AND METHODS

Zhengzhou is located in the central and northern part of Henan Province (China), situated in the Huanghuaihai Plain. The geographical location is 112°42 ' to 114 ° 14'N and 34°16' to 34°58'E, the total area is 7567 km^2, the plain area accounts for approximately 38.4%, and the main planting system of the plain area is winter wheat and summer corn, two crops a year. The study area is a semi-arid and semi-humid warm temperate continental monsoon climate area, with significant seasonal climate changes and uneven rainfall distribution. The average annual temperature is 14.7 ℃, with the lowest average temperature of 0.5 ℃ in January and the highest temperature of 27.1 ℃ in July. The average annual rainfall is 632.40 mm, mainly from June to August, with the most falling in August.

Crop water demand was calculated according to the crop coefficient method proposed by the Food and Agriculture Organization of the United Nations (FAO). The formula used for calculation is shown in Eq. 1,

$$E_{pi} = ET_{oi} \times K_{ci} \tag{1}$$

where E_{pi} is the evapo-transpiration of crops in a certain growth period (mm); ET_{oi} is the potential evapo-transpiration (mm) during the growth period; and K_{ci} is the crop coefficient of this growth period.

The potential evapo-transpiration ET_0 of crops was calculated using the MHS-2 formula. The formula used for calculation is,

$$ET_0 = \frac{[0.00193 R_a (T_{ave} + 17.8)(T_{max} - T_{min})^{0.517}]}{\lambda} \tag{2}$$

where ET_0 is the reference crop evapo-transpiration(mm); R_a is extra-atmospheric solar radiation ($MJ \cdot m^{-2} \cdot d^{-1}$); T_{ave} is the average temperature (°C); T_{max} and T_{min} are the highest and lowest temperature, respectively (°C); and λ is the latent heat of water gasification (λ = 2.45 $MJ \cdot kg^{-1}$).

The part of natural precipitation that can be directly or indirectly utilized by crops is the effective rainfall, which can be calculated according to the effective utilization coefficient method. The calculation formula is given as Eq. 3:

$$P_{ej} = \alpha_j \times P_j \tag{3}$$

In Eq. 3, P_j is the total rainfall(mm); and α_j is the effective utilization coefficient of rainfall. The values of α are as follows: when $P_j \leq 5$ mm, $\alpha_j = 1$; When 5 mm < $P_j \leq 50$ mm, $\alpha_j = 0.9$; $P_j > 50$ mm, $\alpha_j = 0.75$.

The effective rainfall of a certain growth period is the sum of the effective rainfall in the period, and the formula is Eq. 4,

$$P_{ei} = \sum_{j=1}^{n} P_{ej,i} \tag{4}$$

where P_{ei} is the effective rainfall of growth stage *i*(mm); *j* is the number of rainfall in the growth period; and $P_{ej,i}$ is the effective rainfall of the j^{th} rainfall in growth stage *i* (mm).

The application rate of digested slurry was the difference between the water demand and the effective rainfall at each growth stage. The calculation formula used is Eq. 5,

$$BS = \begin{cases} ET_C - P_e, & ET_C - P_e > 0 \\ 0, & ET_C - P_e \leq 0 \end{cases} \tag{5}$$

where *BS* is the application amount of digested slurry water and fertilizer(mm); ET_C is the crop water demand, mm; and P_e is the effective precipitation, mm.

The main nutrient contents (mg/L) of different fermentation substrates digested slurry are shown in Table 1 (Dong *et al*. 2021).

Applying digested slurry to bring nutrients can be calculated according to the amount of digested slurry application and digested slurry nutrient content. The formula used for calculation is shown in Eq. 6,

$$N + P + K = W \cdot (\beta_N + \beta_P + \beta_K) \tag{6}$$

where N, P, and K are the total amount of nitrogen, phosphorus, and potassium provided by applying digested slurry, respectively; W is the application amount of digested slurry; and β_N, β_P, and β_K are the percentages of nutrient contents in applied digested slurry.

Table 1. Nutrient Content of Different Types of Digested Slurry

Digested Slurry Type	TN (mg/L)	TP (mg/L)	TK (mg/L)
Pig manure digested slurry	1166.71	291.60	1144.26
Cow dung digested slurry	1488.59	561.67	1679.10
Chicken manure digested slurry	3226.13	959.71	2858.31
Household biogas digester digested slurry	1369.31	665.90	1240.21

The analysis of water and fertilizer utilization characteristics of digested slurry mainly involves daily rainfall and maximum and minimum temperature in Zhengzhou from 2016 to 2020 from the website *http://www.agdata.cn/*. Microsoft Excel 2021 was used for data analysis, and Microsoft Word 2021 and Origin 2021 were used for chart production.

RESULTS AND DISCUSSION

Winter wheat planting occurs generally from mid-October to mid-June of the next year. The whole growth period was 247 days. Summer corn period is from mid-late June to mid-September. The whole growth period was 102 days. The evapo-transpiration of wheat and corn in each growth period was calculated by Eqs. 1 and 2. The results are shown in Tables 2 and 3 (Yang *et al*. 2008).

Table 2. Water Demand of Wheat at Different Growth Periods

Growth Period	ET_0 (mm)	Crop Coefficient	E_p (mm)
Overwintering	91.69	0.6	49.76
Regreening	93.61	0.7	58.87
Jointing	105.41	0.9	90.11
Heading	151.61	1.1	145.89
Maturity	187.94	0.9	147.06

Table 3. Water Demand of Corn at Different Growth Periods

Growth Period	ET_0 (mm)	Crop Coefficient	E_p (mm)
Jointing	110.97	0.47	43.90
Tasseling	146.39	0.83	108.07
Filling	86.12	1.12	89.43
Maturity	112.63	1.17	112.97

As shown in Tables 2 and 3, the water demand intensity of winter wheat in different growth stages changed significantly, as shown by the following: The water demand increased gradually from 49.8 mm during sowing-overwintering stage to 147 mm during peak heading to maturity stage, and the total evapo-transpiration during the whole growth stage was 492 mm.

The water demand intensity of summer corn fluctuated greatly during the whole growth period, as follows: the water demand increased from sowing to jointing to jointing to tasseling, and then decreased. The water demand increased again during growth to maturity and reached the maximum value of 113 mm, and the total evapo-transpiration during the whole growth period was 354 mm.

The effective rainfall P_e at various growth stages of wheat and corn was calculated by Eqs. 3 and 4, and the application amount BS (mm) of digested slurry was calculated by Eq. 5, taking pig manure as an example, as shown in Table 3. The contribution of rainfall and digested slurry to crop water demand is shown in Fig. 1.

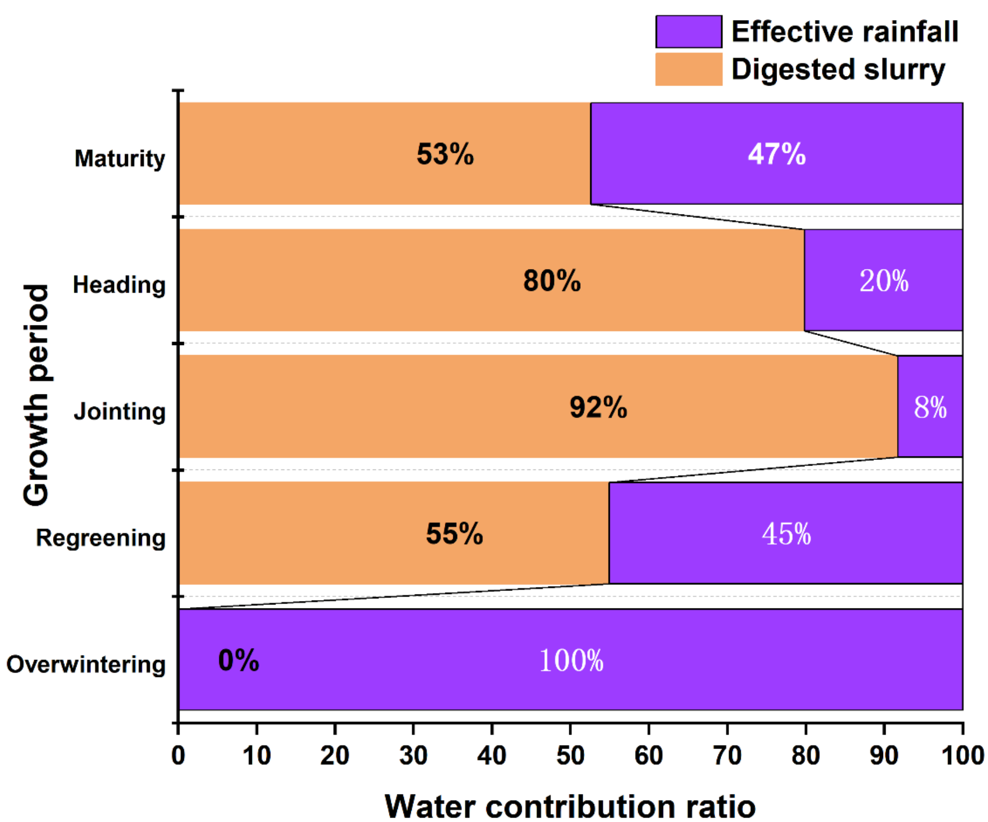

Fig. 1. Contribution ratio of rainfall and digested slurry to water demand at different growth stages of crops

Table 4. Effective Rainfall and Application Amount of Digested Slurry at Different Growth Stages of Wheat

Growth Period	P_e (mm)	*BS* (mm)
Overwintering	56.59	0
Regreening	26.53	32.34
Jointing	7.48	82.62
Heading	29.43	116.46
Maturity	69.68	77.38

Table 5. Effective Rainfall and Application Amount of Digested Slurry at Different Growth Stages of Corn

Growth Period	P_e (mm)	*BS* (mm)
Jointing	47.45	0
Tasseling	116.89	0
Filling	51.39	38.05
Maturity	74.74	38.22

As shown in Tables 4 and 5, the effective rainfall of wheat season was less, and the effective rainfall of the whole growth period was 190 mm; the effective rainfall of heading to maturity period was the most, 69.7 mm; and the least was 7.48 mm, during the greening to jointing period. There was more effective rainfall in the corn season, 290 mm in the whole growth period, 117 mm in the jointing to tasseling stage, and 47.4 mm in the seeding to jointing stage. The application amounts of digested slurry in wheat and corn during the whole rearing period were 309 and 76.3 mm, respectively, and the application amounts per hectare were 3090 and 763 m^3, respectively.

As shown in Fig. 1, the irrigation demand of winter wheat was relatively large. Except for the sowing-overwintering period, digested slurry should be applied as water supplement, accounting for more than 50% and reaching 92% during the greening-jointing period. Compared with wheat, supplementary irrigation was needed only in the tasseling-filling and grain-ripening stages of corn, and the proportion was less than 50%. The reason is that the corn planting season rainfall generally is abundant, while the wheat planting season rainfall is likely to be low, and the water demand is large. During the whole growth period, 3090 m^3 of biogas slurry was applied to wheat and 763 m^3 of biogas slurry was applied to corn per hectare. Irrigation was carried out at different growth stages according to crop water requirements. The application of biogas slurry provided 3600, 902, and 3530 kg of N, P and K for wheat, and 890, 223, and 873 kg of N, P and K for corn, respectively. Converted to N, P_2O_5, K_2O, then the nutrient supply and demand relationship of wheat and corn is shown in Fig. 2.

As shown in Fig. 2, based on the water balance of digested slurry, the supply of N, P, and K for wheat was greater than the demand, while the P supply for corn was insufficient, and the supply of N and K also appears to have been greater than the demand. Long-term excess of nutrient supply had no obvious effect on the quality and yield improvement of crops in the current season. Crop yield reached the highest level in a certain organic fertilizer application level, and the yield level tended to be stable or declined when the application amount of biogas slurry was further increased (Chang *et al.* 2010). Some nutrients such as N, P, and K lost with rainwater can easily lead to eutrophication of water bodies, affecting water quality and causing the risk of non-point source pollution. Horizontal long-term balanced application of organic fertilizer can ensure that crop yield and stability are still maintained after short-term reduction or stop application and can increase soil carbon sequestration (Tian *et al.* 2023).

Scientific application of biogas slurry not only can ensure crop yield and quality, but it also can reduce the risk of environmental pollution. According to the relationship between nutrient supply and demand, the oversupply of N in wheat season and K in corn season is the biggest factor that increases the risk of non-point source pollution. The scientific application dosage of pig manure biogas slurry as the source of nitrogen fertilizer, phosphate fertilizer, potassium fertilizer, and the minimum pollution risk were calculated, and the results are shown in Table 6.

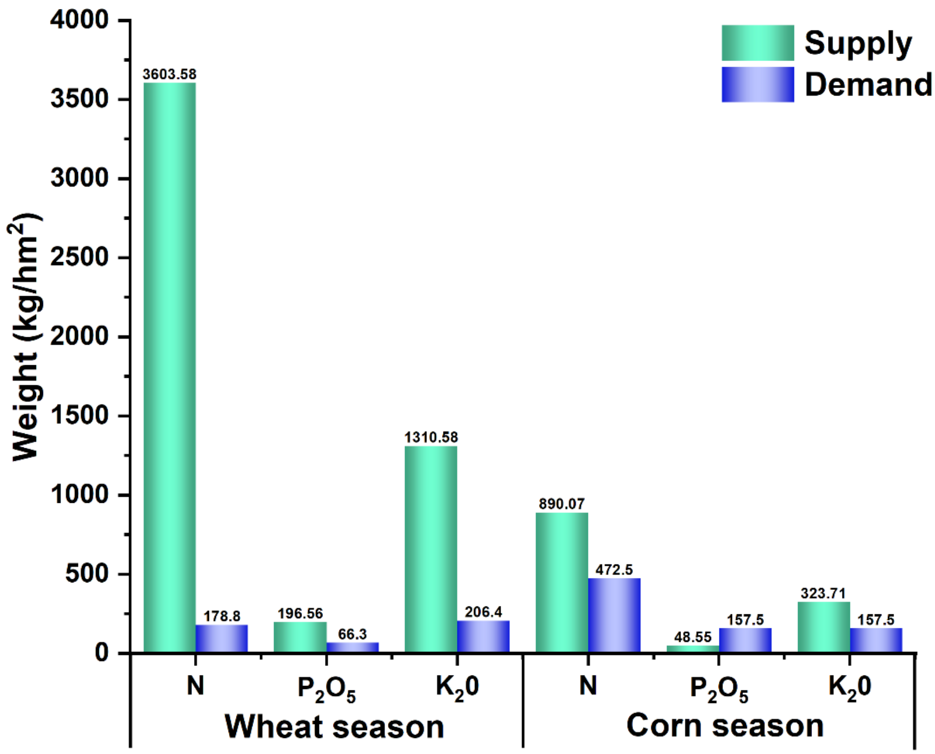

Fig. 2. Relationship between nutrient supply and demand of wheat and corn

Table 6. Application Amount of Biogas Slurry as a Source of Different Nutrient Elements and the Minimum Risk of Pollution

Crop Season	Nitrogenous Fertilizer (m^3)	Phosphate Fertilizer (m^3)	Potassium Fertilizer (m^3)	Minimal Pollution Risk (m^3)
Wheat season	153.21	1041.55	486.31	153.21
Corn season	404.89	2474.26	371.09	371.09

As can be seen from Table 4, when biogas slurry was applied as phosphate fertilizer in wheat season, the maximum amount was 1040 m. At this time, the supply of N and K was still greater than the demand, and the minimum amount was 153 m^3 when it is used as nitrogen fertilizer. At this time, the supply of P and K was less than the demand, and the pollution risk was minimal. When corn biogas slurry was used as phosphate fertilizer, the application amount was the largest, *i.e.* 2470 m, and the supplies of N and K were in excess. When it was used as potassium fertilizer, the amount was the least, and the supply of N and P was less than the demand, and the pollution risk was the least. The application rate of biogas slurry with minimum pollution risk can reduce pollution risk as a scientific application level. In order to ensure crop yield and quality, the corresponding nutrient element fertilizer should be supplemented as needed.

CONCLUSIONS

Based on the analysis of the scientific application mode of digested slurry based on water balance and supplemental nutrient balance in wheat-corn rotation in Zhengzhou, the following conclusions can be drawn:

1. The water demand of winter wheat in the whole growth period of Zhengzhou was 492 mm, the effective rainfall was 190 mm, and the application amount of digested slurry was 309 mm. The overall irrigation demand was large, except for sowing-overwintering period, all needed irrigation, accounting for more than 50%, and the greening-jointing period reached 92%. The water demand of summer corn in the whole growth period was 354 mm, the effective rainfall was 290 mm, and the application amount of digested slurry water and fertilizer was 76.3 mm. The irrigation demand was small, and supplementary irrigation was needed only in the tasseling-grouting and grout-mature stages, and the proportion was less than 50%.
2. N, P_2O_5, and K_2O of digested slurry applied in single rotation per hectare of cultivated land were 3600, 197, and 1310 kg for wheat and 890, 48.6, and 324 kg for corn, respectively. The supply of N, P, and K of wheat was greater than the demand, but the P supply of corn was insufficient, and the supply of N and K was greater than the demand. Long-term oversupply of nutrients had no obvious effect on crop quality and yield improvement. The loss of nutrients is easy to lead to water eutrophication, affecting water quality, and causing the risk of non-point source pollution.

ACKNOWLEDGMENTS

The authors are grateful for the financial support provided by National Key R&D Program of China (2021YFD1700900).

REFERENCES CITED

Ai, P., Jin, K., Alengebawy, A., Elsayed, M., Meng, L., Chen, M., and Ran, Y. (2020). "Effect of application of different biogas fertilizer on eggplant production: Analysis of fertilizer value and risk assessment," *Environmental Technology and Innovation* 19, article ID 101019. DOI: 10.1016/j.eti.2020.101019

Cao, Y., Wang, J., Wu, H., Yan, S., Guo, D., Wang, G., and Ma, Y. (2016). "Soil chemical and microbial responses to biogas slurry amendment and its effect on Fusarium wilt suppression," *Applied Soil Ecology* 107, 116-123. DOI: 10.1016/j.apsoil.2016.05.010

Chang, E.-H., Chung, R.-S., and Tsai, Y.-H. (2010). "Effect of different application rates of organic fertilizer on soil enzyme activity and microbial population," *Soil Science and Plant Nutrition* 53,132-140. DOI: 10.1111/j.1747-0765.2007.00122.

De França, A., von Tucher, S., and Schmidhalter, U. (2021). "Effects of combined application of acidified biogas slurry and chemical fertilizer on crop production and N soil fertility," *European Journal of Agronomy* 123, article ID 126224. DOI: 10.1016/j.eja.2020.126224

Deng, L., Li, Y., Chen, Z., Liu, G., and Yang, H. (2014). “Separation of swine slurry into different concentration fractions and its influence on biogas fermentation,” *Applied Energy* 114, 504-511. DOI: 10.1016/j.apenergy.2013.10.018

Du, Z., Chen, X., Qi, X., Li, Z., Nan, J., and Deng, J. (2016). “The effects of biochar and hoggery biogas slurry on fluvo-aquic soil physical and hydraulic properties: A field study of four consecutive wheat-maize rotations,” *Journal of Soils and Sediments* 16(8), 2050-2058. DOI: 10.1007/s11368-016-1402-9

Dong, Y., Liang, D., Li, D., and Jin, H. (2021). “Characteristic analysis of main nutrient content in biogas slurry,” *Jiangsu Journal of Agricultural Sciences* 37(5), 1206-1214. DOI: 10.3969/j.issn.1000-4440.2021.05.016

Ke, L., Liu, X., Du, B., Wang, Y., Zheng, Y., and Li Q. (2022). “Component analysis and risk assessment of biogas slurry from biogas plants,” *Chinese Journal of Chemical Engineering* 44, 182-191. DOI: 10.1016/j.cjche.2021.05.039

Köthe, T., Martin, S., Reich, G., and Fricker, G. (2020). “Dual asymmetric centrifugation as a novel method to prepare highly concentrated dispersions of PEG-b-PCL polymersomes as drug carriers,” *International Journal of Pharmaceutics* 579, article ID 119087. DOI: 10.1016/j.ijpharm.2020.119087

Li, G., Cui Y., Zhang, H., Li, L., Yue, J., and Jiao, Y. (2017a). “Effect of biomass ash size and high-diameter ratio of filter on purification effect of digested slurry,” *Transactions of the Chinese Society of Agricultural Engineering* 33(18), 237-242. DOI: 10.11975/j.issn.1002-6819.2017.18.031 (in Chinese)

Li, Q., Li, Y., Liu, Z., Min, J., Cui, Y., and Gao, X. (2017b). “Comparison and analysis of organic components of biogas slurry from *Eichhornia crassipes* Solms and corn straw biogas slurry,” *IOP Conference Series: Earth and Environmental Science* 93, article ID 012006. DOI: 10.1088/1755-1315/93/1/012006

Li, L., Xu, J., Wang, H., Liu, X., and Zhang, D. (2020). “Study of the performance of biogas production by mixed fermentation of cow dung, deer manure, and mushroom fungus,” *Energy Science & Engineering* 8(2), article 528. DOI: 10.1002/ese3.528

Liu, C., Liu, C., Wang, J., and Xin, X. (2021a). “The current situation of resource utilization of livestock and poultry manure in China and the countermeasures and suggestions,” *Chinese Journal of Agricultural Resources and Regional Planning* 42(2), 35-43. DOI: 10.7621/cjarrp.1005-9121.20210205 (in Chinese)

Liu, Q., Zhao, Z., Xue, Z., Li, D., Wen, Z., Ran, Y., Mei, Z., and He, L. (2021b). “Comprehensive risk assessment of applying biogas slurry in peanut cultivation,” *Frontiers in Nutrition* 8, article ID 702096. DOI: 10.3389/fnut.2021.702096

Liu, Y., Tan, X., Fu, S., and Shen, W. (2022). “Canopy and understory nitrogen addition alters organic soil bacterial communities but not fungal communities in a temperate forest,” *Frontiers in Microbiology* 13, article ID 888121. DOI: 10.3389/fmicb.2022.888121

Luo, X., Xu, Y., Cheng, M., Ye, F., and Qian, D. (2022). “Dynamic monitoring of nutrients in biogas slurry and its application to fertilizer in rice cultivation,” *Journal of Zhejiang Agricultural Sciences* 63(2), 256-258. DOI: 10.16178/j.issn.0528-9017.20212784 (in Chinese)

Qu, X., Zeng, H., Gao, Y., Mo, T., and Li, Y. (2022). “Bio-hydrogen production by dark anaerobic fermentation of organic wastewater,” *Frontiers in Chemistry* 10, article ID 978907. DOI: 10.3389/fchem.2022.978907

Tang, J., Davy, A. J., Wang, W., Zhang, X., Wu, D., Hu, L., and Yin, J. (2022). “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," *Journal of Soil Science and Plant Nutrition* 22(2), 2406-2417. DOI: 10.1007/s42729-022-00817-9

Tang, Y., Luo, L., Carswell, A., Misselbrook, T., Shen, J., and Han, J. (2021). "Changes in soil organic carbon status and microbial community structure following biogas slurry application in a wheat-rice rotation," *Science of The Total Environment* 757, article ID 143786. DOI: 10.1016/j.scitotenv.2020.143786

Tang, Y., Wen, G., Li, P., Dai, C., and Han, J. (2019). "Effects of biogas slurry application on crop production and soil properties in a rice–wheat rotation on coastal reclaimed farmland," *Water, Air, & Soil Pollution* 230(3), article 51. DOI: 10.1007/s11270-019-4102-4

Tian, X., Zhang, C., and Ju, X. T. (2023). "Crop responses to application of optimum nitrogen fertilizers on soils of various fertilities formed from long-term fertilization regimes," *European Journal of Agronomy* 148, article ID 126857.DOI: 10.1016/j.eja.2023.126857

Wang, M., Qi, X., Shi, Y., Zhao, J., Ahmad, S., Akhtar, K., Chen, B., Lian, T., He, B., and Wen, R. (2023). "Sugarcane straw returning is an approaching technique for the improvement of rhizosphere soil functionality, microbial community, and yield of different sugarcane cultivars," *Frontiers in Microbiology* 14, article ID 1133973. DOI: 10.3389/fmicb.2023.1133973

Wang, S., Yuan, R., Chen, H., Wang, F., and Zhou, B. (2020). "Effect of sulfonamides on the dissolved organic matter fluorescence in biogas slurry during anaerobic fermentation according to the PARAFAC analysis," *Process Safety and Environmental Protection* 144, 253-262. DOI: 10.1016/j.psep.2020.07.033

Wentzel, S., and Joergensen, R. G. (2016). "Effects of biogas and raw slurries on grass growth and soil microbial indices," *Journal of Plant Nutrition and Soil Science* 179(2), 215–222. DOI: 10.1002/jpln.201400544

Westphal, A., Kuecke, M., and Heuer, H. (2016). "Soil amendment with digestate from bio-energy fermenters for mitigating damage to *Beta vulgaris* subspp. by *Heterodera schachtii*," *Applied Soil Ecology* 99, 129-136. DOI: 10.1016/j.apsoil.2015.11.019

Wu, J., Yang, Q., Yang, G., Shen, F., Zhang, X. H., and Zhang, Y. Z. (2013). "Effects of biogas slurry on yield and quality of oil-seed rape," *Journal of Plant Nutrition* 36(13), 2084-2098. DOI: 10.1080/01904167.2013.822511

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

Yan, L., Liu, Q., Liu, C., Liu, Y., Zhang, M., Zhang, Y., Zhang, Y., and Gu, W. (2019). "Effect of swine biogas slurry application on soil dissolved organic matter (DOM) content and fluorescence characteristics," *Ecotoxicology and Environmental Safety* 184, article ID 109616. DOI: 10.1016/j.ecoenv.2019.109616

Yang, Y., Zhou, J., and Wu, M. (2008). "Ecological water demand research on Henan Province's main crop," *Henan Science* 26(6), 676-680.

You, L., Yu, S., Liu, H., Wang, C., Zhou, Z., Zhang, L., and Hu, D. (2019). "Effects of biogas slurry fertilization on fruit economic traits and soil nutrients of *Camellia oleifera* Abel," *Plos One* 14(5), article ID e0208289. DOI: 10.1371/journal.pone.0208289

Yu, X., Zhu, Y., Jin, L., Wang, B., Xu, X., Zou, X., Ruan, H., and Jin, F. (2022). "Contrasting responses of fungal and bacterial communities to biogas slurry addition in rhizospheric soil of poplar plantations," *Applied Soil Ecology* 175, article ID104427. DOI: 10.1016/j.apsoil.2022.104427

Zhang, H., Ma, Y., Shao, J., Di, R., Zhu, F., Yang, Z., Sun, J., Zhang, X., and Zheng, C. (2022). "Changes in soil bacterial community and functions by substituting chemical fertilizer with biogas slurry in an apple orchard," *Frontiers in Plant Science* 13, article ID 1013184. DOI: 10.3389/fpls.2022.1013184

Zhu, P., Li, X., Feng, J., Zhang, R., Bai, H., Bu, D., Dan, Z., Li, W., and Lu, X. (2022). "Short-chain fatty acids production from anaerobic fermentation of sewage sludge: The effect of higher levels polyaluminium chloride," *International Journal of Environmental Research and Public Health* 19(5), article 2806. DOI: 10.3390/ijerph19052806

Zhu, Z., Guo, Y., Zhao, Y., Zhang, R., Yu, Y., Zhang, M., and Zhou, T. (2021). "Sewage denitrification performance and sludge properties variation with the addition of liquid from perishable organic anaerobic fermentation," *Bioresource Technology* 341, article ID 125821. DOI: 10.1016/j.biortech.2021.125821

Article submitted: June 21, 2023; Peer review completed: July 26, 2023; Revised version received and accepted: August 3, 2023; Published: August 23, 2023.
DOI: 10.15376/biores.18.4.7098-7108