EFFECTS OF BIOGAS SLURRY ON *CAPSICUM* SPP. GROWTH AND CONTROL OF SOIL-PATHOGENS

by

ZICHEN WANG

Submitted in fulfilment of the academic

requirements for the degree of

Doctor of Philosophy

in

Ecological Sciences

School of Life Sciences

College of Agriculture, Engineering and Science

University of KwaZulu-Natal

Pietermaritzburg

South Africa

November 2022

PREFACE

The research contained in this thesis was completed by the candidate while based in the School of Life Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the National Research Foundation (NRF).

The contents of this work have not been submitted in any form to another university and, except where the work of others are acknowledged in the text, the results reported are due to investigations by the candidate.

[redacted]

Signed: Prof. E.B.G. Kana (Supervisor)

Date: December 2022

[redacted]

Signed: Prof. A.O. Olaniran (Co-supervisor)

Date: December 2022

[redacted]

Signed: Prof. Xiaomei Ye (Co-supervisor)

Date: December 2022

DECLARATION 1: PLAGIARISM

I, Zichen Wang, declare that:

(i) the research reported in this thesis, except where otherwise indicated, is my original research;

(ii) this thesis has not been submitted for any degree or examination at any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

  a) their words have been re-written but the general information attributed to them has been referenced;

  b) where their exact words have been used, then their writing has been placed in italics and inside quotation marks, and referenced;

(v) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

[redacted]

Signed: Zichen Wang (Candidate)

Date: November 2022

DECLARATION 2: PUBLICATIONS

My role in each paper and presentation is indicated. The *indicates the corresponding author.

Chapter 3

1. Wang Z, Zhang L, Sun G, Zhou W, Sheng J, Ye X, Olaniran AO and Kana EBG* 2022. Adsorption characteristics of three types of soils on biogas slurry ammonium nitrogen. *Frontiers in Environmental Science* 10:942263. https://doi.org/10.3389/-fenvs.2022.942263.

   This original research paper was published on 21 June 2022. The experiment was conceptualized, designed and carried out in the laboratory by Wang Zichen, Wang Zichen also collected, analyzed the data and wrote the paper under the guidance of the other authors.

Chapter 4

2. Wang Z, Sun G, Zhang L, Zhou W, Sheng J, Ye X*, Olaniran AO*, Kana EBG, Shao H 2022. Aging characteristics and fate analysis of liquid digestate ammonium nitrogen disposal in farmland soil. *Water* 14(16):2487. https://doi.org/10.3390/-w14162487.

   This original research paper was published on 12 August 2022. The experiment was designed and carried out in the laboratory by Wang Zichen, Wang Zichen also collected, analyzed the data and wrote the paper under the guidance of the other authors.

[redacted]

Signed: Zichen Wang (Candidate)

Date: November 2022

ABSTRACT

The biogas slurry discharged from intensive large-scale livestock and poultry farms, and biogas projects was more than 1.3 billion tons each year in the world. It has exceeded the maximum fertilizer carrying capacity of plants growth on limited nearby farmland when used as fertilizer, and its application is greatly affected by agricultural seasonality. It is therefore necessary to explore alternative treatments for more efficient utilization of biogas slurry. This raises the possibility of using biogas slurry in soil pretreatment for continuous cropping in protected land to achieve a dual purpose of efficient digestion of biogas slurry per unit area of farmland, and prevention and control of soil-borne diseases in protected land. Additionally, there is a lack of knowledge on the maximum amount (Q_m) of biogas slurry ammonium nitrogen (NH_4^+-N) that could efficiently be absorbed by the soil. There is also a scarcity of reports on the fate of liquid digestate ammonium nitrogen disposal in farmland soil. It is imperative to know the fate of liquid digestate ammonium nitrogen as well as the prevention and control of continuous cropping obstacles such as soil-borne diseases for subsequent crops cultivation. In this study, indoor simulation and field experiments were carried out to investigate the effects of biogas slurry on *Capsicum* spp. growth and control of soil-borne diseases under controlled environment. Firstly, the adsorption of biogas slurry NH_4^+-N of three types of soils (silty loam, loam, and sandy loam) was investigated in a composite kinetic process that comprised two stages of rapid and slow reactions. Rapid adsorption predominantly occurred within 0–1 h, and the adsorption capacity accounted for 35.24–43.55% of the total adsorption. The ExpAssoc equation produced a good fit for the adsorption kinetic behaviour in the three soil types. The equilibrium adsorption were described by the Langmuir equation, the Freundlich equation, the PlPlatt model, and the Langevin model isotherm, among which the Langevin model had the best fit. The theoretical saturated Q_m fitting results of NH_4^+-N were 1038.41–1372.44 mg/kg in silty loam, 840.85–1157.60 mg/kg in loam, and 412.33–481.85 mg/kg in sandy loam. The optimal values were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively.

The Q_m value was positively correlated with soil organic matter, total nitrogen, available phosphorus, available potassium, cation exchange capacity, and particle content of 0.02–0.002 mm, but significantly negatively correlated with soil pH.

Moreover, the simulation experiment of indoor static soil column was used to determine the time-effect of absorbing NH_4^+-N from liquid digestate in saturated water content soil as well as analyze the migration and transformation characteristics and fate ratio of NH_4^+-N from liquid digestate. After 3 days of application, the overlying water NH_4^+-N concentration decreased by 63.5–80.7%, and the reduction rate of total NH_4^+-N was 65.8–82.3%. At Day 4, the NH_4^+-N concentration of pore water in the 0–10 cm soil layer reached the peak value (24.41–28.91 mg/L). Similarly, after 7 days, the NH_4^+-N concentration adsorbed by the 0–10 cm soil layer reached the peak value (66.42–86.89 mg/kg with water-soluble NH_4^+-N, 98.42–121.15 mg/kg with ion-exchanged NH_4^+-N). Finally, after 15 days, the overlying water NH_4^+-N concentration decreased by 97.0–98.7%, with a reduction rate of 97.9–99.2%, while the proportion of NH_4^+- N absorbed in the 0–10 cm soil layer accounted for 63.5–76.3%. The disposal is mainly based on soil sorption and pore water migration. A rapid disposal was observed between 0 and 3 days, and a complete safe digestion was observed after 15 days.

Furthermore, a pilot field application was carried out to assess the applicability of the biogas slurry. During soil pretreatment, soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were closely related to the growth of soil bacteria and fungi. The biogas slurry pretreatment with a concentration of 495 m^3/hm^2 was beneficial to the growth of *Capsicum* spp. This could significantly improve the survival rate of *Capsicum* spp. seedlings, the flowering plants rate, the fruit-bearing plants rate and the plant height, with potential to significantly reduce the rate of rigid seedlings. Interestingly, the use of biogas slurry to pretreat protected soil can increase soil total nitrogen, total phosphorus, available phosphorus, available potassium, organic carbon content and soil pH value. In addition, this could inhibit the growth of soil bacteria, fungi, actinomycetes, and fusarium, as well as influence the soil microbial population, diversity and uniformity of species distribution in the community.

This study has demonstrated the potential of using biogas slurry as an effective measure to overcome the bottleneck of sewage treatment in livestock and poultry farms towards the sustainability of a green environment. The time required for the discharge to avoid surface water pollution so as to provide theoretical basis and technical guidance for the efficient elimination of liquid digestate in farmland under the safety of water environment was also elucidated. Finally, the application of biogas slurry to pretreat protected soil with the dual goals of preventing and controlling soil-borne pathogens and efficiently absorbing biogas slurry in a unit area of farmland was demonstrated.

ACKNOWLEDGMENTS

This thesis was completed under the careful guidance of my supervisors, Prof. Gueguim Kana E.B., Prof. Olaniran A.O. and Prof. Ye X. From the topic selection of the thesis, the formulation of the research plan, the design and development of the experiment, the extraction of the results, the writing and to the polishing of the thesis, they all put in their wealth of experience and hard work to make it a reality. Their rigorous scholastic and open-mindedness will always be an example for me to learn from. Prof. Gueguim Kana E.B., Prof. Olaniran A.O. and Prof. Ye Xiaomei are all good teachers with good personalities and academic charm. During my PhD study, they gave me meticulous care and help in both study and life. On the occasion of the completion of this thesis, I would like to express my sincere gratitude and high respect to them.

I would like to acknowledge the Agricultural Ecology Research Office of the Institute of Agricultural Resources and Environment, Jiangsu Academy of Agricultural Sciences for their strong support and cooperation, and thanks to Prof. Sheng Jing for her careful technical guidance, which has laid a solid foundation for this study. I am also appreciative of Sun Guofeng, Zhang Liping, Zhou Wei, Wang Xin, and Zong Jiao for their support and help in data measurement and result analysis during the study. Special thanks to Prof. Zhang Yuefang for his help, concern and inspiration in the writing of the paper.

I am appreciative of Isaac for his help in polishing the language of the thesis. My thanks also go to the experts who participated in the review of the thesis.

Very special thanks to my parents for their selfless care and encouragement, which is the driving force for me to overcome difficulties and move forward bravely.

I would especially like to thank my wife, Yao Qiaoyun, for encouraging each other and sharing weal and woe through these important four years of my life. Without her support, understanding, help, and relief, I would probably still be trying to finish this thesis. My love and thanks to you always.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

In recent years, the animal husbandry industry of China has gradually developed into an important pillar industry of China's agriculture and rural economy. According to the China Rural Statistical Yearbook (2019), the output value of animal husbandry in 2018 was 2869.7 billion yuan, accounting for 25.3% of the total output value of agriculture, forestry, animal husbandry and fishery. The total output of meat in the country was 86.2 million tons, the output of poultry eggs was 31.3 million tons, and the total output of milk was 31.8 million tons. This industry has made important contributions to meeting the national consumption of meat, eggs, milk and other animal products and improving the living standards of residents. However, with the development of livestock and poultry breeding and the improvement of the degree of intensification and specialization, the excreta of livestock and poultry breeding has also increased significantly. The subsequent waste disposal is facing huge challenges and has become an important source of agricultural source pollution. It is estimated that in 2017, the total output of livestock and poultry excreta in China was about 3.8 billion tons, and in 2020, it exceeded 4.2 billion tons (Zou et al., 2020). Dealing with livestock and poultry excreta in an effective way has become a serious challenge. In 2017, the Communist Party of China (CPC) Central Committee issued a call to vigorously promote the high-efficiency ecological circulation planting and breeding mode, speed up the centralized treatment of livestock and poultry manure, promote the healthy development of large-scale biogas, and promote the pilot of agricultural waste resource utilization with the county as the unit. The general office of the State Council of China stated that biogas and biological natural gas were the recommended treatment channels for livestock and poultry manure, and agricultural organic fertilizer and rural energy were the main utilization channels. As of the end of 2019, the central government has supported 585 large animal husbandry counties to promote the utilization of livestock and poultry manure resources. The Ministry of Agriculture and Rural Affairs has increased the number of pilot counties to replace chemical fertilizers with fruit, vegetable and tea organic fertilizers to 175 per year. The utilization area of solid manure returned to farmland in China has exceeded 8.5 million hectares per year. However, solid manure has been effectively used, but the progress of liquid manure treatment is still slow, and it is urgent to expand consumption and treatment channels and innovate efficient resource utilization methods.

Biogas production by anaerobic fermentation of livestock and poultry excreta is an effective way of treating and utilizing the excreta. By the end of 2020, China has built 43.0 million rural household biogas construction, 128,976 small and medium-sized biogas projects, and 10,122 large-scale biogas projects (Wang et al., 2022). The process of producing methane from organic matter through microbial metabolism is called anaerobic fermentation (Jain et al., 2015). While producing biogas, a large amount of residues such as biogas slurry are also produced. The liquid and solid residues after biogas fermentation are called biogas slurry and biogas residue, respectively. The biogas slurry accounts for more than 90% of the total fermentation residue (Dong et al., 2021). China's annual production of biogas slurry has exceeded 1.1 billion tons (Ma et al., 2018). Due to its composition, low commercial values, high storage and transportation cost, there are serious risk of secondary pollution (Liang et al., 2013). The treatment and utilization of biogas slurry has been a continuous focus of research (Jiang et al., 2011; Wang et al., 2014; Nkoa, 2014; Hagos et al., 2017).

The treatment methods of biogas slurry in developed countries are more inclined to be stored and used as fertilizer to realize field consumption and utilization (Song et al., 2021). However, due to the large scale of intensive aquaculture and the huge output of biogas slurry in China, a large amount of land will be occupied for long-term storage, and the farmland consumption capacity around most farms is limited. The direct discharge of untreated biogas slurry cannot meet the requirements of the discharge standards for livestock and poultry breeding, which is easy to cause farmland pollution (Cheng et al., 2018). At present, for the treatment of biogas slurry, traditional sewage treatment processes can realize its purification, such as activated sludge method, membrane concentration method, chemical flocculation method, etc., but the improvement of disposal efficiency needs further research and refinement, and it also faces waste of resources and high cost input. Biogas slurry recycling fundamentally reduces the effluent discharge of biogas slurry, saves water for dilution, and improves the buffering capacity and gas production of the system (Cao et al., 2018). However, in the actual operation process, biogas slurry recycling also has a series of challenges such as ammonia nitrogen inhibition, volatile organic acid accumulation, and accumulation of refractory substances such as cellulose (Deng et al., 2016). Biogas slurry from livestock and poultry farms has complex components. As a high-concentration organic wastewater, its colloidal substance content is high. There are pollutants such as inorganic matter, organic matter and sediment in the liquid. It has the characteristics of high ammonia nitrogen concentration, low carbon nitrogen ratio and poor biodegradability (Yan et al., 2013). In addition, biogas slurry is also rich in macro elements such as nitrogen, phosphorus and potassium, trace elements such as copper, iron and zinc, and microbial metabolites such as amino acids, hydrolase and vitamins (Kirchmann and Witter, 1992; Walsh et al., 2012; Abubaker et al., 2012) and some biologically active substances such as plant hormones and some antibiotics (Han et al., 2014; Qin et al., 2001). Most of these substances are soluble and can promote plant growth. Compared with traditional nitrogen, phosphorus and potassium fertilizers, biogas slurry as fertilizer can improve the overall maximum yield of crops and the nitrogen mineralization capacity, and increase the soil nitrogen supply capacity during the planting season. Therefore, biogas slurry can be used as a quick acting fertilizer for plants (Qin et al., 2001). Timely and appropriate application of biogas slurry is critical to ensuring the sustainable production capacity of farmland (Tao and Dong, 2017). A large number of research findings have shown that the return of biogas slurry to the field can improve the quality of agricultural products and improve soil conditions (Shen et al., 2010), and partially or fully replace inorganic fertilizers (Shi et al., 2019), an important bridge to realize the combination of planting and breeding with circular agriculture. In addition, biogas slurry has a certain inhibitory effect on a variety of crop pathogenic fungi (Tao et al., 2011; Li et al., 2013). The biogas slurry of 21 large-scale biogas projects in stable operation in Jiangsu Province have been shown to have different degrees of inhibitory effect on the growth of strawberry Fusarium wilt, and the biogas slurry at different storage stages has a significant effect on its antibacterial effect (Ma et al., 2011).

The large amount of acid or physiological acid fertilizers, pesticides and high-intensity single planting mode applied in protected vegetable cultivation can easily cause soil quality degradation, and promote soil-borne diseases (Cao et al., 2004; Perez-Brandan et al., 2014), soil acidification, secondary salinization, nutrient imbalance and other continuous cropping obstacles (Ju et al., 2006; Shi et al., 2009), resulting in a significant drop in vegetable output, seriously affecting farmers' economic income and threatening the sustainable development of vegetable planting, worldwide (Zhu et al., 2013). It is reported that the worldwide vegetable industry loses as much as one billion US dollars every year due to pathogen damage (Lamour et al., 2012). Research on the methods for preventing and controlling soil degradation in facilities has important scientific value and practical significance for promoting sustainable agricultural development. Soil-borne diseases are diseases caused by plant pathogenic fungi, bacteria, nematodes and viruses remaining in the soil, over-reproducing when the conditions are suitable, and infecting from the roots and stems of crops (Cai and Huang, 2016). Among them, the root rot of facility vegetables caused by pathogenic fungi is more serious, and a large number of dead trees will appear after entering the colonization period. The initial symptoms are wilting and death of a single plant, and even the death of the whole plant in the later stage. In severe cases, the yield can be reduced by as much as more than 60%. Soil acidification provides a suitable living environment for the growth of pathogenic fungi. The accumulation of phenolic acid allele-chemicals in soil affects the permeability of root cell membranes, which is the main reason for the auto-toxic effect of continuous cropping of vegetables, and can provide pathogenic fungi with carbon source and energy (Xie et al., 2014). Reductive Soil Disinfestation (RSD) has been proved to be a very strong method to "cure" the infection of soil borne pathogens (Cai et al., 2015; Momma et al., 2013; Blok et al., 2000; Katase et al., 2009; Runia et al., 2010; Butler et al., 2012; Shrestha et al., 2014). The traditional approach of RSD is to prevent air from diffusing into the soil by applying a large amount of decomposable organic materials, irrigation and film covering, so as to create a strong soil reduction condition in a short time and achieve the goal of killing soil-borne pathogens. The biogas slurry is weakly alkaline, which helps to alleviate soil acidification. The biogas slurry is rich in organic carbon and ammonium nitrogen nutrients, which can provide abundant carbon sources and energy for the growth of microorganisms, thereby affecting the number and community structure of soil microorganisms (Tao et al., 2014) and regulating the activity of microorganisms in soil (Li et al., 2007).

Hence, this study focuses on the application of biogas slurry to treat degraded soil for vegetable farming based on the RSD method, and intends to achieve the dual goals of high-efficiency consumption of biogas slurry per unit area of farmland and prevention and control of soil-borne diseases in facilities. The study intends to provide theoretical basis and practical knowledge for expanding the use of biogas slurry, preventing and controlling soil-borne diseases of facilities vegetable fields, and improving the utilization level of waste resources combined with crop cultivation.

The objectives of this study were to:

- Provide insights on the maximum adsorption capacity of the plough layer soil for ammonium nitrogen in biogas slurry, and provide knowledge on the amount of biogas slurry ammonium nitrogen that can be efficiently absorbed by the soil of biogas slurry pretreatment facilities.
- Elucidate the safe cycle of biogas slurry consumption in saturated water content soil and the final fate of ammonium nitrogen in biogas slurry, so as to provide theoretical support for the safe consumption of biogas slurry pretreatment soil.
- Determine the impact of biogas slurry pretreatment on the growth of subsequent crops (such as *Capsicum* spp.), analyze the response changes of soil microorganisms and soil properties, and elucidate the effect of reducing

the continuous cropping obstacle of subsequent crops.

The thesis has been structured into six chapters. Chapter one is the introduction and provides an overview of the background, purpose and significance of the study. Chapter two is a literature review providing an overview of advance in farmland consumption of biogas slurry. Chapter three is a study of adsorption characteristics of three types of soils on biogas slurry ammonium nitrogen predicting the maximum amount of biogas slurry application. Chapter four is a study of aging characteristics and fate analysis of liquid digestate ammonium nitrogen disposal in farmland soil elucidating the safe cycle of biogas slurry disposal. Chapter five focus on the application effect of assessing biogas slurry pretreatment on soil properties, soil microflora and growth of *Capsicum* spp. Each of these chapters (Chapters' three to five) is self-contained and is presented in the format of an independent scientific paper. Chapter six provides a general discussion based on the result findings presented in chapters' three to five, as well as provides a general overview of the major findings and highlights their contribution and relevance; challenges and discuss the future perspectives on the research topic.

References

Abubaker J, Risberg K, Pell M. 2012. Biogas residues as fertilizers: Effects on wheat growth and soil microbial activities. *Applied Energy* 99: 132–133.

Blok WJ, Lamers JG, Termorshuizen AJ, Bollen GJ. 2000. Control of soilborne plant pathogens by incorporating fresh organic amendments followed by tarping. *Phytopathology* 90: 253–259.

Butler DM, Kokalis-Burelle N, Muramoto J, Shennan C, Mccollum TG, Rosskopf EN. 2012. Impact of anaerobic soil disinfestation combined with soil solarization on plant-parasitic nematodes and introduced inoculum of soilborne plant pathogens in raised-bed vegetable production. *Crop Protection* 39: 33–40.

Cai Z, Zhang J, Huang X, Zhu T, Wen T. 2015. Application of reductive soil disinfestation to suppress soil-borne pathogens. *Acta Pedologica Sinica* 52: 469–476. Doi: 10.11766/trxb201411040554

Cai Z, Huang Q. 2016. Soil-borne pathogens should not be ignored by soil science. *Acta Pedologica Sinica* 53: 305–310. Doi: 10.11766/trxb201511190489

Cao R, Chen H, Zhao Y. 2018. Resource utilization of biogas slurry: Current status and future prospects. *China Biogas* 33: 42–45. (in Chinese with English abstract)

Cao Z, Huang J, Zhang C, Li A. 2004. Soil quality evolution after land use change from paddy soil to vegetable land. *Environmental Geochemistry and Health* 26: 97–103.

Cheng J, Chen Y, He T, Liu R, Yi M, Yang Z. 2018. Nitrogen leaching losses following biogas slurry irrigation to purple soil of the Three Gorges Reservoir Area. *Environmental Science and Pollution Research* 25: 29096–29103. Doi: 10.1007/s11356-018-2875-4

Deng Y, Huang Z, Ruan W, Miao H, Zhao M, Ren H. 2016. Effect of digestate recirculation ratio and organic loading rate on fermentation characteristics for anaerobic digestion of straw. *Transactions of the Chinese Society for Agricultural Engineering* 47: 198–206. (in Chinese with English abstract)

Dong Y, Liang D, Li D, Jin H. 2021. Characteristic analysis of main nutrient content in biogas slurry. *Jiangsu Journal of Agricultural Sciences*. 37: 1206–1214. http://qikan.cqvip.com/Qikan/Article/Detail?id=7105949915 (accessed on 9 January 2020).

Department of rural social and economic investigation, National Bureau of Statistics. 2019. China Rural Statistical Yearbook–2019. Beijing: China Statistics Press, pp: 93–94,198,202.

Hagos K, Zong J, Li D, Liu C, Lu X. 2017. Anaerobic co-digestion process for biogas production: progress, challenges and perspectives. Renewable and Sustainable Energy Reviews 76: 1485–1496. https://doi.org/10.1016/j.rser.-2016.11.184.

Han M, Liu K, Wang S, Qin L, Gao C. 2014. Definition, ingredient, approaches and risks for reuse in biogas slurry. *Journal of Agriculture* 4: 54–57. (in Chinese with English abstract)

Jain S, Jain S, Wolf IT, Lee J, Tong YW. 2015. A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste. *Renewable and Sustainable Energy Reviews* 52: 142–154

Jiang X, Sommer SG, Christensen KV. 2011. A review of the biogas industry in China. *Energy Policy* 39: 6073–6081. https://doi.org/10.1016/j.enpol.2011.07.007.

Ju X, Kou C, Zhang F, Christie P. 2006. Nitrogen balance and groundwater nitrate contamination: comparison among three intensive cropping systems on the North China Plain. *Environmental Pollution* 143: 117–125.

Katase M. 2009. Nematicidal activity of volatile fatty acids generated from wheat bran in reductive soil disinfestation. *Japanese Journal of Nematology* 39: 53–62.

Kirchmann H, Witter E. 1992. Composition of fresh, aerobic and anaerobic farm animal dungs. *Bioresource Technology* 40: 137–142.

Lamour KH, Stam R, Jupe J, Huitema E. 2012. The oomycete broad-host-range pathogen Phytophthora capsici. *Molecular Plant Pathology* 13: 329–337.

Li W, Fan J, Li W, Yuan H. 2013. Antibacterial mechanism of cow manure biogas slurry on *Rhizoctonia solani*. *Transactions of the Chinese Society of Agricultural Engineering* 29: 207–212. Doi: 10.3969/j.issn.1002-6819.2013.03.028

Li Y, Zhang Y, Gu S, Li G, Zhang Z. 2007. Study on effects of applying biogas fertilizer on diversity index of microbial communities in soil of protected field. *Renewable Energy Resources* 25: 44–46. Doi: 10.3969/j.issn.1671-5292.-2007.02.016

Liang Y, Guan Y, Wu H, Wang Z. 2013. Study on measures and policies to reduce pollution in raising livestock and poultry in Jiangsu Province. *Asian Agricultural Research* 10: 93–96. http://qikan.cqvip.com/Qikan/Article/Det-ail?id=6565718250484951494848 5050.

Ma Y, Ding J, Zhao L, Meng H, Shen Y, Cheng H, Wang J. 2018. Advances in recycling and reuse of nitrogen from biogas slurry. *Environmental Pollution and Control* 40: 339–344. Doi: 10.15985/j.cnki.1001-3865.2018.03.020

Ma Y, Li H, Chang Z, Xu Y, Zhang J. 2011. Biocontrol effect and mechanism of biogas slurry on plant disease I: primary study of growth inhibition effects and mechanism on phytopathogen fungi. *Journal of Agro-Environment Science* 30: 366–374. (in Chinese with English abstract)

Momma N, Kobara Y, Uematsu S, Kita N, Shinmura A. 2013. Development of biological soil disinfestations in Japan. *Applied Microbiology and Biotechnology* 97: 3801–3809.

Nkoa R. 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: a review. *Agronomy for Sustainable Development* 34: 473–492. https://doi.org/10.1007/s13593-013-0196-z.

Perez-Brandan C, Huidobro J, Grumberg B, Scandiani MM, Luque AG, Meriles JM, Vargas-Gil S. 2014. Soybean fungal soil-borne diseases: a parameter for measuring the effect of agricultural intensification on soil health. *Canadian Journal of Microbiology* 60: 73–84.

Qin W, Egolfopoulos FN, Tsotsis TT. 2001. Fundamental and environmental aspects of landfill gas utilization for power generation. *Chemical Engineering Journal* 82: 157–172. https://doi.org/10.1016/S1385-8947(00)00366-1

Runia WT, Molendijk LPG. 2010. Physical methods for soil disinfestation in intensive agriculture: old methods and new approaches. *Acta Horticulturae* 883: 249–258.

Shi L, Liu J, Wei Y, Li B, Xue Y, Bi Z. 2019. Current status of resource utilization of biogas slurry in agriculture. *Chinese Agricultural Science Bulletin* 35: 109–117. (in Chinese with English abstract)

Shi W, Yao J, Yan F. 2009. Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. *Nutrient Cycling in Agroecosystems* 83: 73–84.

Shrestha U, Wszelaki AL, Butler DM. 2014. Implementing anaerobic soil disinfestation in Tennessee. The University of Tennessee Extension SP 765-B. Available at http://extension.Tennessee. edu/publicatios/Documents/SP765-B. (accessed on 19 March 2014)

Shen L, Liu L, Yao Z, Liu G, Lucas M. 2010. Development potentials and policy options of biomass in China. *Environmental Management* 46: 539–554.

Song Y, Wang G, Li R, Chen G. 2021. Research progress of biogas slurry treatment and resource utilization. *Transactions of the Chinese Society of Agricultural Engineering* 37: 237–250. Doi: 10.11975/j.issn.1002-6819.2021.12.028

Tao L, Chu X, Liu T, Tang C, Li J, Liang Y. 2014. Impacts of organic manure partial substitution for chemical fertilizer on cotton yield, soil microbial community and enzyme activities in mono-cropping system in drip irrigation condition. *Acta Ecologica Sinica* 34: 6137–6146. Doi: 10.5846/stxb201301290184

Tao X, Dong H, Shang B, Chen Y, Huang H. 2011. Comparison of inhibiting effects between fresh effluents of anaerobically digested piggery waste and anaerobically digested dairy waste on plant pathogenic fungi. *Journal of Agro-Environment Science* 30: 1443–1449. (in Chinese with English abstract)

Tao X, Dong H. 2017. Research progress on animal waste treatment and recycling technology. *Journal of Agricultural Science and Technology* 19: 37–42. Doi: 10.13304/j.nykjdb.2016.764

Walsh JJ, Jones DL, Edwards-Jones G, Williams AP. 2012. Replacing inorganic fertilizer with anaerobic digestate may maintain agricultural productivity at less environmental cost. *Journal of Plant Nutrition and Soil Science* 175: 840–845. https://doi.org/10.1002/jpln.201200214

Wang X, Chen Y, Sui P, Gao W, Qin F, Wu X, Xiong J. 2014. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: an emergy evaluation based on LCA. *Journal of Cleaner Production* 65: 234–245. https://doi.org/10.1016/j.jclepro.2013.-09.001.

Wang Z, Sun G, Zhang L, Zhou W, Sheng J, Ye X, Olaniran AO, Kana EBG, Shao H. 2022. Aging characteristics and fate analysis of liquid digestate ammonium nitrogen disposal in farmland soil. *Water* 14, 2487. https://doi.org/10.3390-/w14162487

Xie X, Chen Y, Bu Y, Dai C. 2014. A review of allelopathic researches on phenolic acids. *Acta Ecologica Sinica* 34: 6417–6428.Doi: 10.5846/stxb201302210285

Yan Y, Li Z, Cheng S, Bai X, Zhou X. 2013. A review of anaerobic digested effluent treatment on livestock farm. *China Biogas* 31: 48–52. (in Chinese with English abstract)

Zhu T, Meng T, Zhang J, Cai Z. 2013. Effects of strong reductive approach on remediation of degraded facility vegetable soil. *Chinese Journal of Applied Ecology* 24: 2619–2624. (in Chinese with English abstract)

Zou M, Dong H, Zhu Z, Zhan Y, Zhang Y, Yue C. 2020. Progress and prospect of treatments and resource utilization of biogas slurry on livestock and poultry farms. *China Poultry* 42: 103–109. https://doi.org/10.16372/j.issn.1004-6364.2020.09.016.

CHAPTER 2: LITERATURE REVIEW

(ADVANCEMENT IN FARMLAND CONSUMPTION OF BIOGAS SLURRY – A REVIEW)

2.1 Introduction

Biogas slurry is one of the products of anaerobic fermentation (Jain S et al., 2015; Lou M et al., 2022), which refers to material produced by biodegradable organic wastes such as livestock and poultry manure, agricultural and forestry wastes, human excrement, urine, and kitchen waste (Lu G et al., 2021). These wastes undergo anaerobic fermentation in a closed container to produce methane, carbon dioxide and other gas residues (Deng L et al., 2017). This process is made up of the solid matter called biogas residue, and the liquid matter (biogas slurry) (Han M et al., 2014). Biogas slurry has complex components (Hu Y et al., 2017; Zou M et al., 2020), which are rich in nitrogen, phosphorus, potassium, copper, iron, zinc, manganese, amino acids, organic acids, hydrolases, vitamins and other components that are beneficial to plant growth and development (Rodriguez-Navas C et al., 2013; Shen Q et al., 2014; Wang X et al., 2021; Lou M et al., 2022). It also contains substances such as 8-hydroxy-3,4-dihydroquinoline-2-ketone and 3,4-dihydroquinoline-2-ketone that have inhibitory effects on pests and diseases (Qin W et al., 2001; Huo C et al., 2011; Yin F et al., 2021) as well as heavy metal components such as mercury, cadmium, chromium, arsenic and lead that are harmful to human beings (Song C et al., 2011; Huang H et al., 2018). According to estimates, China's annual production of biogas slurry has exceeded 1.12 billion tons (Ma Y et al., 2018; Zou M et al., 2020; Ke L et al., 2022). The safe consumption and treatment of biogas slurry has become a problem that must be faced and solved in the prevention and control of agricultural source waste pollution in China, and the urgency of the situation has attracted the attention of both government and scientists.

Traditional sewage treatment processes can realize the purification of biogas slurry, such as the oxidation pond method (Zu B et al., 2009; Jin H et al., 2011; Wan J et al., 2017), artificial wetland method (Zhu G et al., 2012; Lang L, 2017), activated sludge method (Yetilmezsoy K et al., 2009; Wang Z et al., 2013), membrane concentration method (Bai X et al., 2015; Zhan Y et al., 2018; Wu L et al., 2019; He Q et al., 2021), chemical flocculation method (Luján-Facundo MJ et al., 2019; Zhang M and Gao D, 2020), but the improvement of treatment efficiency needs further research and refinement. This approach also faces the challenge of waste of resources and high cost input (Song Y et al. 2021). For the direct treatment of biogas slurry, the resource utilization of biogas slurry is more in line with the requirements of sustainable development and a green environment (Zhang C et al., 2014; Nicholson F et al., 2017). Soil fertilization is a major way of waste resource (biogas slurry) utilization (Haraldsen TK et al., 2011; Robles Á et al., 2020), but biogas slurry discharged from intensive large-scale livestock and poultry farms and biogas projects have exceeded the carrying capacity of adjacent farmland. Similarly, biogas slurry discharged is greatly affected by agricultural seasonality. So it is particularly necessary to expand diversified treatment and utilization (Wang Z et al., 2016; Liu C et al., 2021). In order to provide a reference for the development of new ways of eco-friendly and efficient consumption in farmland, there is a need to understudy the approaches, challenges, application methods, and advantages of using biogas slurry.

2.2 Composition of biogas slurry

The physicochemical properties of biogas slurry are closely related to the raw materials and fermentation concentration of anaerobic fermentation (Li H et al., 2016). Through the search and analysis of over 750 documents on biogas slurry release to the field in China in the past 20 years from January 2000 to December 2019 (Dong Y et al., 2021a), the nutrient composition of biogas slurry with different fermentation raw materials are shown in **Table 2.1**. Other research data show that the water content of biogas slurry is as high as 95% or more (Sheets JP et al., 2015), with a weak alkalinity. The amino acids, vitamins and plant hormones content in biogas slurry are shown in **Table 2.2**. The heavy metals, antibiotics and other residual substances content are shown in **Table 2.3**. Since the composition of biogas slurry varies greatly, the composition of biogas slurry should be determined before its resource utilization to achieve scientific and reasonable safe digestion.

Table 2.1 The nutrient composition of different types of biogas slurry (Dong Y et al., 2021a; Wang X et al., 2021)

Element in biogas slurry	PM		DM		CM		MM	
	Range	Average	Range	Average	Range	Average	Range	Average
pH	4 23–9 20	7 52	6 10–9 20	7 75	6 77–8 50	7 80	6 15–8 20	7 37
TN (mg/L)	0 80–7280 00	1166 71	32 00–6500 00	1488 59	400 00–5700 00	3226 13	0 04–5900 00	1369 31
TP (mg/L)	0 54–2220 50	291 60	10 00–3700 00	561 67	49 00–4650 00	959 71	0 03-3900 00	665 90
TK (mg/L)	0 33–8880 00	1144 26	11 00–9650 00	1679 10	390 00–4400 00	2858 31	0 12–3200 00	1240 21
NH_4 -N (mg/L)	66 53–1800 00	597 53	80 35–1098 00	493 47	ND	ND	250 50–787 80	519 15
NO_3^--N (mg/L)	0 19–472 16	67 84	0 70–223 70	71 53	ND	ND	ND	ND
DP (mg/L)	0 16–1730 00	261 40	80 00–1860 00	416 88	ND	ND	0 16–201 10	76 68
DK (mg/L)	0 86–5010 00	986 47	263 20–2500 00	1418 33	ND	ND	0 84–2316 70	764 73

ND: no data; PM: biogas slurry using pig manure as fermentation raw material; DM: biogas slurry using cow dung as fermentation raw material; CM: biogas slurry using chicken manure as fermentation raw material; MM: biogas slurry using two or more of straw, human excrement, pig manure, cow dung, chicken manure and other household waste mixture as fermentation raw material; TN: total nitrogen; TP: total phosphorus; TK: total potassium. NH_4^+-N: ammonium nitrogen; NO_3^--N: nitrate nitrogen; DP: available phosphorus; DK: available potassium.

Table 2.2 Concentration of amino acids, plant hormones and B vitamins in a biogas slurry (Huo C et al., 2011; Shen Q et al., 2014)

Amino acids	Contents (mg/L)	Amino acids	Contents (mg/L)	Plant hormones	Contents (µg/L)	B vitamins	Contents (mg/L)
Cysteine	2 92	Arginine	0 63	Indole acetic acid (IAA)	332	B1	0 089
Serine	2 07	Proline	0 58	Gibberellin (GA4)	0 857	B2	0 022
Threonine	1 41	Valine	0 56	Gibberellin (GA19)	1 47	B6	0 530
Lysine	1 05	Leucine	0 45	Gibberellin (GA53)	0 271	B11	0 078
Glycine	1 01	Methionine	0 36	Cytokinin (iPR)	0 00194	B12	0 009
Tyrosine	0 88	Alanine	0 36	8-hydroxy-3,4-dihydroquinoline-2-ketone	737 5		
Aspartic acid	0 76	Phenylalanine	0 33	3,4-dihydroquinoline-2-ketone	177 5		
Isoleucine	0 75	Glutamate	0 31				
Histidine	0 63						

Table 2.3 The heavy metals, antibiotics and other residual substances content in biogas slurry (Shen Q et al., 2014; Jing D et al., 2016; Huang H et al., 2018; Wang X et al., 2021)

Element in biogas slurry	PM		DM		CM	
	Range	Average	Range	Average	Range	Average
Hg (mg/L)	0–0 167	0 028	0–0 119	0 024	0–0 054	0 014
Cd (mg/L)	0–7 51	0 126	0–0 190	0 039	0–4 3	0 367
As (mg/L)	0–13	0 868	0 001–4 576	0 235	0 01–5 21	0 548
Pb (mg/L)	0–36 07	0 710	0 008–1 056	0 199	0–2 430	0 345
Cr (mg/L)	0–24 18	0 657	0–3 146	0 301	0 001–10 18	1 085
Ni (mg/L)	0–5 85	0 317	0 027–0 063	0 045	0 088–0 55	0 281
Cu (mg/L)	0–99	4 50	0 02–30 03	2 63	0–2 12	0 78
Zn (mg/L)	0–205 43	9 11	0 1–68 15	8 31	0–13 94	4 06
Cl (mg/L)	150–3647 5	917 1	850 5–963	906 8	540–1087	813 5
Na (mg/L)	88 5–559	287 1	994 45	994 45	172 29	172 29
Se (mg/L)	0–0 232	0 049	0 002–0 022	0 012	0 011	0 011
Mn (mg/L)	0–50 8	6 815	0 231–124 6	61 092	0–50 8	7 534
Fe (mg/L)	0 0014–6 05	2 505	0 0084–48 3	18 56	0 0054–13 3	4 962
Mg (mg/L)	0 0057–253 34	109 6	0 352–553	225 06	0 0109–89 46	32 82
Ca (mg/L)	0 0042–264	81 65	0 785–769	280 8	0 0426–96 1	61 14
Oxytetracycline (mg/L)	0 0001–0 994	0 1456	0 5748	0 5748	0 0759–0 4007	0 2383
Tetracycline (mg/L)	0–0 9821	0 0296	0 0208–0 5608	0 2908	0 0289–12 862	4 3106
Chloromycin (mg/L)	0 0002-0 642	0 0415	ND	ND	ND	ND
Norfloxacin (mg/L)	0-0 204	0 0191	0 0054–0 1189	0 0641	0 056–0 2048	0 1065
Ciprofloxacin (mg/L)	0 0002-0 0513	0 0052	0 016–0 0227	0 0183	0 005–0 0071	0 0058
Enrofloxacin (mg/L)	0–0 1513	0 0108	0 0058–0 089	0 0520	0 0073–0 0676	0 0519

ND: no data; PM: biogas slurry using pig manure as fermentation raw material; DM: biogas slurry using cow dung as fermentation raw material; CM: biogas slurry using chicken manure as fermentation raw material.

2.3 Advance in farmland consumption of biogas slurry

2.3.1 Approaches of using biogas slurry in farmland

2.3.1.1 Seed soaking

The abundant nitrogen, phosphorus, potassium, various trace elements, growth hormones and other substances in biogas slurry can be absorbed and utilized by seeds through seed soaking and infiltration. It can accelerate the formation and metabolism of seeds during the dormant period, thereby promoting seed germination. Reports have shown that the proper concentration of biogas slurry and soaking time could improve the germination rate of seeds and promote the growth of seedlings. Soaking seeds with 50% biogas slurry for 5 hours had the best comprehensive effect on the germination of marigold seeds and seedling growth (Yuan D et al., 2011). For instance, the germination rate and seedling rate of watermelon seeds treated with 40% biogas slurry for 24 hours was observed to give the best performance (Cheng W et al., 2018). Similarly, soaking seeds with 25% biogas slurry for 5 h had significant effect on seed germination and seedling growth of *Astragalus membranaceus var. mongholicus* (Bunge)P.K.Hsiao (Lu G et al., 2019). In addition, soaking seeds with biogas slurry can increase crop yield. The seed soaking treatment of wheat seeds with biogas slurry with better maturity and longer fermentation time can increase the germination rate by about 13% compared with the water treatment. Resulting in the seeds emerging 3 days earlier, the leaf length, leaf width, dry weight of seedlings increase by 1.70 cm, 0.10 cm, 0.70 g respectively. And the maturity period shortens by 2 days with the yield per hectare increases by 379.50 kg (Shi L et al., 2019). Hence, biogas slurry could be a potential fertilizer for improving agricultural productivity and a sustainable green environment

2.3.1.2 Foliar fertilizer using biogas slurry

Biogas slurry is often used as foliar fertilizer for it contains a variety of available nutrients and amino acids which can promote plant growth, increase yield and improve quality (Yan L et al., 2019; Yang W et al., 2020). Biogas slurry has been directly used as foliar fertilizer to spray on fruit trees and vegetables, which can significantly increase chlorophyll content and yield (Zhao X et al., 2011; Hao S et al., 2012). For instance, proper application of biogas slurry sprayed on the leaves can improve the growth, yield and quality of tomato (HL2109 produced by Beijing Yinyue Seed Industry) plants (Jia L et al., 2017). Similarly, investigating the effect of biogas slurry application on the high-efficiency production of walnuts, Bi T et al. (2020) observed that the biogas slurry has a good promotion effect on the improvement of walnut quality and the prevention and control of pests and diseases. The authors pointed out that when biogas slurry is used as leaf fertilizer and pest control, it should be diluted and sprayed on the back of leaves. The application of biogas slurry has become a hotspot in the research field in recent years. Likewise, foliar topdressing of biogas slurry concentrate can increase the yield of cucumber by 6% and tomato by 8% (Xue S et al., 2013). Adding humic acid and other nutrients to biogas slurry concentrated to 10% of the original volume, and compounding into organic fertilizer with large, medium and trace elements, as a foliar fertilizer, it can significantly improve the yield and quality of Chinese cabbage. The yield of Chinese cabbage increased by 23.3%, and the content of vitamin C and soluble sugar increased by 68.5% and 43.1%, respectively. At the same time, soil fertility and enzyme activity were improved, and soil nutrient content increased significantly (Fan B et al., 2015). In addition, topdressing biogas slurry concentrate can increase *Capsicum* spp. yield (Cui W et al., 2021), and increase the content of vitamin C, soluble sugar, and protein in *Capsicum* spp., among which the vitamin content increases by 18.32% compared with the market foliar fertilizer (Fu Y, 2018).

2.3.1.3 Base fertilizer using biogas slurry

Biogas slurry as basic fertilizer is the most traditional approach of farmland application of biogas slurry. Compared with chemical fertilizer group, under the treatment condition of biogas slurry as base fertilizer (52.5 t/hm^2) and root irrigation twice (0.25kg/root · time), the length, diameter, leaf area and chlorophyll content of sweet melon (Xitian No. 1, provided by Xi'an Hejia Seedlings Co., Ltd) vine can be increased as well as the weight of melon and the melon plant can be increased (Wu Z et al., 2015). A study by Li and Jiang (2016), shows that when the concentration of biogas slurry is between 10% and 20%, it is favourable for the growth of container seedlings of *Dendrobium candidum* on the substrate of water moss, and between 10% and 30%, was found to be favourable for the growth of disk seedlings of *Dendrobium candidum* on the substrate of sawdust pine bark. Under the condition of the total application amount of biogas slurry with 600 t/hm^2 (base fertilizer: top dressing=1:1), the total panicle number of rice and the yield could be increased, and the content of heavy metals in grains did not increase (Shao W et al., 2017). Using livestock manure to ferment biogas slurry as base fertilizer in autumn and topdressing in the next spring can improve the yield and quality of spring tea and ensure the content of heavy metals in soil and tea within the safe range. However, when the biogas slurry is applied alone, potassium depletion will occur. Therefore, it is necessary to pay attention to the supplement of potassium in practical application (Hu Z et al., 2020). Practically, the treatment of biogas slurry should be carried out according to the ratio of base fertilizer to fruit expanding fertilizer of 1:1. There was no significant difference in plant height and stem diameter when the biogas slurry was applied at 70–110 t/hm^2 compared with applying compound fertilizer 600 kg/hm^2 treatment. When the total application amount of biogas slurry was 180 t/hm^2 (base fertilizer 90 t/hm^2, fruit expansion fertilizer 90 t/hm^2), it could promote the growth of melon plants and dry matter accumulation, improve fruit quality, and can be popularized in melon production (Wang L et al., 2021a).

2.3.1.4 Top dressing fertilizer using biogas slurry

The application of biogas slurry instead of chemical fertilizer for crop top dressing can increase the content of nitrogen and phosphorus in the soil, and it increases with the increase of the application amount of biogas slurry. The yield of rice treated with pure nitrogen 396 kg/hm^2 of biogas slurry is greater than that treated with chemical fertilizer, and the utilization rate of nitrogen and phosphorus is the highest (Wang W et al., 2014). Compared with no biogas slurry topdressing treatment, 10 times of biogas slurry topdressing treatment can increase the yield of *angelica sinensis* by 112.89kg, an increase of 58.01%. This significantly reduces the disease index of angelica hemp (*Angelica sinensis (Oliv) Diels*. Mingui No. 1) mouth disease and the preventive effect can reach 82.3%. The special grade yield of *angelica sinensis* increased by 7.4%, and the first-class yield of *angelica sinensis* increased by 2.4% (Zhou J, 2015). By using nutrient balance method, it was found that there was no significant difference in muskmelon dry matter quality, nutrient content and carrying capacity of roots, stems, leaves and fruits between biogas slurry integrated water and fertilizer topdressing group and fertilizer group, which proved that biogas slurry integrated water and fertilizer could completely replace fertilizer topdressing (Gao X, 2019).

2.3.1.5 Hydroponics

Using biogas slurry to replace the inorganic nutrient solution of hydroponic cash crops for vegetable cultivation is one approach of resource utilization of biogas slurry. The celery was hydroponic in biogas slurry of different concentration by the technology of bio-floating bed. After 80 days of planting, the celery which was hydroponically cultured in 30–40 times diluted biogas slurry achieved high environmental and economic benefits (Zhang L et al., 2011). In the concentration range of 3%–5%, the stepwise addition and one-time addition of chicken manure biogas slurry can increase the chlorophyll content, biomass and vitamin C content of water spinach in the solar greenhouse, and reduce the nitrite content (Wang H et al., 2013). Compared with ordinary soil cultivation treatment, biogas slurry soilless cultivation treatment can significantly increase the number of lateral roots and total yield of water spinach by 45.4% and 12.8%, respectively as well as reduce nitrate nitrogen content in water spinach by 31.5% and increase soluble sugar content by 68.5% (Yu C et al., 2015). In another related study using biogas slurry as a nutrient substitute for the second growth stage of lettuce (Lactuca sativa, Jinshulu Seed), the replacement of nutrient solution with biogas slurry had a better effect on lettuce yield, photosynthetic characteristics and quality. The replacement ratio of 40% biogas slurry has the best effect, and the yield is 66.97% higher than that of the control (lettuce hydroponics with a nutrient solution prepared by the original Yamasaki formula) (Yang X et al., 2017). After the biogas slurry deamination was pretreated and diluted 5–10 times, lettuce was hydroponically cultured for 35 days. Then compared with hydroponics in nutrient solution, the relative growth of lettuce increased by 60%, the leaf width became wider by 4–5cm, the number of leaves increased by 2 pieces on the average, the carotenoids content increased by 20.4%, and the content of nitrate nitrogen from 2.11%–4.02% compared to that of chemical nutrient solution group (Liang F et al., 2018).

Biogas slurry hydroponic microalgae is a new type of resource treatment process with potential and stable operation. Compared with traditional biochemical methods, it can improve the nitrogen removal efficiency of biogas slurry by about 20% (Odlare M et al., 2011b), and obtain higher efficiency functional microalgae products. Five species of microalgae were cultured with pig manure fermentation biogas slurry, and the nitrogen removal ability and sugar accumulation degree were investigated. *Chlorella vulgaris* ESP-6 showed the best sugar production capacity, with the maximum sugar content and average daily sugar production capacity of 61.50 % and 395.73 g/L respectively. The ammonia nitrogen removal rate and daily average removal concentration were 96.30% and 91.7 mg/L, respectively, which underscored the good purification ability of microalgae on biogas slurry. Accumulating more carbohydrates in microalgae cells can be regarded as a new strategy for sugar production, which fully proves the value of biogas slurry hydroponic microalgae utilization and the regeneration potential of biogas slurry waste resources (Tan F et al., 2016).

2.3.1.6 Animal feed

The use of biogas slurry as animal feed and feed additive is another environmentally friendly approach to solve the comprehensive utilization of biogas slurry to realize both ecological and economic benefits. The literature reports are mostly found in empirical research and attempts. For instance, feeding pigs with biogas slurry can achieve the effects of promoting growth, shortening the fattening period and improving the ratio of meat to feed. It is estimated that using biogas slurry as a feed additive for pigs can save about 50 kg of feed per pig, and shorten the fattening period by 20–40 days (Wu X, 2006), which can increase the weight of pigs by 0.2 kg per day and reduce the swine morbidity (Zhang H et al., 2009). The anatomical analysis and meat quality analysis after slaughtering live pigs with biogas slurry showed no abnormality in the main organs and meat quality and no infectious diseases and parasitic diseases detected (Wang H and Zhang Z, 2006). The number of heterotrophic bacteria in the sediments of fish ponds with biogas slurry or biogas slurry combined with feed was higher than that of cattle dung or biogas slurry combined with inorganic fertilizers. Similarly, the sediment-water interaction in fish ponds with biogas slurry was better than the conventionally fertilized fish ponds (Das M et al., 2013). Fish farming with biogas slurry can increase the yield and economic benefits of feeding and filter- feeding fish, however, attention should be paid to the amount, frequency and timing of biogas slurry dosing (Jing D et al., 2016).

2.3.2 Challenges of using biogas slurry in farmland

2.3.2.1 Water environment

2.3.2.1.1 Surface runoff

The nitrogen and phosphorus nutrients in biogas slurry are mostly and readily available nutrients. When the nitrogen and phosphorus nutrients provided in the biogas slurry exceed the needs of crop growth, they will continue to accumulate in the soil, in the face of heavy rainfall, improper irrigation and poor drainage system, it is easy to cause nutrient loss, leading to eutrophication of rivers and lakes (Song D et al., 2020). A case study is the paddy field engineering approach to biogas slurry valorization. The use of paddy field engineering for digesting biogas slurry is different from the utilization of paddy field fertilizer, which is a new way to deal with biogas slurry (Wang Z et al., 2016). The first 3 days after irrigation is a critical period for the digestion of biogas slurry in paddy fields (Wang Z et al., 2015a; Wang Z et al., 2015b; Yang R et al., 2017), and it is also a critical period for controlling nitrogen loss in paddy field runoff (Jiang L et al., 2011; Li S 2011; Wang Z et al., 2016). The risk of nutrient loss in the application of biogas slurry in paddy fields increased with the increase of application years, which was not only reflected in the soil fertility index and nutrient accumulation rate, but also reflected in the low proportion of soil C:P and N:P (Dong Y et al., 2021b). There may be a risk of nutrient loss in paddy soil with continuous application of biogas slurry for 4 years. To reduce the risk, the construction of farmland infrastructure such as farmland ecological interception ditch system should be strengthened, and a series of agronomic, biological and other supporting measures such as fertilizer and water management should be taken.

2.3.2.1.2 Downward leaching

While the application of biogas slurry increases the nutrients such as nitrogen and phosphorus in the soil (Wang J et al., 2019), these nutrients may also be leached downward with the biogas slurry and rainwater. It may pose a potential threat to farmland health and even cause secondary environmental pollution (Tan F et al., 2016). For example, when biogas slurry is applied in vegetable fields, soil nitrogen and phosphorus nutrients are surplus, phosphorus accumulations while, nitrogen leaching loss occur in surface soil (Kang L et al., 2011). The pollution risk of digesting biogas slurry by paddy field engineering measures to the infiltration water is mainly concentrated in base tiller stage. Ammonium nitrogen pollution is the main risk, nitrate nitrogen pollution risk is small, and the degree of pollution varies with the depth of water seepage.The amount of biogas slurry digested in the paddy field at the base tiller stage should be controlled within 211.76 t/hm^2. The capacity of the paddy field in panicle fertilizer stage to digest biogas slurry is relatively strong and the risk of pollution is small. The single digested biogas slurry amount (< 423.53 t/hm^2) can be regarded as a safe amount in a rice growth cycle (Wang Z et al., 2016). A 3-year field trial of the mixed application of biogas slurry and irrigation water during the wheat-maize rotation was carried out in the North China Plain. It was found that the use of medium-concentration biogas slurry instead of chemical fertilizers is a reasonable method to ensure high crop yield, high nitrogen usage efficiency and reduction of nitrate leaching losses (Du H et al., 2019). The leaching amount of ammonium nitrogen produced by the application of biogas slurry in autumn fallow period is related to the growing season of crops, the amount of biogas slurry and the application method of biogas slurry. The increase of biogas slurry application rate increases the risk of ammonium nitrogen leaching. Meanwhile, biogas slurry injection treatment increases the leaching potential of ammonium nitrogen compared to the spray treatment. Field experiments for three consecutive years showed that the content of ammonium nitrogen in soils of each biogas slurry nitrogen treated soil was lower than that of no nitrogen application, indicating that no leaching of ammonium nitrogen occurred.

2.3.2.2 Soil environment

2.3.2.2.1 Heavy metals and antibiotic residues

Due to the use of different chemical compounds in animal feeds with various chemical additives and antibiotics being abused, the utilization rate of heavy metal elements and antibiotics by livestock and poultry is low. Hence, a considerable part of heavy metal and antibiotic pollutants are left in the faeces (Ma H, 2014; Qian M et al., 2016). During the anaerobic fermentation process, the heavy metals and antibiotic pollutants enriched in the manure will also remain in the biogas slurry (Wei D et al., 2014; Huang H et al., 2018; Shen A et al., 2019). Although the content is very low, if biogas slurry is applied blindly for a long time, it will cause the risk of excessive heavy metals and residual antibiotic pollutants in farmland, which will destroy the farmland ecosystem causing food security problems (Lai X et al., 2018; Zhou Y et al., 2020). Detection and analysis of soil and crops after application of biogas slurry showed that Cd, As, Pb, Ni, Cr, Cu and Zn accumulated in different degrees in soil, and Cd, As, Pb, Ni, Cr and Zn were enriched in different degrees in crops (Bian B et al., 2015; Zhou L and Lv L, 2017; Wang Y, 2018). Long term or high concentration application of biogas slurry fermented with pig manure, chicken manure, cow manure and other raw materials will lead to the accumulation of heavy metals in the soil. However, due to the different types of livestock and the different types and amounts of feed added, the content of heavy metals in the biogas slurry will be different. Similarly, after a long- term biogas slurry application, the accumulation of heavy metals in the soil will be different (Liu X et al., 2018). When the application amount of biogas slurry is low, it can help to reduce the effectiveness of three heavy metals such as lead, copper, and zinc in the soil. On the other hand, when the dosage is high, although the availability increases, but heavy metal soil environmental pollution increases. Therefore, reasonable control of the application amount of biogas slurry will reduce the pollution of heavy metals in the soil (Han J et al., 2021). A standard control of feed additives to block the input of heavy metals and antibiotics is the key link for the subsequent safe utilization of livestock and poultry manure biogas slurry. In this regard, the Chinese government has formulated safe use specifications for additives in feed, and issued announcement policy on the complete prohibition of antibiotics in Chinese feed from 2020.

2.3.2.2.2 Secondary salinization

As a renewable water resource, biogas slurry can provide a large amount of nitrogen and phosphorus nutrients while solving the water shortage in arid and semiarid areas. Therefore, biogas slurry irrigation is one of the important ways of recycling and using wastes at present (Wu G et al., 2014; Cui B et al., 2019). However, biogas slurry also contains excess sodium ions, potassium ions and bicarbonate ions. Improper irrigation may cause excessive accumulation of soil salt, leading to soil salinization and potential pollution risks to farmland soil. For instance, in the vegetable planting base of Yining, Xinjiang, China, five consecutive years of biogas slurry irrigation show that with increase of years of biogas slurry irrigation, salt accumulates in farmland soil, resulting in secondary salinization of the soil in facility vegetable field (Yang L et al., 2012). Also, the nutrient and salinity accumulation in the soil of protected vegetable field applied with pig manure biogas slurry for 0, 1, 3, 5 and 7 years was investigated. The results showed that the available nitrogen, organic matter, total copper, total zinc and electrical conductivity in the soil showed an increasing trend year by year. After 7 years, each index was 3.4, 1.5, 3.3, 1.3, 3.9, 1.88 and 4.74 times of that in the soil without the application of pig manure biogas slurry, respectively. This led to the rapid accumulation of salt while simultaneously increasing soil nutrients that put the soil at a risk of soil pollution (Guo Q et al., 2020). In another study, the biogas slurry microbial fertilizer prepared by anaerobic digestion of kitchen waste was applied to single season rice and winter wheat. It was observed that the water-soluble total salt and chloride ion in winter wheat and rice soil showed weak accumulation, although no salt forcing phenomenon occurred (Sun T et al., 2020). The field experiment used Na^+ concentration of about 35 mmol/L biogas slurry to irrigate oil sunflower for a long time. Under the low irrigation amount (150 m^3/hm^2), the agronomic profile of oil sunflower did not change much, and the difference of K^+/Na^+ was not significant. But under high irrigation (600 m^3/hm^2), various agronomic indicators of oil sunflower growth were inhibited, and K^+/Na^+ of each tissue decreased by 57%–88%. The high pH damage caused by alkaline salt is higher than that of salt ion osmotic stress. The HCO_3^- and CO_3^{2-} in the slurry should be controlled, and the pH of wastewater should be adjusted to reduce damage to crops. Alkaline salt could damage the ion homeostasis of oil sunflower to a greater extent, affecting the germination and growth of oil sunflower

(Fan J et al., 2022). Using biogas slurry on farmland as regenerated water resources for the irrigation of farmland. Therefore, when applying biogas slurry in agriculture, consideration should be given to controlling the amount of salt accumulation in the soil from the source and reducing the risk of soil salinization.

2.3.2.3 Atmospheric environment

More than 70% of the nitrogen in the biogas slurry in the form of NH_4^+-N (Jin H et al., 2012), can be directly decomposed into gaseous ammonia and volatilized after being applied to the soil (Jin H et al., 2011). Therefore, the application of biogas slurry will increase the amount of soil ammonia volatilization (Deng O et al., 2011; Jin H et al., 2013; Li H et al., 2019a), and become the most important contributor to the loss of NH_3-N after returning to the field (Martines AM et al., 2010; Cheng J et al., 2018). The amount of biogas slurry application, application time, temperature, and application method will all affect the amount of ammonia volatilization. The larger the amount of biogas slurry applied in the field, the larger the amount of ammonia volatilization (Wu H et al., 2012). For instance, in a pot experiment with medium soil fertility, it was found that the total amount of ammonia volatilization from farmland under conventional chemical fertilizer treatment was 77.0 kg/hm^2, while the amount of ammonia volatilization from 100% biogas slurry treatment and 75% biogas slurry plus 25% pig manure organic fertilizer treatment was higher, which were 120.7 kg/hm^2 and 88.0 kg/hm^2, respectively (Zhou W et al., 2019). Moreover, when biogas slurry was applied at low temperature in autumn fallow period, the peak value of ammonia volatilization in spraying and injection treatment was 0.22 kg/(hm^2·d) and 0.65 kg/(hm^2·d) respectively (Liu C et al., 2021; Wu H et al., 2012; Yuan Y et al., 2019). Furthermore, a study by Jin H et al. (2013), pointed out that more than 58% of ammonia volatilization loss is related to environmental temperature after biogas slurry has been applied to soil. When the temperature during biogas slurry application is higher, the amount of ammonia volatilization increases significantly. Studies also show that after the application of biogas slurry, the volatilization of ammonia was higher the in the previous week, after which the volatilization of ammonia gradually decreased and became stable (Yang R et al., 2017; Gao B et al., 2022). In addition to the influence of environmental temperature on ammonia volatilization, there is a positive correlation between the ammonia volatilization flux and the NH_4^+-N concentration of biogas slurry in the field surface water (Tian Y et al., 2007; Yang S et al., 2012; Li X et al., 2015).

The reason for the increase in ammonia volatilization rate is not only due to the increase in NH_4^+-N content, environmental temperature, and the presence of surface water in soil (Jin H et al., 2013). But also due to the large amount of soluble organic carbon in biogas slurry, which can stimulate the mineralization of soil organic nitrogen (Sommer SG et al., 2003; Martines AM et al., 2010). Usually the amount of ammonia volatilization loss correlate with the proportion of biogas slurry application, and the proportion of nitrogen loss caused by ammonia volatilization could reach 20% (Gao B et al., 2022). Ammonia volatilization in paddy field application of biogas slurry can account for 42.2%–72.0% of total nitrogen loss (Li H et al., 2019a). However, in conventional storage of biogas slurry, 25%–35% of N will be lost in the form of NH_3-N (Wang Y et al., 2016; Wang Y et al., 2017), much higher than the loss of ammonia volatilization from farmland reuse. Therefore, in the valorization of biogas slurry, it is necessary to clarify the whereabouts of the ammonium nitrogen, not only to reduce the loss of ammonia volatilization, but also to evaluate the risk of ammonia volatilization loss.

2.3.2.4 Crop safety environment

Appropriate biogas slurry concentration and dosage can promote plant growth and development, as well as improve yield and quality. However, when the concentration and dosage are improperly applied, the growth and development of crops will be inhibited. Ammonia, phenols, hydrogen sulfide and high chemical oxygen demand (COD) in biogas slurry may cause anoxic death of plant roots and slow growth development of plants (Gao M et al., 2019). Under the condition of equal amount of nitrogen, phosphorus and potassium, COD content is the key limiting factor affecting the use of biogas slurry in farmland. Low amount of biogas slurry COD (1566 kg/hm^2) promotes seedling growth, accelerates the peak supply of soil available phosphorus, while high amount of biogas slurry COD (3132 kg/hm^2) inhibits seedling growth, and delays the peak supply of soil available phosphorus. The optimal application safety threshold of COD is 1102–1442 kg/hm^2 and the maximum application safety threshold is 2208–2884 kg/hm^2. This factor needs to be taken into consideration for farmland biogas slurry safe usage and efficiency (Wang Z et al., 2019). Moreover, when the concentration of ammonium nitrogen and lactic acid in biogas slurry is higher than 336 and 61 mg/L, respectively, it could produce phytotoxicity to seed germination (Zhang Y et al., 2021). Excessive application of biogas slurry increases NH_4^+-N concentration and electric conductivity (EC) value in soil solution, resulting in inhibited seedling growth, decreased plant height, and increased root yellowing rate. The maximum safe absorption threshold of NH_4^+-N in biogas slurry-water mixture by seedlings was 314.0 mg/L. It is also found that the EC value of biogas slurry increases with the increase of biogas slurry concentration, a possible synergistic effect between EC and NH_4^+-N concentration still needs further studied (Zhang L et al., 2021).

In addition, the application of biogas slurry can increase the content of heavy metals in plants. For instance, Shao W et al. (2017), observed a varying concentration of Hg, As, Cr and Pb in rice straw. Also, the application of high-concentration pig farm fermentation biogas slurry (l.8×10^5 kg/hm^2) significantly increase the copper content in lettuce and in Chinese Cabbage, but lower than the limit range stipulated by the national food hygiene standards (Ye J et al., 2014; Yang J et al., 2015). When the biogas slurry contains 4 times the nitrogen equivalent, it will increase the excessive enrichment of Cu and Zn elements, which will have a negative effect and reduce the yield and quality of plants such as corn (Li J et al., 2021). 5-year irrigation experiment using pig manure biogas slurry in rice-wheat rotation field in Dongtai, Jiangsu, China, the detected Zn in the grains of wheat and rice increased by 24% and 16%, respectively, compared with the control (Tang Y et al., 2019a).

2.3.2.5 Pathogen transmission

Livestock and poultry manure contains a variety of pathogens (including bacteria, fungi, parasites, viruses, etc.), these pathogens can survive in the anaerobic fermentation process, and may remain in biogas residue and biogas slurry (Nag R et al., 2020). The top 10 pathogens associated with the farming of livestock and poultry manure biogas slurry in Ireland with potential risks were assessed: *Cryptosporidium parvum, Salmonella, Norovirus, Streptococcus pyogenes, Escherichia coli enteropathy, Mycobacterium, Salmonella typhi (followed by Salmonella paratyphi), Clostridium, Listeria monocytogenes, and Campylobacter coli* (Nag R et al., 2020). It shows that untreated livestock manure biogas slurry agricultural use can introduce pathogens into farmland and spread disease through the food chain (mainly ready-to-eat crops) (Nag R et al., 2019). Hence, before the biogas slurry is used for agriculture, it is necessary to ensure the pathogenic presence standardization. This can be achieved by high-temperature, ultraviolet radiation and other treatments for sterilization and disinfection.

2.3.3 Application methods of using biogas slurry in farmland

2.3.3.1 Drip irrigation

The biogas slurry is applied in the planting of protected vegetables and melons and fruits, and drip irrigation measures are mostly adopted, which have the advantages of uniform application, cost saving, production increase and nutrient improvement. Strict filtration and blockage prevention systems need to be put in place in drip irrigation. Compared with spraying biogas slurry, drip irrigation with biogas slurry can make the available nutrients in the substrate higher, as well as improve the growth of crops (Li S et al., 2014). Using the method of biogas slurry aeration drip irrigation to conduct a plot test on leeks in a greenhouse, it was found that when the concentration of biogas slurry was 80%, with aeration coefficient of 1.0, the yield of leeks was the highest up to 230.50 kg/667m^2, an increase of 28.53% compared with the control. At the same time, the content of vitamin C in chives increased by 77.78%, while the content of soluble sugar increased by 91.20%, and the content of soluble protein increased by 70.59% (Chu C et al., 2013). Similarly, the drip irrigation biogas slurry treatment in watermelon, cucumber, strawberry, grape and tomato fruit cultivation achieved 13.9% increase in watermelon fruit weight (Zhou G et al., 2014), 15.7% increase in strawberry fruit weight (Yuan C et al., 2013), and 18.1% increase in tomato fruit weight (Sui H et al., 2016). The strawberry yield increased by 18.1% (Yuan C et al., 2013), grape yield increased by 18.3% (Wang Z and Ma D, 2018), cucumber yield increased by 47% (Wang Z, 2018) and tomato yield increased by 20.7%–59.4% (Wang X et al., 2013; Ma D et al., 2017). Increase in the fruit soluble total sugar, Vitamin C, titratable acid, and improved fruit firmness were observed (Sui H et al., 2016).

Furthermore, after the biogas slurry was diluted with water, it was dripped into the saline-alkali soil. The results showed that the soil fertility was significantly improved, the soil pH was reduced, and the desalination effect was significant in the 0–20 cm soil layer, but salt accumulation occurred below the 20 cm soil layer (Wang X et al., 2018). From the economic point of view, integrated drip irrigation of biogas slurry, water and fertilizer greatly reduces the manpower and material costs of the previous use of biogas slurry distribution vehicles to transport to the fields. It also realizes the resource utilization of biogas slurry and reduces the application of chemical fertilizers (Gao X et al., 2019). Compared with the biogas slurry flood irrigation treatment, the biogas slurry water and fertilizer integrated drip irrigation treatment significantly improved the yield and quality of pear fruit, and the soil nitrogen nutrient accumulation was significantly reduced. Likewise, comparing the use of biogas slurry with conventional fertilization, 43% of chemical fertilizer usage can be avoided and can reduce soil nitrogen accumulation (Wang L et al., 2021b). The integrated drip irrigation of biogas slurry, water and fertilizer for pear trees also significantly improves the yield and quality of pear fruit, providing an economical and effective fertilization mode for precise fertilization of pear trees.

2.3.3.2 Ditch irrigation and flood irrigation

At present, the methods used to absorb biogas slurry in farmland are still mainly furrow irrigation, flood irrigation and surface application, which not only requires a large amount of labor and high labor intensity, but also has large loss of ammonia volatilization. Long-term application may cause secondary soil salinization, heavy metal accumulation, and increased groundwater contamination risk (Wang Y, 2010; Li J et al., 2021). It was found that the irrigation of biogas slurry could increase the root system and the yield of *Codonopsis pilosula*, towards the commercialization level of *Codonopsis pilosula* (An J and Song Z, 2011). Similarly, the furrow irrigation biogas slurry application significantly increased the yield of tomato. The yield increase rate was 10%, and the vitamin C content increased was 1.54 times better compared wth the control (Zhang F et al., 2013). In ditch irrigation, when the amount of biogas slurry applied was the same, the content of ammonium nitrogen and nitrate nitrogen in the soil treated by furrow application was higher than that of surface application and deep ploughing (Yuan Y et al., 2019). Moreover, biogas slurry flood irrigation significantly increases the content of soil organic matter, total nitrogen, alkali-hydrolyzed nitrogen, available potassium. Long-term application will increase the risk of secondary soil salinization.

2.3.3.3 Spraying application

The spraying of biogas slurry is more common with foliar spraying and soil surface spraying. It is necessary to pay attention to the spraying concentration and spraying amount. Studies have shown that spraying 60% concentration of biogas slurry or root application of biogas slurry, the yield of tomato, radish, celery, and anal bean can significantly be increased. Similarly, in celery (*Apium graveolens* L.) production, spraying 40% concentration of biogas slurry has the best yield increase effect (Jiang H et al., 2007). Spraying nectarine leaves with different concentrations of biogas slurry can increase the nutrition of nectarine leaves, and at the same time, the single fruit weight, soluble sugar content and sugar-acid ratio of nectarine fruit are also improved (Wang C, 2010). Foliar spraying of biogas slurry can effectively increase the single melon quality of cantaloupe and improve its quality. Furthermore, spraying 75% concentration biogas slurry has the best effect (Song B et al., 2016; He M et al., 2018). And foliar spraying of biogas slurry can increase the yield of apple trees and increase the content of vitamin C and soluble sugar in the fruit (Chen J et al., 2017). The use of biogas slurry spray irrigation can improve the soil content of alkali-hydrolyzed nitrogen, available phosphorus and available potassium in the deep soil (Wang K et al., 2019).

2.3.3.4 Compatible application

The application of biogas slurry is no longer limited to drip irrigation, furrow irrigation, flood irrigation, spraying and other conventional means. In order to maximize the benefits of biogas slurry resources and promote its high value usage, the application of biogas slurry in combination with chemical fertilizer (Xu K et al., 2020), solid organic fertilizer (Zhou W et al., 2019), biochar (Yuan J et al., 2022), duckweed (Song D et al., 2020), as well as pesticide (Cheng H et al., 2018; Ran Y et al., 2020; Qi B et al., 2021), has become desirable.

A study found that 150 mL/m^2 biogas slurry plus 27g/m^2 urea combined application was beneficial to increase the yield of dandelion, increase the content of vitamin C, nitrate and soluble protein (Kang X et al., 2019). In related studies, the combined application of pig manure biogas slurry and earthworm fertilizer significantly improve the yield and quality of flat peach fruit (Li H et al., 2019b), while, the combination of biogas slurry and biochar increase the mass fraction of soil water stable aggregates (Li C et al., 2014). Moreover, the combined application of biogas slurry and biochar for 3 years effectively increase the mass fraction of soil water-stable aggregates with a particle size of >0.25 mm, which is 13.0%–36.3% higher than that of the control (Yuan J et al., 2022). When biochar application is constant (12 t/hm^2), soil water-stable aggregate organic carbon shows a trend of increasing gradually with the increase of biogas slurry concentration, as well as increase in the range (4.8% to 37.1%) of soil organic matter (Zheng J et al., 2020b). When the ratio of biogas slurry is constant, with the increase of biochar dosage, the soil quality gradually decreases (Zheng J et al., 2020a). The application of 6% biochar from biogas residues can significantly reduce the leaching amount of biogas slurry nitrogen in lime-soil, and the leaching amounts of total nitrogen, ammonium nitrogen, nitrate nitrogen and nitrite nitrogen were reduced by 12.06, 11.82, 1.14, and 0.103 kg/hm^2, the declines were 35. 89%, 52. 99%, 25. 53%, and 23. 25%, respectively (Jiang T et al., 2021).

Furthermore, combined application of biogas slurry concentrate and chemical fertilizer increased the rapeseed yield by 9.7% (Luo L, 2010). Also, combined application of biogas slurry concentrates with chemical fertilizer and chicken manure significantly improve the quality of tomato with the contents of vitamin C and sugar increased by 9.36% and 49.52%, respectively, while the nitrite content was decreased by 27.05% (Liu J, 2013). Similarly, the application of biogas slurry concentrated with amino acid formula fertilizer increased banana yield by 4.09%, banana fruit protein by 10.67%, and vitamin C by 3.32%. It also increased the pH value of acidic soil and soil organic matter content by 2.98% and 3.93%, respectively (Gao L et al., 2017). While, foliar spraying of amino acid biogas slurry increased the pulp hardness and soluble solid content of cantaloupe by 13.9% and 7.7%, respectively (Chen N et al., 2021). Similarly, the addition of nutrients to biogas slurry concentrate, combined with berberine showed a strong inhibitory effect on tomato botrytis cinerea (Liu J et al., 2018). A related study using chicken manure biogas slurry concentrate diluted 300–500 times and mixed with pyridaben reduced by 10% can reduce the amount of pesticide application by 10%– 20%. It not only achieves the purpose of pest control, but also delays the enhancement of pest resistance, and reduced medication costs (Liu M et al., 2019). Also, concentrated chicken manure biogas slurry and flonicamid were used in a combination to control apple yellow aphid, when the pesticides were reduced by 10% to 20%, the control effect was better than or equal to the conventional dosage of flonicamid (Wang H et al., 2019).

2.3.4 Advantages of using biogas slurry in farmland

2.3.4.1 Soil fertilization

Farmland application of biogas slurry can improve the physical and chemical properties of farmland soil (Möller K, 2015; Niyungeko C et al., 2020; Tang Y et al., 2021) while effectively valorizing the biogas slurry (Chen S et al., 2015). This has a direct positive effect on increasing soil organic matter, maintaining soil structure, and fertility (Xu C et al., 2013; Liu X et al., 2018; Yu D et al., 2018).

The decrease in soil organic matter content is one of the reasons for the deterioration of soil structure and the reduction of soil productivity (Yılmaz E et al., 2019). The application of biogas slurry rich in organic matter to farmland can increase the content of organic matter, especially dissolved organic matter in the soil, thereby improving soil structure (Song Z et al., 2011; Yan L et al., 2019; Huang H et al., 2021). For instance, the pig manure biogas slurry can increase the organic matter content of the topsoil to 3.0 kg/hm^2 (Chen Y et al., 2011). After 5 years of biogas slurry irrigation, the soil organic carbon content increased significantly by 90.3% compared with the soil with chemical fertilizers (Yang L et al., 2012). However, some studies applying biogas slurry from chicken manure, pig manure and cow manure on the soil in comparison to the control had no significant effect on soil organic matter content (Li Y et al., 2021b). The input of nitrogen from biogas slurry promotes the consumption of organic carbon by non-autotrophic microorganisms (Wang W et al., 2010), thereby offsetting the accumulation of organic matter carried by biogas slurry in the soil (Huang J et al., 2016b). The effect of biogas slurry application on soil organic matter content is related to the application mode and the concentration of biogas slurry. Under the same nitrogen substitution conditions in biogas slurry, the increase of organic matter content in the injection treatment is higher than that in the spray treatment (Liu C et al., 2021). The increase of soil organic matter content was proportional to the amount of biogas slurry application (Huang J et al., 2013). The soil organic matter content of all the fertilizers applied gradually decreased with the growth of corn, while the biogas slurry treatment was the opposite. At the mature stage, the organic matter content of all the treatments with biogas slurry was found to increased (Cui Y et al., 2020).

Consumption of biogas slurry on farmland can enhance soil permeability, water retention and fertilizer retention capabilities, and avoid damage to soil environment, an advantage that chemical fertilizers do not have (Li J et al., 2021). The 3-year application of biogas slurry (165.1 and 182.1 t/hm^2) improved the nutrient content of yellow soil under rice-rape rotation and promoted the formation of aggregate soil structure (Xu M et al., 2019). With the increase of the amount of biogas slurry in the mixed solution, the stability indicators of dry-fed red soil aggregates: soil >0.25 mm water-stable aggregate content (WR0.25), aggregate mean mass diameter (MWD), geometric mean diameter

(GMD), the aggregate stability rate (AR) showed an upward trend, and the fractal dimension (D) showed a downward trend. After long-term biogas slurry irrigation, soil porosity, soil aggregate structure and microorganisms in soil increased (Ruan R et al., 2021).

Similarly, the application of biogas slurry can effectively adjust the proportion of various nutrients in the soil, enhance the balanced nutrient absorption capacity of crops, increase crop resistance to diseases (Nzila A, 2018), improve soil organic quality, and structure (Shahbaz M et al., 2014). For example, soil ammonium nitrogen and soil nitrate increased by 47.8% and 19.0% compared with the control, respectively (Chen S et al., 2015). Also, after applying biogas slurry formulated fertilizer in the orchard, the soil organic matter content in each soil layer increased from 2.98% to 3.93%, the available phosphorus increased from 5.59% to 18.64%, and the available potassium increased from 25.20% to 39.20% (Gao L et al., 2017). Compared with the control treatment (no fertilization), the application of chicken manure biogas slurry, pig manure biogas slurry and cow manure biogas slurry under isonitrogen conditions could improve soil inorganic nitrogen, total nitrogen, available phosphorus, available potassium, pH and electrical conductivity. It is worth noting that the increase in soil nitrate nitrogen in pig manure biogas slurry treatment is the largest, followed by chicken manure biogas slurry treatment (Li Y et al., 2021b). The maximum growth rate of available phosphorus, total phosphorus, available nitrogen and total nitrogen were 81.12%, 12.66%, 84.88%, and 127.70% in winter wheat soil samples after biogas slurry fertilizer was applied in paddy and wheat rotation fields. Continuous application of biogas slurry could increase the contents of total nitrogen, total potassium and alkaline hydrolyzed nitrogen in farmland soil (Lai X et al., 2018; Qiao F et al., 2018). The content of soil organic matter, cation exchange capacity, electrical conductivity, total soil nitrogen, total phosphorus, total potassium, alkali-hydrolyzed nitrogen, available phosphorus, available potassium and NH4-N content of paddy field with continuous application of biogas slurry four (4) years were significantly higher than those without biogas slurry application (Dong Y et al., 2021b). Interestingly, a tea garden with extremely low soil fertility level reached high fertility level after continuous application of biogas slurry for 2 years. The soil indexes of the treatment with biogas slurry for 4 years were significantly improved compared with the treatment without biogas slurry (Dong Y et al., 2022).

2.3.4.2 Improvement in crop production

Achieving the increase in crop yield is the primary object of concern for biogas slurry fertilizer utilization (see **Table 2.4**). Meta-analysis method was used to quantitatively analyze the effect of biogas slurry application on crop yield under different conditions (Zheng J et al., 2019). The results showed that: the effect of biogas slurry application on crop yield of yield of wheat, corn, tomato and rice were all improved. Moreover, the impact of biogas slurry on farmland could be soil type or climate specific. For example, biogas slurry application in northwest and north China increased crop yield significantly compared with other regions, while that in southwest and east China was slightly lower.

Identifying the physicochemical properties, application period and application amount of biogas slurry plays an important role in formulating technical measures for safe and efficient use of biogas slurry (Odlare M et al., 2011a; Liu X et al., 2018; Xu M et al., 2019). Applying 50% biogas slurry instead of chemical fertilizer can obtain the same corn yield as chemical fertilizer treatment (Wu H et al., 2012). Similarly, biogas slurry fermented by pig urine and feces significantly increase the yield of corn. When the concentration was controlled within the range of 60–90 t/hm^2, maximum corn yield was obtained (Chen B, 2010). Also, many studies have shown that the application of biogas slurry was beneficial in rice cultivation to increase rice yield (Tang W et al., 2010; Huang H et al., 2013; Huang J et al., 2016a; Wang G et al., 2018). It was also reported that the complete replacement of fertilizer with full biogas slurry will significantly reduce rice yield (Wang W et al., 2014; Wang Z et al., 2016). Hence, the application of appropriate biogas slurry is critical in improving rice than conventional fertilization (Hou F et al., 2019).

Table 2.4 Yield-increasing effect of applying biogas slurry to farmland

Slurry type	crops	Production increase range		References
		Comparison with conventional chemical fertilizer	Comparison with no fertilization	
PM	Rice	0.2%–20.4%	1.0%–102.5%	(Huang H et al., 2013; Huang J et al., 2016a; Shao W et al., 2017; Song S, 2017; Wang G et al., 2018; Hou F et al., 2019; Xu K et al., 2020; Sun G et al., 2021)
	Wheat	2.9%–22.4%	97.1%–217.5%	(Huang H et al., 2013; Song S, 2017)
	Corn	0.6%	5.6%–13 2%	(Chen B, 2010; Wu J et al., 2014)
	Barley	1.1%–2.0%	31.9%–111.9%	(Yang Z et al., 2019)
	Watermelon	0.2%–24 9%	ND	(Zhou G et al., 2014; Cao Y et al., 2015; Cheng W et al., 2018)
	Pear	12.0%	3.1%–7.4%	(Hao S et al., 2012; Wang L et al., 2021b)
	Grape	ND	10.7%–18.3%	(Wang Z and Ma D, 2018)
	Peach	ND	9.7%–43.7%	(Li H et al., 2019b)
	Cabbage	ND	75.4%–133.9%	(Lin S et al., 2019)
	Tea	ND	9.3%–93.4%	(Hu Z et al., 2020)
DM	Corn	ND	59.2%–81.7%	(Qiao F et al., 2018)
	Melon	8.8%–32 2%	8.6%–33.0%	(Song B et al , 2016; He M et al , 2018; Chen N et al., 2021)
	Grape	30.0%–170.0%	ND	(Hao Y, 2019)
CM	Corn	9.0%–26 2%	12.9%–107.7%	(Cui Y et al., 2020; Li J et al., 2021)
	Apple	2.0%–3.5%	42.8%–67.0%	(Gao W et al., 2020)
	Leafy vegetables	9.1%–45 1%	45.1%	(Zhao F et al., 2010; Wang H et al , 2013; Li S et al., 2014)
MM	Rice	4.6%–7.7%	4.1%	(Huang L et al., 2014; Zhang Y, 2018)
	Wheat	ND	28.2%–71.1%	(Wang J et al., 2019)
	Tomato	0.49%–21.59%	15.6%–39.8%	(Sui H et al., 2016; Jia L et al., 2017)
	Cabbage	8.5%–41 2%	ND	(Ma X and Tao Z, 2019)
	Tangerine	11.8%–24.8%	32.4%–56.4%	(Xi H et al., 2021; Liu Y et al , 2022)

ND: no data; PM: biogas slurry using pig manure as fermentation raw material; DM: biogas slurry using cow dung as fermentation raw material; CM: biogas slurry using chicken manure as fermentation raw material; MM: biogas slurry using two or more of straw, human excrement, pig manure, cow dung, chicken manure and other household waste mixture as fermentation raw material; TN: total nitrogen; TP: total phosphorus; TK: total potassium. NH_4^+-N: ammonium nitrogen; NO_3^--N: nitrate nitrogen; DP: available phosphorus; DK: available potassium.

2.3.4.3 Quality improvement

The digestion of biogas slurry in farmland can improve the nutritional quality of cultivated crops (increase the content of protein, soluble solids, reducing sugar and minerals in crops) (Tang W et al., 2010; Wu J et al., 2014). This will turn enhance the commodity economic value. For instance, the increasing use of biogas slurry in irrigation of rapeseed cultivation improve, Fe, Mn, Cu and Zn mineral content, while the content of oleic acid, Ca and Mg in rapeseed increased first and then decreased. The optimal quality of rape was achieved when biogas slurry was applied in the range of 78.8–101.3 t/hm^2 (Wu J et al., 2013). The application of biogas slurry can increase the protein content of rice and improve the nutritional quality of rice (Tang W et al., 2010; Wang G et al., 2018). But some studies also shown that the application of biogas slurry has little effect on the nutritional quality of rice. (Moreno-García B et al., 2017; Yang X et al., 2021). Based on the 8–9 years data analysis of long-term biogas slurry application, an improvement in the rice yield, taste value of rice, and gel consistency of rice when compared with those obtained from chemical fertilizer treated soil (Sun G et al., 2021). The application of biogas slurry promoted the accumulation of vital components such as polysaccharides, carotenoids, flavonoids and betaine in lycium barbarum fruit, thereby improving the nutritional quality of lycium barbarum and its efficacy (Zhou Q, 2012). Similarly, the application of nitrogen fertilizer and fermented pig manure in the cultivation of Chinese cabbage showed lower content of amino acids and soluble sugar when compared with the application of pig manure biogas slurry alone (Xu P et al., 2014). Likewise, in a related study, the effects of biogas slurry treatment with concentration of 25%, 50%, 75% and original liquid on the quality of *Capsicum* spp. were studied. The results showed that with the increase of biogas slurry concentration, the chlorophyll content, vitamin C content, soluble sugar content and organic acid content of *Capsicum* spp. were improved (Cui Y et al., 2019). It was also found that applying biogas slurry to replace chemical fertilizer could significantly increase the soluble sugar, soluble solids and sugar acid ratio of muskmelon (Gao X et al., 2019).

2.3.4.4 Bacteriostatic

Biogas slurry undergoes long-term anaerobic fermentation to produce a variety of biologically active substances, such as organic acids, vitamin B12, gibberellin, that inhibit the proliferation of soil bacteria, fungal and viruses (Huo C et al., 2011). In addition, the high concentration of NH_4^+-N in the biogas slurry has the potential of killing pests and pathogenic bacteria (Cao Y et al., 2013a; Cao Y et al., 2013b). For instance, fresh biogas slurry from cattle farm has strong inhibition effect on *Botrytis cinerea (Hyphomycetes), Phytophthora capsici, Alternaria solani, Colletotrichum gloeosporioides* Penz., and *Botrytis capsici*. However, when biogas slurry storage time was increased, the inhibition rate of biogas slurry against *phytophthora capsici* and f*usarium solani* decreased significantly (Shang B et al., 2011). Similarly, concentrated biogas slurry remarkably inhibit the growth of cotton verticillium wilt mycelium (the inhibitory effect of 0.50% concentrated solution biogas slurry on cotton verticillium wilt disease was 64.89%). The biogas slurry also prevent spore production, conidial germination and microsclerotia germination. (Feng Z et al., 2018). Likewise, the application of biogas slurry had effective repellent effect on adult brown rice plant hopper (Huang L et al., 2014). The spraying of biogas slurry with 66.6% concentration had the best repellent effect (Ma X and Tao Z, 2019).

Furthermore, the application of biogas slurry was effective in the prevention and control of soil borne diseases of crops (Min YY et al., 2011; Cao Y et al., 2016b; Li Y et al., 2020). Although nitrogen input is considered to be the key factor to stimulate soil microbial biomass carbon (Möller K, 2015), however, a large amount of ammonium nitrogen in biogas slurry may play a role in inhibiting microbial growth in the short term. The bacteria population in soil decreased, after biogas slurry was applied in pot culture system (Cao Y et al., 2013b). For example, irrigation with high concentration of biogas slurry in broccoli field reduces soil fungi by 55.03% (Yang Z et al., 2017), thus significantly reducing the plant disease index. Similarly, when biogas slurry was applied to watermelon, a significant inhibitory effect on Fusarium wilt was observed, and the disease index was lowered by 36.4% compared to the control treatment (Cao Y et al., 2016b). Further analysis showed that the inhibition of basidiomycota and mortierella growth was the reason for the decrease disease index (Wang L et al., 2021a). Remarkably, root irrigation with biogas slurry effectively prevent and cure astragalus root rot, the same inhibitory effect was obtained when this was repeated many times (Sang D and Yong S, 2011). Likewise the inhibitory effect of 1.25% biogas slurry concentrate on cotton verticillium wilt by root irrigation reached 78.01% (Feng Z et al., 2018).

2.3.4.5 Prevention and control of soil acidification

Soil acidification is one of the main factors affecting agricultural productivity as well as negatively impacting the environment. Soil acidification will destroy the structure of biological cell membranes, reduce microbial activity of soil microorganisms, consequently, crop growth and productivity. Prevention and control of soil acidification is of great significance to maintaining sustainable agricultural development (Wang A et al., 2019). The consumption of biogas slurry in farmland can effectively regulate the proportion of various nutrients in the soil, enhance the ability of soil to buffer acid and alkali changes. It can reduce the pH in alkaline soil (Lin S et al., 2019) and increase the pH in acidic soil, thereby improving soil quality (Zheng X et al., 2016b; Wang K et al., 2019). Studies have shown that irrigation with biogas slurry in coastal poplar forests and coastal saline-alkali rice-wheat rotation fields cause pH reduction (Tang Y et al., 2019b; Zhu R, 2019). For instance, soil pH of alkaline paddy field treated with biogas slurry for 4 years was significantly lower than that of soil without biogas slurry application (Dong Y et al., 2021b). Compared with conventional fertilization treatment, biogas slurry application can effectively inhibit soil acidification caused by long-term application of chemical fertilizers (Sun G et al., 2021). Similarly, a 3-year field experiment was carried out on the yellow soil under rice-rape rotation as the experimental site, and it was found that the application of biogas slurry (165.1 and 182.1 t/hm^2) could increase the soil pH value (Xu M et al., 2019). Lower concentration of biogas slurry do not prevent soil acidification, while higher biogas slurry concentration inhibited the growth of acidobacteria, thereby reducing soil acidification (Wang L et al., 2021a). Likewise, long term application of biogas slurry, resulted in increasing trend of soil pH of cultivated Hongmeiren citrus. The soil pH after 4 years biogas slurry application was significantly higher than that of the conventional fertilization (Liu Y et al., 2022). Also, the application of biogas slurry in economic fruit plantation such as tea garden (Li W et al., 2021), grapefruit (Huang H et al., 2021), apple (Gao W et al., 2020) and citrus (Xi H et al., 2021) showed similar results of increasing soil pH value.

2.3.4.6 Improved microbial structure and soil enzyme activity

The role of soil organisms in underground ecological processes are vital to maintaining a healthy farmland (Cao Z, 2013). An important group of soil organisms are the microorganisms; as decomposer in the food web (Li Y et al., 2018), they occupy more than 80% of food web biomass (Li Y et al., 2021a). These microbes participate in the decomposition and synthesis of soil organic matter, the fixation and release of nutrients, and the degradation of pollutants. The impact of farmland application of biogas slurry on underground ecological processes will inevitably lead to changes in microbial community structure, metabolic characteristics and functional diversity, which in turn can be used as important indicators for the evaluation of the health of farmland.

Soil microbial biomass C/N ratio reflects the composition of soil microbial flora. The lower the microbial biomass C/N ratio, the more bacteria in the soil. Application of biogas slurry can increase the culturable quantity of soil bacteria (Feng D et al., 2014), fungi (Tang Y et al., 2021) and actinomycetes (Yu F et al., 2010) to a certain extent. In a related study, after biogas slurry application, the ratio of soil microbial biomass C/N decreased by 25.2%–48.0% (Liu Y et al., 2022). The application of biogas slurry promoted the proliferation of soil bacteria, and the activity of soil bacteria increased significantly with long-term application of biogas slurry on farmland (Chai Y et al., 2019). The ratio of bacteria and fungi (B/F) in the soil is usually used to evaluate the soil microbial flora (Sun Y et al., 2021). A high B/F value indicates that the soil is a "bacterial type" with high fertility and less damage to the soil, while a low B/F value indicates that the soil is a "fungal type" with low fertility and high damage to the soil. For instance, the treatment of biogas slurry mixed with chemical fertilizer reduced the B/F value. Increase in the concentration of biogas slurry application resulted in B/F value that initially decreased and then increased, while, the application of pure biogas slurry increased the B/F value considerably (Zheng X et al., 2015). Hence, the B/F value of soil can be kept stable or even increased by using appropriate biogas slurry, and consequently, improving the soil fertility.

Nitrogen, phosphorus, potassium, organic matter, growth hormone, humic acid, cellulose and other substances in biogas slurry can further promote the growth and enrichment of soil dominant bacteria (Lv W et al., 2011) as well as promote microbial alpha diversity by improving soil structure and increasing organic matter (Abubaker J et al., 2013; Cao Y et al., 2013b; Xu C et al., 2013; Cao Y et al., 2016a; Cao Y et al., 2016b; Wentzel S and Joergensen RG, 2016). For example, paddy soil with biogas slurry applied continuously for 6 years, campylobacter, proteus and acidobacter were the dominant bacteria, which shows that biogas slurry can improve soil microbial structure and consequently, soil quality and soil fertility (Chen Z et al., 2020). Moreover, with increase in biogas slurry concentration resulted in actinomycetes population, however, excessive biogas slurry application inhibits the growth of actinomycetes (Xu M et al., 2019; Wang L et al., 2021a). The Chao1 index and Shannon index of soil bacteria treated with 180 t/hm^2 biogas slurry were higher than those of control treatments. However, the Chao1 index of fungi was lower than that of chemical fertilizer (100 t/hm^2 and 220 t/hm^2 treatments). The application amount of biogas slurry at 180 t/hm^2 can improve the bacteria richness and diversity, while reducing the diversity of fungi (Wang L et al., 2021a).

In addition, the application of biogas slurry in farmland has a certain impact on the activities of soil animals. When the concentration of biogas slurry increased from 0 to 300m^3/hm^2, the density of soil animals increased by 94%, the number of groups increased by about 2, and the dominance index increased by 9.4% (P<0.05). When 66% of biogas slurry was used to replace chemical fertilizer, soil animal density, number of groups and dominance index were the highest. The principal component analysis showed the application of the biogas slurry alone or mixed with the chemical fertilizer, collembola, prestoma, and ortychia were the most sensitive, and they could be used as indicators of the response of small arthropods in the soil to digesting biogas slurry.

Proper application of biogas slurry in farmland can increase soil enzyme activity (see **Table 2.5**) thereby improving soil carbon and nitrogen transformation. Studies have shown that applying biogas slurry increased the activities of soil phosphatase, protease, dehydrogenase, sucrase, catalase and urease. After 4 years of biogas slurry application, the activities of the six (6) enzymes were significantly higher than those of the control (Liu Y et al., 2022).

Table 2.5 Improvement of soil enzyme activity by digested biogas slurry in farmland

Soil type	Crops	Slurry type	Total nitrogen consumption of slurry (kg/hm^2)	Years	Improvement range of soil enzyme activity		References
					Comparison with no fertilization	Comparison with conventional chemical fertilizer	
Yellow loamy paddy soil	Rice-rape	PM	157.5−694.9	3	Urease 31.8%−74.6%, catalase 4.4%−85.1%, sucrase 30.4%−228.6%	Urease 21.7−61.1%, catalase 19%−111%, sucrase 45.4%−266.4%	(Feng D et al., 2014)
Retention paddy soil	Rice-wheat	PM	210.3−540.9	3	Urease 30.5%−79.5%, protease 19.1%−41.4%, phosphatase 11.3%−29.7%, catalase 6.4%−40.1%, sucrase 0.2%−39.3%, amylase 53.1%−161.4%, cellulase 15.8%−104.8%, lactase 30.1%−65.2%	Urease 26.7%−74.8%, protease 9.1%−43.3%, phosphatase 7.3%−8.8%, catalase 14.9%−30.2%, sucrase 3%−49.4%, amylase 28%−145.7%, cellulase 38.5%−48.3%, lactase 13.3%−37.1%	(Song S, 2017)
Medium loam	Wheat	PM	60−180	1	Urease 57.5%−72.5%, protease 31.7%−62.6%	Urease 10.5%−21.1%, protease 6%−30.1%	(Guan T et al., 2010)
Red soil	Peanut	PM	36−240	2	Urease 16.2%−62.3%, dehydrogenase 48.6%−133.1%	Urease 11.3%−24.1%, dehydrogenase 33.8%−120.5%	(Zheng X et al., 2015)
Aeolian sandy soil	Grape	DM	190−1160	2	ND	Urease 41%−113.8%, phosphatase 32.4%−106.4%, sucrase 62.7%−98%	(Hao Y, 2019)
ND	Cucumber	(P+C)M	37.5−150	1	Polyphenol oxidase 13.49%−14.75%, cellulase 68.7%−71.9%, chitinase 41.0%−57.5%,	ND	(Zhang H and Wang G, 2011)
ND	Cabbage	(P+S)M	504−675	3	ND	Urease 2.4%, protease 95.4%−139.7%, phosphatase 50.5%−137.6%, invertase 55.7%−64.0%,	(Hao X et al., 2011)
Paddy soil	Citrus	(P+D)M	450	4	ND	Urease 53.8%−100.0%, protease 23.1%−100.0%, phosphatase 20.2%−42.3%, catalase 107.0%−127.5%, dehydrogenase 36.6%−96.0%, sucrase 47.4%−111.8%	(Liu Y et al., 2022)

ND: no data; PM: biogas slurry using pig manure as fermentation raw material; DM: biogas slurry using cow dung as fermentation raw material; (P+C)M: biogas slurry using pig manure and chicken manure as fermentation raw material; (P+S)M: biogas slurry using pig manure and straw as fermentation raw material; (P+D)M: biogas slurry using pig manure and cow dung as fermentation raw material.

2.4 Prospects

It is important to reduce the pollution risk of biogas slurry disposal through its valorization. There are numerous advantages of biogas slurry application as listed above. However, farmland application of biogas slurry needs to be further studied to:

1) establish fitting models for different components of biogas slurry adsorbed by soil, maximum adsorption capacity of different types of soil and environmental factors affecting soil adsorption; 2) explore the transformation and characteristics of biogas slurry components in its farmland application, the time cycle of safe application, as well as assessment of associated potential risks; 3) develop combined technologies to increase biogas slurry utilization and valorization; and 4) analyze the mechanism and microecological mechanism of biogas slurry digested in farmland to improve soil fertility, and yield to establish the theoretical and practicable application of biogas slurry on farmland.

2.5 References

Abubaker J, Cederlund H, Arthurson V, Pell M. 2013. Bacterial community structure and microbial activity in different soils amended with biogas residues and cattle slurry. *Applied Soil Ecology* 72: 171−180. https://doi.org/10.1016/j.apsoil.-2013.07.002

An J, Song Z. 2011. A preliminary study of effect of application biogas residue and biogas slurry on *Codonopsis pilosula*. *China Biogas* 29: 51–52. http://-qikan.cqvip.com/Qikan/Article/Detail?id=40354989 (accessed on 15 August 2011)

Bai X, Li Z, Yin F, Cheng S, Bai X, Zhang Y. 2015. Evaporation treatment on biogas slurry from anaerobic fermentation. *Transactions of the Chinese Society for Agricultural Machinery* 46: 164–170. https://doi.org/10.6041/j.issn.1000-1298.2015.05.022

Bi T, Hu H, Liu L, Guo D, Wang C, Zhao X, Wu K, Yang B, Yin F, Zhang W. 2020. Effect of biogas slurry application on high efficient production of walnut. *Journal of Northeast Agricultural Sciences* 45: 119–121, 128. https://doi.org/10.16423/j.cnki.1003-8701.2020.06.028

Bian B, Zhou L, Li L, Lv L, Fan Y. 2015. Risk assessment of heavy metals in air, water, vegetables, grains, and related soils irrigated with biogas slurry in Taihu Basin, China. *Environmental Science and Pollution Research* 22: 7794–7807.

https://doi.org/10.1007/s11356-015-4292-2

Cao L, Tang Q, Guo Y, Tang Y, Han J, Zhu Y. 2022. Effect of biogas slurry application on small- and medium-sized arthropods communities in coastal reclaimed wheat fields. *Acta Ecologica Sinica* 42: 646−655. https://doi.org/10.5846/stxb2020-12033088

Cao Y, Chang Z, Ma Y, Yang H, Fu G. 2013a. Control mechanism of phytophthora blight of chilli pepper by anaerobically digested pig slurry – The roles of ammonium and humic acid in biogas slurry. *Chinese Journal of Eco-Agriculture* 21: 1119−1126. https://doi.org/10.3724/SP.J.1011.2013.01119

Cao Y, Chang Z, Ma Y, Yang H, Fu G. 2013b. Effects of application of anaerobically digested slurry on suppression of pepper (*Capsicum frutescens* L.) blight and soil biological characteristics. *Scientia Agricultura Sinica* 46: 507−516. https://doi.org/10.3864/j.issn.0578-1752.2013.03.007

Cao Y, Ma Y, Wu H, Wang G, Guo D, Wang Q, Yan S. 2016a. Suppression of fusarium wilt of watermelon by biogas slurry application and its effect on soil microbiological characteristics. *Soil and Fertilizer Sciences in China* 1: 34−41. https://doi.org/10.11838/sfsc.20160106

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

Cao Y, Wu H, Guo D, Wang Q, Yan S, Wang G, Ma Y. 2015. Effect of biogas slurry application on incidence of fusarium wilt, fruit yield and quality of watermelon. *Soils* 47: 904–910. https://doi.org/10.13758/j.cnki.tr.2015.05.015

Cao Z. 2013. Future orientation of ecological agriculture. *Chinese Journal of Eco-Agriculture* 21: 29−38. http://cqvip.com/QK/97771A/201301/44558809.Html-(accessed on 06 October 2012)

Chai Y, Huang L, Dong Y, Li Y, Wang Z, Shan S, Ping L, Zhang W. 2019. Effects of biogas slurry application rates on soil physical and chemical properties and carbon storage of bamboo forest. *Transactions of the Chinese Society of*

Agricultural Engineering 35: 214−220. https://doi.org/10.11975/j.issn.1002-6819.2019.08.025

Chen B. 2010. Effect of the agricultural usage of biogas slurry on maize yield, quality and environmental quality of soil. *MScAgric dissertation, Sichuan Agricultural University, Chengdu, China*. http://cdmd.cnki.com.cn/Article/CDMD-10626-2010244613.htm (accessed on 16 April 2011)

Chen D, Jiang L, Huang H, Toyota K, Dahlgren RA, Lu J. 2013. Nitrogen dynamics of anaerobically digested slurry used to fertilize paddy fields. *Biology and Fertility of Soils* 49: 647–659. https://doi.org/10.1007/s00374-012-0752-8

Chen J, Jia L, Zhao J, Wang Y, Ren G, Yang G. 2017. Effect of spraying biogas slurry on apple yield, quality and sucrose metabolism enzyme activity. *Northern Horticulture* 18: 35–41. http://www.cqvip.com/QK/97019X/201718/67324931-0.html (accessed on 5 April 2017)

Chen N, Mao H, Chen S, Wei Y, Fang S. 2021. Effect of biogas slurry foliar spraying on leaf photosynthesis characteristics, fruit yield and quality of pepino in greenhouse. *China Cucurbits And Vegetables* 34: 88–93. https://doi.org-/10.16861/j.cnki.zggc.2021.0092

Chen S, Yu W, Zhang Z, Luo S. 2015. Soil properties and enzyme activities as affected by biogas slurry irrigation in the Three Gorges Reservoir areas of China. *Journal of Environmental Biology* 36: 513−520. http://jeb.co.in/journal_issues/201503_mar15/paper_26.pdf (accessed on 29 September 2014)

Chen Y, Dong H, Tao X, Shang B. 2011. Effect of irrigating winter wheat with anaerobic digested swine farm wastewater (ADSFW) on soil quality. *Chinese Agricultural Science Bulletin* 27: 154−158. http://www.cqvip.com/Main/Detail.aspx?id=-37292128 (accessed on 07 September 2010)

Chen Z, Wang Q, Ma J, Chapman S, Zou P, Ye J, Yu Q, Sun W, Lin H, 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: 15–25. https://doi.org/10.1007/s10333-019-00761-y

Cheng H, Zhang Y, Meng H, Shen Y, Ding J, Zhan S. 2018. Parameter optimization of preparation for biogas slurry based water-soluble liquid fertilizer containing humic acid. *Transactions of the Chinese Society of Agricultural Engineering* 34: 227–233. https://doi.org/10.11975/j.issn.1002-6819.2018.14.029

Cheng J, Chen Y, He T, Liu R, Yi M, Yang Z. 2018. Nitrogen leaching losses following biogas slurry irrigation to purple soil of the Three Gorges Reservoir Area. *Environmental Science and Pollution Research* 25: 29096–29103. https://doi.org/10.1007/s11356-018-2875-4

Cheng W, Zhang A, Cai X, Zhu J, Wang P, Li Y, Yang Y. 2018. Effects of soaking seed with biogas slurry and foliar spraying it on germination, agronomic traits and quality of watermelon. *Journal of Hebei Agricultural Sciences* 22: 34–36. https://doi.org/10.16318/j.cnki.hbnykx.2018.05.009

Chu C, Li S, Ma D, Pan Z, Cao Y. 2013. Effect of subsurface drip irrigation with aerated biogas slurry on yield and quality of Chinese chives. *China Biogas* 31: 41–47. https://doi.org/10.3969/j.issn.1000-1166.2013.02.010

Cui B, Gao F, Hu C, Li Z, Fan X, Cui E. 2019. The use of brackish and reclaimed waste water in agriculture: A review. *Journal of Irrigation and Drainage* 38: 60–68. https://doi.org/10.13522/j.cnki.ggps.20180686

Cui W, Li S, Li G, Chen Q, Li Y, Zhang B, Luo W. 2021. Current research status and perspectives on liquid organic fertilizer utilization based on concentrating biogas slurry. *Journal of Agro-Environment Science* 40: 2482–2493. https://doi.org/10.11654/jaes.2021-0996

Cui Y, Azeem M, Sun J, Zhang Z, Yang S. 2020. Effects of biogas slurry combined with chemical fertilizer on soil chemical properties and corn yield and quality. *Shandong Agricultural Sciences* 52: 77–81. https://doi.org/10.14083/j.issn.1001-4942.2020.05.015

Cui Y, Ma D, Zhao Y, Lei Q, Ding S. 2019. Impacts of biogas slurry application on growth and quality of pepper. *Jiangsu Agricultural Sciences* 47: 131–134. https://doi.org/10.15889/j.issn.1002-1302.2019.01.031

Das M, Ayyappan S, Dash B, Muduli HK. 2013. Heterotrophic bacterial populations and dehydrogenase activity in fish ponds under different fertilisation practices.

Indian Journal of Fisheries 60: 87–90. -http://eprints.cmfri.org.in/id/eprint/9599 (accessed on 30 October 2013)

Deng L, Liu Y, Zheng D, Wang L, Pu X, Song L, Wang Z, Lei Y, Chen Z, Long Y. 2017. Application and development of biogas technology for the treatment of waste in China. *Renewable and Sustainable Energy Reviews* 70: 845–851. https://doi.org/10.1016/j.rser.2016.11.265

Deng O, Jiang L, Chen D, Yang S, Lv J. 2011. Ammonia volatilization from the biogas slurry irrigation paddy field. *Journal of Soil and Water Conservation* 25: 233–236. https://doi.org/10.13870/j.cnki.stbcxb.2011.06.043

Dong Y, Liang D, Li D, Jin H. 2021a. Characteristic analysis of main nutrient content in biogas slurry. *Jiangsu Journal of Agricultural Sciences* 37: 1206–1214. https://doi.org/10.3969/j.issn.1000-4440.2021.05.016

Dong Y, Liu Y, Ye B, Jin J, Nie X, Fan Z. 2022. Effect of continuous application of biogas slurry on soil properties in tea garden. *Journal of Zhejiang Agricultural Sciences* 63: 52-55,59. https://doi.org/10.16178/j.issn.0528-9017.20212930

Dong Y, Zhou X, Ye B, Liu Y. 2021b. Effect of long-term biogas slurry application in rice field on soil chemical properties and C-N-P stoichiometry. *Journal of Zhejiang Agricultural Sciences* 62: 2398-2401.https://doi.org/10.16178/j.issn.0528-9017.20212829

Du H, Gao W, Li J, Shen S, Wang F, Fu L, Zhang K. 2019. Effects of digested biogas slurry application mixed with irrigation water on nitrate leaching during wheat-maize rotation in the North China Plain. *Agricultural Water Management* 213: 882–893. https://doi.org/10.1016/j.agwat.2018.12.012

Fan B, Ni L, Shi W. 2015. Effects of concentrated slurry fertilizers on pakchoi growth and soil quality. *Soils* 47: 868–873. https://doi.org/10.13758/j.cnki.tr.2015.05.009

Fan J, Li Y, Hu C, Li J, Zhang Z, Li D, Li W. 2022. Response of sunflower to salt and alkali stress induced by biogas slurry irrigation. *Journal of Agricultural Resource and Environment* 39: 193–200. https://doi.org/10.13254/j.jare.-2021.0609

Feng D, Wu J, Yang G, Zhang L, Zhang Y, Wang J. 2014. Influence of long-term applications of biogas slurry on microbial community composition and enzymatic activities in surface soil under rice-rape rotation. *Journal of Agro-Environment Science* 33: 1644–1651. https://doi.org/10.11654/jaes.2014.08.025

Feng Z, Dong T, Zhao L, Fu C, Li Y, Shi Y, Feng H, Wei F, Zhang D, Zhu H. 2018. The control effect and mechanism of concentrated biogas slurry on verticillium wilt of upland cotton. *Cotton Science* 30: 375–385. https://doi.org/10.11963/1002-7807.fzlzhq.20181008

Feng Z, Li P. 2018. The genesis and evolution of the concept of carrying capacity: a view of natural resources and environment. *Journal of Natural Resources* 33: 1475–1489. https://doi.org/10.31497/zrzyxb.20170967.

Fu Y. 2018. Study on the selection of biogas slurry concentration-separation process and effect of biogas slurry. *MScAgric dissertation, Inner Mongolia University of Technology, Hohhot, China*. https://cdmd.cnki.com.cn/Article/CDMD-10128-1018795510.htm(accessed on 16 December 2018)

Gao B, Wang K, Li H, Sun X, Ma J, Zhang J, Yang Z. 2022. Effects of surface application of biogas slurry and urea in different proportions on ammonia volatilization in paddy field. *Journal of Anhui Agricultural Sciences* 50: 154–157. https://doi.org/10.3969/j.issn.0517-6611.2022.01.041

Gao L, Yu X, Li R, Yang Q, Cui X, Li S, Wang P. 2017. Effects of biogas formulated manure on yield and quality of banana and soil quality. *Journal of Tropical Biology* 8: 209–215. https://doi.org/10.15886/j.cnki.rdswxb.2017.02.014

Gao M, Wang D, Wang Y, Wang X, Feng Y. 2019. Opportunities and challenges for biogas development: a review in 2013-2018. *Current Pollution Reports* 5: 25–35. https://doi.org/10.1007/s40726-019-00106-7

Gao W, Azeem M, Sun J, Zhang Z, Li J, Yang S. 2020. Influences of combined application of biogas slurry and chemical fertilizers on apple growth and soil physic-chemical properties – Taking Yantai Red Fuji apple as an example. *Jiangsu Agricultural Sciences* 48: 160–165. https://doi.org/10.15889/j.issn.1002-1302.2020.21.028

Gao X. 2019. Effects of integrated application of biogas slurry water and fertilizer instead of chemical fertilizer on greenhouse crops and soil properties. *MScAgric dissertation, Northwest A & F University, Yangling, China*. http://cdmd.-cnki.com.cn/Article/CDMD-10712-1019845671.htm (accessed on 06 August 2019)

Gao X, Kong X, Guo Y, Li J, Raza S, Chen Z. 2019. Effects of chemical fertilizers replacement by biogas slurry on yield, quality and nutrient uptake of muskmelon. *Northern Horticulture* 14: 25–31. https://d.wanfangdata.com.cn/periodical-/bfyany201914005 (accessed on 06 March 2019)

Gao Y, Qiao H, Han W, Zhao Y, Chen H. 2016. Effect of different dilution of biogas slurry on the prevention of peach leaf curl. *Northern Horticulture* 10: 112–115. http://www.cqvip.com/QK/97019X/201610/669023440.html (accessed on 25 December 2015)

Guan T, Feng W, Wang H, Wang Y, Zhu Y, Guo T. 2010. Effect of topdressing amount of biogas slurry on soil microorganisms and enzyme activities in winter wheat. *Journal of Triticeae Crops* 30: 721–726. http://www.cqvip.com/QK/96016B/2-01004/1001412009.html(accessed on 10 January 2010)

Guo Q, Gong X, Liu H. 2020. Study on effect of long-term application of biogas manure on soil nutrients and salt in protected-land vegetable field. *Acta Agriculturae Boreali-occidentalis Sinica* 29: 127–134. https://doi.org/10.7606/j.issn.1004-1389.2020.01.015

Han J, Fan D, Guo Y, Shen J, Han J. 2021. Effect of pig slurry on the availability of heavy metals in soils with different pH. *Research of Agricultural Modernization* 42: 2–9. https://doi.org/10.13872/j.1000-0275.2021.0028

Han M, Liu K, Wang S, Qin L, Gao C. 2014. Definition, ingredient, approaches and risks for reuse in biogas slurry. *Journal of Agriculture* 4: 54–57. http://www-w.cqvip.com/qk/97993a/201410/662779509.html (accessed on 12 February 2014)

Hao S, Yin S, Huang Y, Du X, Zhang L, Li S. 2012. Effects of foliar spraying of biogas slurry on the quality and yield of Huangguan pear. *China Fruits* 1: 24–26. https://doi.org/10.16626/j.cnki.issn1000-8047.2012.01.017

Hao X, Hong J, Qiao Z. 2011. Effect of biogas slurry on biological properties of cabbage continuous cropping soil. *Chinese Journal of Applied Environmental Biology* 17: 384–387. https://doi.org/10.3724/SP.J.1145.2011.00384

Hao Y. 2019. Effect of biogas slurry applying on soil quality in vineyard and grape yield and quality. *MScAgric dissertation, Gansu Agricultural University, Lanzhou, China*. https://doi.org/10.27025/d.cnki.ggsnu.2019.000125

Haraldsen TK, Andersen U, Krogstad T, Sørheim R. 2011. Liquid digestate from anaerobic treatment of source-separated household waste as fertilizer to barley. *Waste Manage* 29: 1271–1276. https://doi.org/10.1177/0734242X11411975

He M, Jiang Z, Xu J, Song B, Chen Y. 2018. Effect of biogas slurry spraying on yield and plant physiology of greenhouse melon. *Chinese Agricultural Science Bulletin* 34: 24–28. http://www.cqvip.com/QK/91831X/201811/675205700.html (accessed on 21 December 2017)

He Q, Shi M, Feng L, Ai P, Yuan Q, Yan S. 2021. Research progress of biogas slurry resourceful treatment by membrane distillation. *Transactions of the Chinese Society of Agricultural Engineering* 37: 259–268. https://doi.org/10.11975/-j.issn.1002-6819.2021.08.030

Hou F, Chen Y, Yang Z, Jin C, Shi K, Chen C, Feng G, Li H. 2019. Effects of digested pig slurry application on agronomic trait, yield and forage quality of indica rice. *Journal of Zhejiang University (Agric & Life Sci)* 45: 325–331. https://doi.org/10.3785/j.issn.1008-9209.2018.07.261

Hu Y, Cheng H, Tao S. 2017. Environmental and human health challenges of industrial livestock and poultry farming in China and their mitigation. *Environment International* 107: 111–130. https://doi.org/10.1016/j.envint.2017.07.003

Hu Z, Wan Q, Li H, Li Y, Li R, Yang Y. 2020. Effects of sprinkler irrigation with biogas slurry on tea garden soil and tea yield. *Journal of Southern Agriculture* 51: 2757–2763. https://doi.org/10.3969/j.issn.2095-1191.2020.11.019

Huang H, Cao J, Chang Z, Cao Y. 2013. Effects of digested pig slurry application on yields, nitrogen and phosphorous uptakes by rice and wheat. *Soils* 45: 412–418. https://doi.org/10.3969/j.issn.0253-9829.2013.03.005

Huang H, Wu Y, Li X, Wu R, Wu L, Jiang Q. 2018. Measurement of nutrient content, heavy metal and antibiotic residue in livestock and poultry manure of Ningxia farm and safety evaluation analysis. *Journal of Agricultural Sciences* 39: 1–8. https://doi.org/10.13907/j.cnki.nykxyj.2018.02.001

Huang H, Zhuang H, Zhang C, Dang H, Ping L, Zhang C, Fan Z, Shan S. 2021. Effects of biogas slurry substituting for chemical fertilizer on soil fertility and quality of citrus Changshan-huyou. *Journal of Zhejiang Agricultural Sciences* 62: 324–329. https://doi.org/10.16178/j.issn.0528-9017.20210227

Huang J, Peng Z, Xu P, Tu Y, Yang L, Wu X, Lin Z. 2016a. Effects of paddy field disposal of biogas slurry on rice production, soil fertility and environmental safety. *Guangdong Agricultural Sciences* 43: 69–76. https://doi.org/-10.16768/j.issn.1004-874X.2016.10.013

Huang J, Wu Z, Gao L, Tang X, Ma Y, Zheng B. 2013. Effects of biogas slurry on soil quality and yield quality of Chinese cabbage. *Journal of Anhui Agricultural University* 40:849–854. https://doi.org/10.13610/j.cnki.1672-352x.2013.05.024

Huang J, Xu P, Peng Z, Yu J, Tu Y, Yang L, Wu X, Lin Z. 2016b. Biogas slurry use amount for suitable soil nutrition and biodiversity in paddy soil. *Journal of Plant Nutrition and Fertilizer* 22: 362−371. https://doi.org/10.11674/zwyf.14503

Huang L, Lou R, Xu Y, Li J, Zhu Y. 2014. Preliminary study on insect repellent and disease control effect of biogas fertilizer on rice. *China Biogas* 32: 79–82. https://doi.org/10.3969/j.issn.1000-1166.2014.06.018

Huo C, Wu S, Guo J, Cheng H, Ren H, Dong R, Pang C. 2011. Analysis of phytohormone and qunolin-ketone components in anaerobic digestion effluent. *China Biogas* 29: 7–10. https://www.cnki.com.cn/Article/CJFDTOTAL-ZGZQ201105003.htm(accessed on 23 May 2011)

Jain S, Jain S, Wolf IT, Lee J, Tong YW. 2015. A comprehensive review on operating parameters and different pretreatment methodologies for anaerobic digestion of municipal solid waste. *Renewable and sustainable energy reviews* 52: 142–154. https://doi.org/10.1016/j.rser.2015.07.091

Jia L, Zhao J, Yang C, Liu L, Chen J, Yang G, Ren G. 2017. Effect of topdressing biogas fertilizer on growth, yield and quality of tomato. *Acta Agriculturae Boreali-occidentalis Sinica* 26: 897–905. https://doi.org/10.7606/j.issn.1004-1389.2017.06.013

Jiang H, Wang Z, Li Z, Li B. 2007. Effects of firedamp liquid on yield and quality of tomato, radish, celery and China bean. *Guizhou Agricultural Sciences* 35: 99–100. https://doi.org/10.3969/j.issn.1001-3601.2007.02.038

Jiang L, Wang Q, Chen D, Li A, Qian S, Fu J, Wang J. 2011. Effects of paddy field disposal of biogas slurry on the rice production, soil quality and environmental safety. *Journal of Agro-Environment Science* 30: 1328–1336. https://d.wanfangdata.com.cn/periodical/nyhjbh201107011 (accessed on 06 January 2011)

Jiang T, Wang L, Sun F, Cheng J, He T, Qin S, Fan C, Yin W. 2021. Effects of solid-digestate biochar application on soil nitrogen leaching and cabbage yield with liquid-digestate irrigation in karst-mountainous region of southwest China. *Acta Agriculturae Zhejiangensis* 33: 2104–2115. https://doi.org/10.3969/j.issn.1004-1524.2021.11.13

Jin H, Chang Z, Wu H, Guo D, Huang H, Ma Y, Xu Y, Zhang J. 2013. NH3 and N2O emission and nitrogen loss rate from biogas liquid produced by pig slurry after topdressing on vegetable fields. *Journal of Plant Nutriton and Fertilizer* 19: 1155–1165. https://doi.org/10.11674/zwyf.2013.0515

Jin H, Chang Z, Ye X, Ma Y, Zhu J. 2011. Physical and chemical characteristics of anaerobically digested slurry from large-scale biogas project in Jiangsu Province. *Transactions of the CSAE* 27. https://doi.org/10.3969/j.issn.1002-6819.2011.01.047

Jin H, Fu G, Chang Z, Ye X, Chen G, Du J. 2012. Distribution of nitrogen in liquid and solid fraction of pig and dairy manure in anaerobic digestion reactor. *Transactions of the Chinese Society of Agricultural Engineering* 28: 208–214. http://qikan.cqvip.com/Qikan/Article/Detail?id=43900673(accessed on 30 May 2012)

Jing D, Chen Y, Dai C, Li P. 2016. Research situation and prospect of biogas slurry utilization in fish culture. *Hubei Agricultural Sciences* 55: 5886–5890. https://doi.org/10.14088/j.cnki.issn0439-8114.2016.22.040

Kang L, Zhao Z, Qu M, Chen Q. 2011. Effects of biogas waste on solanaceae vegetable growth and soil nutrient accumulation in greenhouse. *China Vegetables* 22/24: 57–62. https://www.cnki.com.cn/Article/CJFDTotalZGSC2011Z1017.htm (acc-essed on 10 October 2010)

Kang X, Zheng Y, Li Q. 2019. Effects of combined use of biogas slurry and nitrogen fertilizer on yield and quality of Taraxacum mongolicum. *Journal of Changjiang Vegetables* 16: 74–77.https://d.wanfangdata.com.cn/periodical/cjsc 201916026(accessed on 29 March 2019)

Ke L, Liu X, Du B, Wang Y, Zheng Y, Li Q. 2022. Component analysis and risk assessment of biogas slurry from biogas plants. *Chinese Journal of Chemical Engineering* 44: 182–191. https://doi.org/10.1016/j.cjche.2021.05.039

Lai X, Wu J, Wang J, Xu M, Mao X, Li Y. 2018. The long-term effects of biogas slurry on soil properties and potential risks of heavy metals in soils. *Journal of Soil and Water Conservation* 32: 359–364. https://doi.org/10.13870/j.cnki.stbcxb.20-18.06.052

Lang L. 2017. Study on the effect of ecological filter – constructed wetland combined process on waste biogas slurry. *MScAgric dissertation, Anhui Agricultural University, Hefei, China*. https://cdmd.cnki.com.cn/Article/CDMD-10364-1017256026.htm

Li C, Qu Z, Gou M, Su Y, Huo X. 2014. Effects of biochar amendment on soil water and nutrient utilization efficiencies and tomato growth. *Journal of Agro-Environment Science* 33: 2187–2193. https://doi.org/10.11654/jaes.2014.11.017

Li H, Luo N, Ma J, Li N, Chen X, Shen A, Guo B, Fu Q. 2019a. Effect of biogas slurry irrigation on farmland soils and environment. *Journal of Zhejiang Agricultural Sciences* 60: 1317–1321. https://doi.org/10.16178/j.issn.0528-9017.20190814

Li H, Tan F, Ke L, Xia D, Wang Y, He N, Zheng Y, Li Q. 2016. Mass balances and distributions of C, N, and P in the anaerobic digestion of different substrates and relationships between products and substrates. *Chemical Engineering Journal* 287: 329–336. https://doi.org/10.1016/j.cej.2015.11.003

Li H, Wang Y, Sun G, Li T. 2019b. Study on the correlation between fertilization and quality and yield of flat peach. *Shihezi Science and Technology* 2: 1–7. https://doi.org/10.3969/j.issn.1008-0899.2019.02.001

Li J, Jiang H. 2016. The effect of biogas manure on the growth of the seedling of Dendrobium officinale KimuraetMigo. *Ningxia Journal of Agriculture and Forest Science and Technology* 57: 48–49. https://doi.org/10.3969/j.issn.1002-204X.2016.09.020

Li J, Sun J, Yang L, Azeem M, Zhang Z, Yang S. 2021. Effects of excessive biogas slurry returning on soil environmental capacity and maize growth. *Journal of Henan Agricultural Sciences* 50: 49–56. https://doi.org/10.15933/j.cnki.1004-3268.2021.05.007

Li S. 2011. Nitrogen dynamics in paddy field after irrigation of biogas slurry and its impact on the environment. *MScAgric dissertation, Zhejiang University, Hangzhou, China*. http://cdmd.cnki.com.cn/article/cdmd-10335- 1011052437.-htm (accessed on 19 January 2011)

Li S, Liu J, Xia Y, Sun Z. 2014. Effects of biogas slurry application patterns on the nutrient absorption of pakchoi and substrate environment. *Acta Agriculturae Shanghai* 30: 68–72. https://doi.org/10.3969/j.issn.1000-3924.2014.02.017

Li W, Hu C, Yang L, Wang H, Liu X, Li S. 2021. Effects of biogas slurry on tea plantation soil nutrients and tea quality. *Journal of Hubei Polytechnic University* 37: 17–22. https://doi.org/10.3969/j.issn.2095-4565.2021.02.005

Li X, Yang J, Wang C, Bai G, You L, Yi Y, Huang F, Li B, Zeng P. 2015. Effects of pig manure applications on ammonia volatilization in soil during rice season in Chengdu Plain. *Journal of Agro-Environment Science* 34: 2236–2244. https://doi.org/10.11654/jaes.2015.11.028

Li Y, Chen Y, Li J, Sun Q, Li J, Xu J, Liu B, Lang Q, Qiao Y. 2021a. Organic management practices enhance soil food web biomass and complexity under greenhouse conditions. *Applied Soil Ecology* 167: 104010. https://doi.org-/10.1016/j.apsoil.2021.104010

Li Y, Li J, Li J, Yang H. 2018. Effects of different management practices on microbial biomass carbon and protozoa abundance under greenhouse conditions. *Soils* 50:

696−704. https://doi.org/10.13758/j.cnki.tr.2018.04.007

Li Y, Liu B, Xu J, Li J, Lang Q, Qiao Y, Sun Q. 2020. Effects of soil flooding of biogas slurry on root-knot nematode (Meloidogyne spp.) and soil nematode community. *Chinese Journal of Eco-Agriculture* 28: 1249−1257. https://doi.org/10.13930/-j.cnki.cjea.200099

Li Y, Xu J, Liu B, Sun Q, Li J, Liu J, Lang Q, Sun R, Jin H. 2021b. Effects of different biogas slurries on soil microbial carbon metabolism. *Chinese Journal of Eco-Agriculture* 29: 1921−1930. https://doi.org/10.12357/cjea.20210274

Liang F, Cui Q, Tu T, Yu G, Wang W, Yan S. 2018. Benign treatment of biogas slurry and improvement in lettuce quality using hydroponics. *Journal of Agro-Environment Science* 37: 788–795. https://doi.org/10.11654/jaes.2017-1261

Lin S, Ling W, Sun Q, Han J, Li P. 2019. Effects of biogas slurry application on purple cabbage growth and the soil properties in coast saline-alkali land. *China Biogas* 37: 80–87. https://doi.org/10.3969/j.issn.1000-1166.2019.01.016

Liu C, Zheng Y, Liu S, Liu Q, Yan L. 2021. Effects of biogas slurry application on nitrogen loss soil in black soil area during the autumn fallow period. *Journal of Agro-Environment Science* 40: 2528–2536. https://doi.org/10.11654/jaes.2021-1022

Liu J. 2013. Biogas slurry coupled with other source of manure application reseach in culthure of organic ground substance. *MScAgric dissertation, Henan Agricultural University, Zhengzhou, China* doi:10.7666/d.Y2432256. https://doi.org/10.7666/d.Y2432256

Liu J, Li Y, Tian P, Li K, Ge X. 2018. Preparation and function of medicine and fertilizer integrated aqua based on berberine and biogas slurry. *Science and Technology of Food Industry* 39: 309–313. https://doi.org/10.13386/j.issn1002-0306.2018.19.054

Liu M, Wang H, Wang Y, Luan B, Chen M. 2019. Field control effects of mixed application of pesticides fertilizer. *Agrochemicals* 58: 929–931. https://doi.-org/10.16820/j.cnki.1006-0413.2019.12.022

Liu X, Wang L, Wu D, Luo X, Dong R, Shao L. 2018. Effects of long-term application of biogas slurry on soil and products. *China Biogas* 36: 87–91.

https://doi.org/10.3969/j.issn.1000-1166.2018.02.015

Liu Y, Luo G, Ye Z, Wu J, Ye B. 2022. Effect of biogas slurry application on Hongmeiren fruit quality and soil fertility. *Journal of Zhejiang Agricultural Sciences* 63: 86–89, 93. https://doi.org/10.16178/j.issn.0528-9017.20213121

Lou M, Jin H, Liang D, Zhu Y, Zhu N, Li D. 2022. Fluorescence spectra characteristics of dissolved organic matter in mesophilic anaerobic digestion of pig and dairy manure slurries. *Spectroscopy and Spectral Analysis* 42: 141–146. https://doi.org/10.3964/j.issn.1000-0593(2022)01-0141-06

Lu G, Yang F, Chen H, Du T. 2021. Research progress on application of biogas slurry. *Soil and Fertilizer Sciences in China* 1: 339–345. https://doi.org/-10.11838/sfsc.l673-6257.19611

Lu G, Yang F, Wang H, Du T, Zheng J, Xing H. 2019. Effects of biogas slurry soaking seeds on seed germination and physiological characteristics of Astragalus membranaceus var. mongholicus seedling. *Soil and Fertilizer Sciences in China* 5: 155–162. https://doi.org/10.11838/sfsc.1673-6257.18434

Luján-Facundo MJ, Iborra-Clar MI, Mendoza-Roca JA, Also-Jesús M. 2019. Alternatives for the management of pig slurry: phosphorous recovery and biogas generation. *Journal of Water Process Engineering* 30: 100473. https://doi.org/10.1016/j.jwpe.2017.08.011

Luo L. 2010. Effects of concentrated biogas slurry application combined with chemical fertilizers on rice and rape yield and quality. *MScAgric dissertation, Zhejiang A&F University, Hangzhou, China*. http://cdmd.cnki.com.cn/Article/CDMD-10341-1011026892.htm(accessed on 09 June 2010)

Lv W, Wu J, Gou S, Yang G, Wang L, Chen J. 2011. The research of biogas slurry on yield and safety. *Applied Mechanics and Materials* 71-78: 3142−3146. https://doi.org/10.4028/www.scientific.net/AMM.71-78.3142

Ma D, Chu C, Li S, Bi Y, Zhang L. 2017. Effects of underground drip irrigation with biogas slurry and aeration after irrigation on tomato yield and quality. *Agricultural Engineering Technology* 37: 18–19. https://doi.org/10.16815/j.cnki.11-5436/s.2017.08.012

Ma H. 2014. Antibiotic residue and human health - Be on guard against the abuse of antibiotics in poultry farming. *Capital Medicine* 23: 23–24. http://med.wanfangdata.com.cn/Paper/Detail/PeriodicalPaper_sdyy201423008 (accessed on 21 January 2015)

Ma X, Tao Z. 2019. Effects of biogas slurry spraying on the pest and yield of cabbage. *China Biogas* 37: 90−92. https://doi.org/10.3969/j.issn.1000-1166.2019.03.015

Ma Y, Ding J, Zhao L, Meng H, Shen Y, Cheng H, Wang J. 2018. Advances in recycling and reuse of nitrogen from biogas slurry. *Environmental Pollution and Control*40: 339–344. https://doi.org/10.15985/j.cnki.1001-3865.2018.03.020

Martines AM, Nogueria MA, Santos CA, Nakatani AS, Andrade CA, Coscione AR, Cantarella H, Sousa JP, Cardoso EJBN. 2010. Ammonia volatilization in soil treated with tannery sludge. *Bioresource technology* 101: 4690–4696. https://doi.org/10.1016/j.biortech.2010.01.104

Min YY, Toyota K, Sato E, Takada A. 2011. Effects of anaerobically digested slurry on Meloidogyne incognita and Pratylenchus penetrans in tomato and radish production. *Applied and Environmental Soil Science* 2011: 1−6. https://doi.org/10.1155/2011/528712

Möller K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development* 35: 1021−1041. https://doi.org/10.1007/s13593-015-0284-3

Moreno-García B, Guillén M, Quílez D. 2017. Response of paddy rice to fertilization with pig slurry in northeast Spain :Strategies to optimize nitrogen use efficiency. *Field Crops Research* 208: 44–54. https://doi.org/10.1016/j.fcr.2017.01.023

Nag R, Auer A, Markey BK, Whyte P, Nolan S, O'Flaherty V, Russell L, Bolton D, Fenton O, Richards K et al. 2019. Anaerobic digestion of agricultural manure and biomass - Critical indicators of risk and knowledge gaps. *Science of The Total Environment* 690: 460–479. https://doi.org/10.1016/j.scitotenv.2019.-06.512

Nag R, Whyte P, Markey BK, O'Flaherty V, Bolton D, Fenton O, Richards

KG,Cummins E. 2020. Ranking hazards pertaining to human health concerns from land application of anaerobic digestate. *Science of The Total Environment* 710: 136297. https://doi.org/10.1016/j.scitotenv.2019.136297

Nicholson F, Bhogal A, Cardenas L, Chadwick D, Misselbrook T, Rollett A, Taylor M, Thorman R, Williams J. 2017. Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. *Environmental Pollution* 228: 504–516. https://doi.org/10.1016/j.envpol.2017.-05.023

Niyungeko C, Liang X, Liu C, Zhou J, Chen L, Lu Y, Tiimub BM, Li F. 2020. Effect of biogas slurry application on soil nutrients, phosphomonoesterase activities, and phosphorus species distribution. *Journal of Soils and Sediments* 20: 900−910. https://doi.org/10.1007/s11368-019-02435-y

Nzila A. 2018. Biodegradation of high-molecular-weight polycyclic aromatic hydrocarbons under anaerobic conditions: Overview of studies, proposed pathways and future perspectives. *Environmental Pollution* 239: 788–802. https://doi.org/10.1016/j.envpol.2018.04.074

Odlare M, Arthurson V, Pell M, Svensson K, Nehrenheim E, Abubaker J. 2011a. Land application of organic waste - Effects on the soil ecosystem. *Applied Energy* 88: 2210−2218. https://doi.org/10.1016/j.apenergy.2010.12.043

Odlare M, Nehrenheim E, Ribé V, Thorin E, Gavare M, Grube M. 2011b. Cultivation of algae with indigenous species - Potentials for regional biofuel production. *Applied Energy* 88: 3280–3285. https://doi.org/10.1016/j.apenergy.2011.-01.006.

Ovejero J, Ortiz C, Boixadera J, Serra X, Ponsá S, Lloveras J, Casas C. 2016. Pig slurry fertilization in a double-annual cropping forage system under sub-humid Mediterranean conditions. *European Journal of Agronomy* 81: 138–149. https://doi.org/10.1016/j.eja.2016.09.005

Qi B, Wang H, Li J, Jiang X, Li R, Wang W. 2021. Fertilizer efficiency and safety of liquid digestate membrane concentrate based fertilizer on pakchoi (Brassica chinensis L.). *Southwest China Journal of Agricultural Sciences* 34: 89–93.

https://doi.org/10.16213/j.cnki.scjas.2021.1.013

Qian M, Wu H, Wang J, Zhang H, Zhang Z, Zhang Y, Lin H, Ma J. 2016. Occurrence of trace elements and antibiotics in manure-based fertilizers from the Zhejiang Province of China. *Science of The Total Environment* 559: 174–181. https://doi.org/10.1016/j.scitotenv.2016.03.123

Qiao F, Xiao Y, Zhao S. 2018. Consecutive application of biogas manure affects maize production and soil chemical properties in Hailin farm. *Chinese Agricultural Science Bulletin* 34: 93–98. http://www.cqvip.com/QK/91831X/201836/-6100080027.html (accessed on 01 September 2018)

Qin W, Egolfopoulos FN, Tsotsis TT. 2001. Fundamental and environmental aspects of landfill gas utilization for power generation. *Chemical Engineering Journal* 82: 157–172. https://doi.org/10.1016/S1385-8947(00)00366-1

Ran Y, Wu Y, Xu L, Liang F, Yan S. 2020. Growth performance of rice at the tillering stage after applying CO2-rich biogas slurry. *Journal of Agricultural Resources and Environment* 37: 202–208. https://doi.org/10.13254/j.jare.2019.0089

Robles Á, Aguado D, Barat R, Borrás L, Bouzas A, Giménez JB, Martí N, Ribes J, Ruano MV, Serralta J et al. 2020. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the circular economy. *Bioresource Technology* 300: 122673. https://doi.org/10.1016/j.biortech.2019.122673

Rodriguez-Navas C, Björklund E, Halling-Sørensen B, Hansen M. 2013. Biogas final digestive byproduct applied to croplands as fertilizer contains high levels of steroid hormones. *Environmental Pollution* 180: 368–371. https://doi.org/-10.1016/j.envpol.2013.05.011

Ruan R, Tu R, Li Y, Hu H, Wu J. 2021. Study on the response of the stability of red soil aggregates to chemical fertilizer mixture with biogas slurry in dryland farming. *Soil and Fertilizer Sciences in China* 4: 26−32. https://doi.org/10.11838/-sfsc.1673-6257.20234

Sang D, Yong S. 2011. Field test report on controlling root rot of Astragalus membranaceus with biogas slurry and biogas residue. *China Biogas* 29: 55–56. https://doi.org/10.3969/j.issn.1000-1166.2011.04.016

Shahbaz M, Akhtar MJ, Ahmed W, Wakeel A. 2014. Integrated effect of different N-fertilizer rates and bioslurry application on growth and N-use efficiency of okra (Hibiscus esculentus L.). *Turkish Journal of Agriculture and Forestry* 38: 311–319. https://doi.org/10.3906/tar-1303-65

Shang B, Tao X, Chen Y, Dong H, Huang H. 2011. Inhibitory effect of biogas slurry of cattle manure on vegetable pathogens. *Journal of Agro-Environment Science* 30: 753–760. http://www.cqvip.com/QK/71135X/201107/37546934.html (accessed on 25 August 2010)

Shao W, Ji L, Sun C, Jiang X, Wen T, Tang J, Zhang A. 2017. Effects of application rate of biogas slurry on growth, grain yield and heavy metals contents of rice. *Acta Agriculturae Zhejiangensis* 29: 1963–1969. https://doi.org/10.3969/j.issn.1004-1524.2017.12.02

Sheets JP, Yang L, Ge X, Wang Z, Li Y. 2015. Beyond land application: Emerging technologies for the treatment and reuse of anaerobically digested agricultural and food waste. *Waste Management* 44: 94–115. https://doi.org/10.1016/-j.wasman.2015.07.037

Shen A, Xi H, Jiang M, An W, Wang Y, Chen X. 2019. Establishment and operation effect of ecological recycling model of biogas slurry from livestock. *Journal of Zhejiang Agricultural Sciences* 60: 1271–1274. https://doi.org/10.16178/j.-issn.0528-9017.20190801

Shen Q, Shan S, Zhou J, Wang Z. 2014. Determination and analysis of compositions in biogas alurry produced by swine manure digestion. *China Biogas* 32: 83–86. http://www.cqvip.com/qk/90336x/201403/50110248.html (accessed on 24 March 2013)

Shi L, Liu J, Wei Y, Li B, Xue Y, Bi Z. 2019. Current status of resource utilization of biogas slurry in agriculture. *Chinese Agricultural Science Bulletin* 35: 109–117. https://www.cnki.com.cn/Article/CJFDTotal-ZNTB201935018.htm(accessed on 13 August 2018)

Sommer SG, Génermont S, Cellier P, Hutchings NJ, Olesen JE, Morvan T. 2003. Processes controlling ammonia emission from livestock slurry in the field.

European journal of agronomy 19: 465–486. https://doi.org/10.1016/S1161-0301(03)00037-6

Song B, Cao X, Ma H, Mu X, Wu L, Zhang C, Shi H, Ma C. 2016. Effect of spraying biogas slurry on fruit quality of hami melon. *Tianjing Agricultural Sciences* 22: 11–14. https://doi.org/10.3969/j.issn.1006-6500.2016.09.003

Song C, Shan S, Zhang M, Wen X. 2011. Concentration and determination of composition of biogas slurry. *Transactions of the CSAE* 27: 256–259. https://doi.org/10.3969/j.issn.1002-6819.2011.12.048

Song D, He Z, Dong Y, Dai W, Yang X, Cao L, Sha Z. 2020. Nitrogen losses and Cu, Pb changes of paddy field affected by adding duckweed under biogas slurry application. *Chinese Journal of Eco-Agriculture* 28: 608–618. https://doi.org/-10.13930/j.cnki.cjea.190825

Song S. 2017. Effects of biogas manure on crop growth and soil microbial properties under rice-wheat rotation system in Chengdu plain. *DScAgric dissertation, Sichuan Agricultural University, Chengdu, China*. http://cdmd.cnki.com.cn/-Article/CDMD-10626-1018071320.htm(accessed on 16 November 2018)

Song Y, Wang G, Li R, G C. 2021. Research progress of biogas slurry treatment and resource utilization. *Transactions of the Chinese Society for Agricultural Engineering* 37: 237–250. https://doi.org/10.11975/j.issn.10026819.2021.12.-028

Song Z, Song Z, Shan S. 2011. Particle fractionation and organic carbon content in coastal saline soils with natural fallow and pig slurry amendments. *Journal of Zhejiang A&F University* 28: 214–218. https://doi.org/10.3969/j.issn.2095-0756.2011.02.007

Sui H, Chen X, Qin N, Wang G, Xu K, Ai P. 2016. Effects of drip irrigation with biogas slurry on yield and quality of tomato and physical and chemical properties of soil. *Shandong Agricultural Sciences* 48: 80–84. https://doi.org/10.14083/j.issn.1001-4942.2016.02.019

Sun G, Wang X, Sheng J, Zhang L, Wang Z, Zhou W. 2021. Rice quality and nitrogen use efficiency under long-term application of pig manure or biogas slurry.

Journal of Agro-Environment Science 40: 2521−2527. https://doi.org/10.11654/jaes.2021-1023

Sun T, Wang P, Chen X, Cai Y, Ren L, Lv Z. 2020. Effects of liquid bacterial fertilizer prepared by biogas slurry from food waste digesting on physical and chemical properties of farmland Soil. *Environmental Engineering* 38: 201-206. https://doi.org/10.13205/j.hjgc.202008033

Sun Y, Wang S, Qiu X, Wang J. 2021. Progress of biogas slurry drip irrigation technology. *China biogas* 39: 68–73.http://qikan.cqvip.com/Qikan/Article/Detail?id=7106483997 (accessed on 16 March 2021)

Tan F, Wang Z, Zhouyang S, Li H, Xie Y, Wang Y, Zheng Y, Li Q. 2016. Nitrogen and phosphorus removal coupled with carbohydrate production by five microalgae cultures cultivated in biogas slurry. *Bioresource Technology* 221: 385–393. https://doi.org/10.1016/j.biortech.2016.09.030

Tang W, Wu J, Sun B, Yang G, Yang Q. 2010. Effects of application amounts of biogas slurry on yield and quality of rice. *Journal of Agro-Environment Science* 29: 2268–2273. http://www.cqvip.com/QK/71135X/201107/36464981.html (accessed on 19 May 2010)

Tang Y, Luo L, Carswell A, Misselbrook T, Shen J, 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: 143786. https://doi.org/10.1016/j.scitotenv.2020.143786

Tang Y, Wang L, Wu D, Dai C, Han J. 2019a. Assessment of heavy metal pollution and bearing capacity estimation of continuous biogas slurry application on cropland: A case study of the coastal rice-wheat rotated farmland in Jiangsu, China. *China Environmental Science* 39: 1687–1695. https://doi.org/10.19674/j.cnki.issn1000-6923.2019.0204

Tang Y, Wen G, Li P, Cheng D, Han J. 2019b. Effects of biogas slurry application on crop production and soil properties in a rice-wheat rotation on coastal reclaimed farmland. *Water, Air and Soil Pollution* 230: 1–13. https://doi.org/10.1007/-s11270-019-4102-4

Tian Y, He F, Yin B, Zhu Z. 2007. Ammonia volatilization from paddy fields in the Taihu lake region as affected by N and P combination in fertilization. *Acta Pedologica Sinica* 44: 893–900. http://cqvip.jskjwx.org/article/detail.aspx?id= 25442262(accessed on 10 May 2006)

Tigini V, Franchino M, Bona F, Varese GC. 2016. Is digestate safe? A study on its ecotoxicity and environmental risk on a pig manure. *Science of The Total Environment* 551-552: 127–132. https://doi.org/10.1016/j. scitotenv.2016.02.004

Tong W, Zhou X, Liu Y, Ye Q, Qin T, Nie X, Li Z, Chai Y. 2019. Application prospect and potential environmental effects of mixed application of biogas slurry concentrate and crude wood vinegar in farmland. *Journal of Zhejiang Agricultural Sciences* 60: 2127–2131. https://doi.org/10.16178/j.issn.0528-9017.20191162

Wan J, Fu Y, Deng M, Yu X, Wang J. 2017. Treatment of hogpen biogas slurry by A/O-SBBR-oxidation pond constructed wetlands. *Industrial Water Treatment* 37: 101–104. http://www.cqvip.com/qk/95815x/20178/673012906.html (accessed on 07 June 2017)

Wang A, Zhao X, Sun L, Li H, Luo X. 2019. Effect of soil conditioner of biogas slurry on acid soil improvement in Jiaodong area. *China Biogas* 37: 98–102. http://www.cnki.com.cn/Article/CJFDTotal-ZGZQ201904016.html (accessed on 20 November 2018)

Wang C. 2010. Effect of spraying biogas and KH2PO4 on the leaves photosynthetic characteristics and fruit quality of nectarine (Prunes per sick var. Nectarina Maxim). *MScAgric dissertation, Gansu Agricultural University, Lanzhou, China*. http://cdmd.cnki.com.cn/Article/CDMD-10733-1011026398.html (acc-essed on 16 May 2011)

Wang D, Zheng X, Liu C, Chen J, Liu L, Wu X, Yan Y. 2018. Preliminary study on the correction technology of yellow leaves of spring shoots of Citrus "red beauty". *Journal of Zhejiang Agricultural Sciences* 59: 207–209. https://doi.org/-10.16178/j.issn.0528-9017.20180215

Wang G, Kou X, Zhang J, Wang S, Xu R, Han G, Tang H, Zhu L, Bi J, Wu L. 2018.

Effect of chemical fertilizer nitrogen substitution by biogas slurry on the growth and quality of rice. *Chinese Journal of Ecology* 37: 2672–2679. https://doi.org/10.13292/j.1000-4890.201809.017

Wang H, Wang E, Wang Y, Luan B, Wang P, Chen M. 2019. The field control effects of the mixture of chicken manure and fluridamide on Aphis citricola. *China Fruits* 6: 83–86. https://doi.org/10.16626/j.cnki.issn1000-8047.2019.06.018

Wang H, Xu Y, Zhou S, Qu Y. 2013. Effect of different concentration of biogas slurry on growth and quality of Ipomoea aquatic floating cultured in solar greenhouse. *Journal of Shenyang Agricultural University* 44: 650–655. https://doi.org/-10.3969/j.issn.1000-1700.2013.05.026

Wang H, Zhang Z. 2006. Application of liquid biogas residue in agricultural production. *Shanxi Journal of Agricultural Sciences* 3: 89–91. http://qikan.cqvip.com-/Qikan/Article/Detail?id=21940879(accessed on 30 May 2005)

Wang J, Wang Y, Yin J, Zhang J, Zhang Y, Tang J, Wu D. 2019. Effects of short-term biogas slurry returning on wheat yield and soil physiochemical properties. *Journal of Henan Institute of Science and Technology (Natural Science Edition)* 47: 5–9.https://d.wanfangdata.com.cn/periodical/hnzjsyxb201904002 (accessed on 30 May 2019)

Wang K, Xu Y, Dai H, Lian M, Xiang X, Zong D, Ju J, Shu J. 2019. Application of biogas slurry in soil improvement. *Jiangsu Agricultural Sciences* 47: 299–303. https://doi.org/10.15889/j.issn.1002-1302.2019.24.066

Wang L, Wang G, Wang H, Zhou G, Zhao C, Wang P, Jiang S. 2021a. Effects of applying biogas slurry instead of chemical fertilizer on the growth of melon and soil microorganism. *Journal of Southern Agriculture* 52: 2498–2506. https://doi.org/10.3969/j.issn.2095-1191.2021.09.020

Wang L, Ye X, Du J, Zhang Y, Lin J, Xi Y, Kong X. 2021b. Effects of different application methods of biogas slurry on pear orchard soil and pear fruit yield and quality. *Jiangsu Agricultural Sciences* 49: 138–143. https://doi.org-/10.15889/j.issn.1002-1302.2021.20.021

Wang W, Chen C, Qiu Z, Wu J, Wang W, Cao W, Du L, Bian X. 2014. Effects of application amounts of biogas slurry on rice growth and the balance of nitrogen, phosphorus in soil system. *Crops* 3: 85–91. https://doi.org/10.16035/j.issn.-1001-7283.2014.03.022

Wang W, Wei J, Ma W, Yang Y, Guo C. 2010. Effect of nitrogen amendment and straw-stubble input on accumulation of soil organic matter in typical farmlands of Huang-Huai-Hai Plain. *Acta Ecologica Sinica* 30: 3591−3598. http://www.-cnki.com.cn/Article/CJFDTotal-STXB201013026.htm (accessed on 15 November 2009)

Wang X, Liu Y, Shi Q, Liu D. 2013. Effect of drip irrigation with biogas slurry on yield and quality of processing tomato. *China Biogas* 31: 59–62. https://doi.org-/10.3969/j.issn.1000-1166.2013.06.015

Wang X, Sun Z, He J, Jiao B. 2018. Research on the effect of drip irrigation of biogas slurry improved alkaline-saline soil in Gansu. *China Rural Water and Hydropower* 3: 55–58, 61. http://www.cqvip.com/QK/91883A/201803/674842-076.html (accessed on 26 September 2017)

Wang X, Yan X, Li X. 2021. Environmental safety risk for application of anaerobic fermentation biogas slurry from livestock manure in agricultural land in China. *Scientia Agricultura Sinica* 54: 110–139. https://doi.org/10.3864/j.issn.0578-1752.2021.01.009

Wang Y. 2010. Research on the use of farmland disposal technology by biogas slurry and soil environmental effects. *MScAgric dissertation, Zhejiang Normal University, Hangzhou, China*. https://doi.org/10.7666/d.y1804349

Wang Y. 2018. Effects of irrigation intensity of biogas slurry on soil and plant nutrient and heavy metal content. *MScAgric dissertation, Guangxi University, Nanning, China*. https://doi.org/10.7666/d.Y3435188

Wang Y, Dong H, Zhu Z, Gerber PJ, Xin H, Smith P, Opio C, Steinfeld H, Chadwick D. 2017. Mitigating greenhouse gas and ammonia emissions from swine manure management：A system analysis. *Environmental Science & Technology* 51: 4503–4511. https://doi.org/10.1021/acs.est.6b06430

Wang Y, Dong H, Zhu Z, Li L, Zhou T, Jiang B, Xin H. 2016. CH4, NH3, N2O and NO emissions from stored biogas digester effluent of pig manure at different temperatures. *Agriculture, Ecosystems and Environment* 217: 1–12. https://doi.org/10.1016/j.agee.2015.10.020

Wang Z. 2018. Effect of underground drip irrigation with biogas slurry on yield and quality of cucumber. *Agricultural Engineering Technology* 38: 15–16. https://doi.org/10.16815/j.cnki.11-5436/s.2018.02.010

Wang Z, Guan Y, Sheng J, Liang Y, Wu H, Chen L, Zheng J. 2015a. Effects of biogas slurry application on paddy field water nitrogen content at tillering stage. *Chinese Journal of Eco-Agriculture* 23: 1544–1551. https://doi.org/10.13930-/j.cnki.cjea.150687

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2015b. Effects of biogas slurry degradation on nitrogen content in paddy field water of panicle fertilizer stage. *Journal of Soil and Water Conservation* 29: 246–251. https://doi.org-/10.13870/j.cnki.stbcxb.2015.06.043

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2016. Analysis of water environment risk on biogas slurry disposal in paddy field. *Transactions of the Chinese Society of Agricultural Engineering* 32: 213–220. https://doi.org/-10.11975/j.issn.1002-6819.2016.05.030

Wang Z, Ma D. 2018. Effect of indirect underground drip irrigation with biogas slurry on yield and quality of red grape. *Anhui Agricultural Science Bulletin* 24: 46–47. https://doi.org/10.16377/j.cnki.issn1007-7731.2018.05.021

Wang Z, Wang X, Zhang Y, Guo Z, Sheng J, Zheng J. 2019. COD in biogas slurry: effects on cucumber seedling growth and soil environmental factors. *Chinese Agricultural Science Bulletin* 35: 15–22. http://www.cqvip.com/qk/91831x/-20194/907884665048495748524848 51.htm l(accessed on 04 June 2018)

Wang Z, Wu H, Guan Y, Liang Y, Liu Y. 2013. Integrated technology of “Three Separations and One Purification” treatment on livestock and poultry farm fecal sewage. *Journal of Agricultural Resources and Environment* 30: 63–67. http://cqvip.jskjwx.org/article/detail.aspx?id=47427008(accessed on 13 May

2013)

Wei D, Wan M, Liu R, Wang G, Zhang X, Wen X, Zhao Y, Chen L. 2014. Study on the quality of digested piggery wastewater in large-scale farms in Jiaxing. *Environmental Science* 35: 2650–2657. https://doi.org/10.13227/j.hjkx.-2014.07.031

Wentzel S, Joergensen RG. 2016. Effects of biogas and raw slurries on grass growth and soil microbial indices. *Journal of Plant Nutrition and Soil Science* 179: 215−222. https://doi.org/10.1002/jpln.201400544

Wu F. 2020. Response of farmland purple soil to high load utilization of biogas slurry in pig farm. *MScAgric dissertation, Southwest University, Chongqing, China*. https://cdmd.cnki.com.cn/Article/CDMD-10635-1020328621.htm(accessed on 04 June 2020)

Wu G, Liao X, He D, Li J. 2014. Current situation and countermeasures of livestock industry pollution control in China. *Journal of Agro-Environment Science* 33: 1261–1264.http://qikan.cqvip.com/Qikan/Article/Detail?id=663951755 (accessed on 16 May 2014)

Wu H, Guo D, Ma Y, Chang Z. 2012. Effects of pig manure-biogas slurry application on soil ammonia volatilization and maize output and quality. *Chinese Journal of Eco-Agriculture* 20: 163–168. https://doi.org/10.3724/SP.J.1011.2012.00163

Wu J, Wang J, Zhang L, Liu Y, Chen B, Meng X. 2014. Effects of biogas slurry on yield and quality of maize. *Journal of Nuclear Agricultural Sciences* 28: 905–911. https://d.wanfangdata.com.cn/periodical/hnxb201405022 (accessed on 01 August 2013)

Wu J, Yang Q, Yang G, Shen F, Zhang X, Zhang Y. 2013. Effects of biogas slurry on yield and quality of oil-seed rape. *Journal of Plant Nutrition* 36: 2084–2098. https://doi.org/10.1080/01904167.2013.822511

Wu L, Chi X, Zhou W, Du D, Peng J, Xiao N. 2019. Experimental study on piggery biogas slurry concentration process by reverse osmosis membrane. *Environmental Engineering* 37: 87–90. https://doi.org/10.13205/j.hjgc.20190-3016

Wu X. 2006. Application of marsh gas and marsh liquid in poultry enterprise. *Guizhou Agricultural Sciences* 34: 116–118. https://doi.org/10.3969/j.issn.100136-01.2006.04.044

Wu Z, Jin L, Wang G. 2015. Effect of biogas slurry fertilizer on yield and quality of muskmelon in greenhouse. *Chinese Horticulture Abstracts* 10: 38–39. http://www.cqvip.com/qk/60020x/201510/666329359.html (accessed on 22 June 2015)

Xi H, Li G, Tao A, Gu P, Han D, Li N, Chen X. 2021. Effect of drip fertigation with organic liquid fertilizer on soil environment, fruit yield, quality, and economic benefits of citrus cv. beni madonna. *Acta Agriculturae Zhejiangensis* 33: 670–677. https://doi.org/10.3969/j.issn.1004-1524.2021.04.12

Xu C, Tian Y, Sun Y, Dong L. 2013. Effects of biogas slurry irrigation on growth, photosynthesis, and nutrient status of Perilla frutescens seedlings. *Communications in Soil Science and Plant Analysis* 44: 3381–3390. https://-doi.org/10.1080/00103624.2013.847447

Xu K, Li C, Wu C, Jiang Z, Li Y. 2020. Application of biogas slurry in rice production. *Shanghai Agricultural Science and Technology* 1: 115–116. https://doi.org-/10.3969/j.issn.1001-0106.2020.01.050

Xu M, Xian Y, Wu J, Gu Y, Yang G, Zhang X, Peng H, Yu X, Xiao Y, 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: 2534–2542. https://doi.org/10.1007/s11368-019-02258-x

Xu P, Huang J, Peng Z, Yu J, Lin Z, Yang L, Wu X. 2014. Effects of slurry on yield, quality and nutrition absorption of Chinese cabbage. *Guangdong Agricultural Sciences* 41: 71–73. https://doi.org/10.16768/j.issn.1004-874x.2014.07.035

Xue S, Zhang C, Liu X, Wang L. 2013. Experimental report on the effect of spraying pure biogas concentrate on cucumber and tomato. *Jilin Agriculture* 2: 72. http://www.cqvip.com/qk/86121x/201304/45702718.html(accessed on 01 April 2013)

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

Yang J, Feng W, Jia L, Han B, Yang Z, Chang Y, Dou F, Liu M, Xing S, Wang P. 2015. Effects of topdressing biogas slurry on the content of heavy metals in Chinese cabbage and soil. *Journal of Hebei Agricultural Sciences* 19: 68–73. https://doi.org/10.16318/j.cnki.hbnykx.2015.05.019

Yang L, Wang K, Pang W, Zhang F. 2012. Effect of biogas slurry on soil quality of intensive plantation field in Xinjiang oasis for 5 years. *Soil and Fertilizer Sciences in China* 5: 17–21. https://d.wanfangdata.com.cn/periodical/trfl2012-05004 (accessed on 03 March 2012)

Yang R, Sun Q, Zhao H, Zou G, Liu B, Li L. 2017. Precision application of biogas slurry and its environmental effects in paddy fields. *Journal of Agro-Environment Science* 36: 1566–1572. https://doi.org/10.11654/jaes.2016-1617

Yang S, Peng S, Xu J, Yao J, Jin X, Song J. 2012. Characteristics and simulation of ammonia volatilization from paddy fields under different water and nitrogen management. *Transactions of the Chinese Society of Agricultural Engineering* 28: 99–104. https://doi.org/10.3969/j.issn.1002-6819.2012.11.017

Yang W, Shao D, Zhou Z, Xia Q, Chen J, Cao X, Zheng T, Sun S. 2020. Carbon quantum dots (CQDs) nanofiltration membranes towards efficient biogas slurry valorization. *Chemical Engineering Journal* 385: 123993. https://doi.org/-10.1016/j.cej.2019.123993

Yang X, Jia Q, Wang C, Zhang Z. 2021. Effect of pig manure and urine returning to the field on fertilizer reduction and efficiency improvement in rice planting. *Modern Agricultural Science and Technology* 12: 9–11. https://doi.org/-10.3969/j.issn.1007-5739.2021.12.003

Yang X, Wang W, Hu X, Li X, Fan Y. 2017. Effect of biogas slurry on photosynthesis, yield and quality of lettuce grown in hydroponic culture. *Journal of Irrigation and Drainage* 36: 55–59,85. https://doi.org/10.13522/j.cnki.ggps.2017.07.010

Yang Z, Chen W, Wang W, Li W, He X, Yang X. 2017. Effects of biogas slurry on soil microbial characteristics of broccoli. *Chinese Agricultural Science Bulletin* 29: 112–115. http://www.cqvip.com/QK/91831X/201729/673598109.html (accessed on 21 March 2017)

Yang Z, Ding H, Chen Y, Jin C, Shi K, Hou F, Feng G, Huang Q. 2019. Effects of different application amount of biogas-slurry on barley agronomic traits & feeding quality. *Acta Ecologiae Animalis Domastici* 40: 59–65. https://doi.-org/10.3969/j.issn.1673-1182.2019.05.012

Ye J, Miao J, Huang Y, Li Y, Li Z. 2014. Effects of biogas slurry irrigation on heavy metal content and yield of lettuce. *Acta Agriculturae Jiangxi* 26: 96–99. https://doi.org/10.19386/j.cnki.jxnyxb.2014.07.025

Yetilmezsoy K, Sertyesilisik B, Kocak E, Sapci-Zengin Z. 2009. Ameliorative effect of different doses of MgNH4PO4·6H2O precipitate recovered from the effluent of UASB treating poultry manure wastewater: Growth of Lolium perenne. *International Journal of Food Agriculture abd Environment* 7. https://pub-ag.nal.usda.gov/catalog/774748

Yılmaz E, Çanakcı M, Topakcı M, Sönmez S, Ağsaran B, Alagöz Z, Çıtak S, Uras DS. 2019. Effect of vineyard pruning residue application on soil aggregate formation, aggregate stability and carbon content in different aggregate sizes. *Catena* 183: 104219. https://doi.org/10.1016/j.catena.2019.104219

Yin F, Zhan Y, Yue C, Hu X, Zhu Z, Dong H. 2021. Research progress on membrane technology for treatment of husbandry biogas slurry and wastewater. *Journal of Agro-Environment Science* 40: 2335–2341. https://doi.org/10.11654/jaes.2021-1118

Yu C, Wang C, Sheng M, Pan L. 2015. Application effect of piggery biogas slurry on the soilless culture of swamp cabbage. *Journal of Nuclear Agricultural Sciences* 29: 178–182. https://d.wanfangdata.com.cn/periodical/hnxb201501023 (accessed on 10 January 2014)

Yu D, Wen Z, Li X, Song X, Wu H, Yang P. 2018. Effects of straw return on bacterial communities in a wheat-maize rotation system in the North China Plain. *PLoS One* 13: e0198087. https://doi.org/10.1371/journal.pone.0198087

Yu F, Luo X, Song C, Zhang M, Shan S. 2010. Concentrated biogas slurry enhanced soil fertility and tomato quality. *Acta Agriculturae Scandinavica Section B - Soil and Plant Science* 60: 262−268. https://doi.org/10.1080/09064710902893385

Yuan C, Wang Y, Yao L, Zhang H, Guo H, Liu Y. 2013. Effect of biogas slurryapplication on *strawberry* planting. *China biogas* 31: 36–39. https://doi.org/10.3969/j.issn.1000-1166.2013.05.008

Yuan D, Liu C, Pu G, Wu D. 2011. Effects of seed soaking with biogas slurry on seed germination and seedling growth of tageteserecta. *China Journal of Chinese Materia Medica* 36: 817–822. https://pubmed.ncbi.nlm.nih.gov/21761715 (accessed on 23 October 2010)

Yuan J, Qi X, Zhao J, Li P, Du Z, Li K, Wang P. 2022. The effect of biochar amendment and slurry application on soil aggregation and organic carbon distribution. *Journal of irrigation and drainage* 41: 80–86. https://doi.org/10.13522/j.-cnki.ggps.2021351

Yuan Y, Gao Z, Jia S, Gao X, Zhang W, Liu C, Wang D. 2019. Effects of digestate application on N2O and NH3 emissions of apple orchard soil. *Journal of Hebei Agricultural University* 42: 57–64. https://doi.org/10.13320/j.cnki.jauh.2019.01-01

Zhan Y, Dong H, Yin F, Yue C. 2018. The combined process of paper filtration and ultrafiltration for the pretreatment of the biogas slurry from swine manure. *International Journal of Environment Research and Public Health* 15: 1894. https://doi.org/10.3390/ijerph15091894

Zhang C, Xu Z, Li Y, Zhang Y, Lin H, Wang J. 2014. Comprehensive evaluation of several typical pollution control engineerings of livestock and poultry breeding. *Chinese Journal of Environmental Engineering* 8: 4555–4560. http://www.-cqvip.com/qk/90325c/201410/72747490504849524948485653.ht ml(accessed on 20 September 2013)

Zhang F, Hu S, Kang K, Huang H, Yang H, Li C, Li T. 2013. Effect of highly efficient biogas slurry fertilizer on greenhouse tomatoes. *Journal of Northwest A&F University (Nat Sci Ed)* 41: 75–78. https://doi.org/10.13207/j.cnki.jnwafu.-

2013.06.022

Zhang H, Li J, Shao K. 2009. Safety and effect of biogas slurry in swine feed. *Acta Ecologiae Animalis Domastici* 30: 68–72. https://doi.org/10.3969/j.issn.1673-1182.2009.03.017

Zhang H, Wang G. 2011. Effects of biogas slurry combinated with nitrogen fertilizer on soil microbial biomass and enzyme activities. *Journal of Anhui Agricultural Sciences* 39: 16601−16603. https://doi.org/10.13989/j.cnki.05176611.201-1.27.146

Zhang L, Li Z, Liu H, Liu S, Wang Y, He Y, Zhang H. 2011. Water purification of aquatic cultivated celery in the diluted slurry with different concentrations. *Resources and Environment in the Yangtze Basin* 20: 154–158. http://qikan.cqvip.com/Qikan/Article/Detail?id=1002326304 (accessed on 30 November 2010)

Zhang L, Sun G, Wang Z, Zong J, Zhou W, Sheng J. 2021. Analysis of rice seedling growth restriction factors under biogas slurry application. *Journal of Agro-Environment Science* 40: 2537–2543. https://doi.org/10.11654/jaes.2021-1025

Zhang M, Gao D. 2020. Ozonation and flocculation combination treatment biogas slurry of cow dung. *China Biogas* 38: 37–44. http://www.cqvip.com/qk/9033-6x/202001/7101184388.html (accessed on 21 March 2019)

Zhang Y. 2018. Comparative experiment on the effect of biogas fertilizer and conventional fertilizer on rice yield. *Agriculture of Jilin* 1: 63. https://do-i.org/10.14025/j.cnki.jlny.2018.01.026

Zhang Y, Li Z, Zhang L, Li S, Zhang Q, Zhan X. 2021. Effect of physicochemical properties of liquid digestate of pig manure on seed germination of maize. *China Biogas* 39: 13–21. https://doi.org/10.3969/j.issn.1000-1166.2021.01.003

Zhao F, Sun Q, Li J, Liu C, Wei Z, Zhang J, Liu B. 2010. Effects of different biogas fertilizers on yield, quality and nitrogen use efficiency of the rape. *Journal of Soil and Water Conservation* 24: 127−130. http://www.cnki.com.cn/article/cj-fdtotal-trqs201003028.htm (accessed on 01 January 2010)

Zhao X, Wang C, Li K, Chen B, Wang F. 2011. Effect of biogas slurry spraying on leaf photosynthetic characteristics of nectarine (Prunus persica var. nectarina) in solar greenhouse. *Journal of Fruit Science* 28: 680–684. http://qikan.cq-vip.com/Qikan/Article/Detail?id=38527477 (accessed on 10 November 2010)

Zheng J, Li X, Ma J, Ma B, Wang Y, Wang L. 2020a. Effect of biogas slurry combined with straw biochar on soil organic matter and total nitrogen content. *Journal of Agro-Environment Science* 39: 1111–1121. https://doi.org/10.11654/jaes.2019-1255

Zheng J, Li X, Ma J, Xiang P, Wang J. 2020b. Effects of combined application of biochar and biogas slurry on percolate electrical conductivity, total nitrogen and soil physical and chemical properties. *Agricultural Research in the Arid Areas* 38: 134–144. https://d.wanfangdata.com.cn/periodical/ghdqnyyj202003018 (accessed on 17 September 2019)

Zheng J, Yan F, Pan Z, Feng Z, Li X. 2019. Meta analysis on the effect of biogas slurry on crop yield in China. *China Biogas* 37: 78−84. https://doi.org/10.3969-/j.issn.1000-1166.2019.02.015

Zheng X, Fan J, Cui J, Xu L, Zhu Z, Zhou J, He Y. 2016a. Analysis on metabolic characteristics and functional diversity of soil edaphon communities in upland red soil under biogas slurry application. *Acta Ecologica Sinica* 36: 5865−5875. https://doi.org/10.5846/stxb201503230555

Zheng X, Fan J, He Y, Cui J, Xu L, Zhu Z, Zhou J. 2015. Effect of total nitrogen ratio of biogas slurry/chemical fertilizer on microflora and enzyme activities of soil. *Transactions of the Chinese Society of Agricultural Engineering* 31: 142−150. https://doi.org/10.11975/j.issn.1002-6819.2015.19.020

Zheng X, Fan J, Zhou J, He Y. 2016b. Effects of combined application of biogas slurry and chemical fertilizer on soil nutrients and peanut yield in upland red soil. *Acta Pedologica Sinica* 53: 675–684. https://doi.org/10.11766/trxb201509210375

Zhong Z, Song Y, Huang X, You X, Weng B, Huang Q, Chen Z, Feng D. 2016. Effects of biogas slurry application on the soil microorganisms of *P.americanum* × *P. purpureum* grassland. *Acta Agrestia Sinica* 24: 54−60. https://d.wanfang-data.com.cn/periodical/cdxb201601008 (accessed on 07 February 2015)

Zhou G, Xue X, Su S, Gu G. 2014. Effects of drip irrigation with biogas slurry on yield and quality of watermelon. *Journal of Changjiang Vegetables* 12: 59–60. https://doi.org/10.3865/j.issn.1001-3547.2014.12.019

Zhou J. 2015. Study on the effect of biogas slurry root irrigation on the yield and stress resistance of *Angelica sinensis*. *China Biogas* 33: 84–86. http://qikan.c-qvip.com/Qikan/Article/Detail?id=666413994 (accessed on 11 March 2015)

Zhou L, Lv L. 2017. Characteristics of heavy metal in biogas slurry, soil and vegetable system. *Journal of Nanjing Tech University (Natural Science Edition)* 39: 63–69. https://doi.org/10.3969/j.issn.1671-7627.2017.03.012

Zhou Q. 2012. Effects of applying biogas liquid manure and two kinds of microbiological fertilizer on the growth and quality of *Lycium.barbarum* L. *MScAgric dissertation, Gansu Agricultural University, Lanzhou, China*. http://cdmd.cnki.com.cn/Article/CDMD-10733-1012034349.htm (accessed on 16 June 2012)

Zhou W, Sun G, Wang X, Tong H, Sheng J. 2019. Risk of nitrogen loss under the combined application of biogas slurry and organic fertilizer. *Journal of Agro-Environment Science* 38: 1743–1750. https://doi.org/10.11654/jaes.2018-1614

Zhou Y, Feng R, Zhu P, Li Z, Kang Q. 2020. Review of pretreatment technology before biogas slurry used as resource in China. *Advances in Environmental Protection* 10: 249–258. https://doi.org/10.12677/aep.2020.102029

Zhu G, Zhao J, Zhao X, Lu X. 2012. Characteristics of nutrients removal from stored algae anaerobic biogas slurry in artificial aquatic vegetable wetlands. *Applied Mechanics and Materials* 178-181: 777–782. https://doi.org/10.4028/www.scientific.net/AMM.178-181.777

Zhu R. 2019. Effects of biogas slurry and biochar on soil aggregate organic carbon and microbial community diversity. *MScAgric dissertation, Nanjing Forestry University, Nanjing, China*. http://cdmd.cnki.com.cn/article/cdmd-10298-1020802002.htm(accessed on 18 June 2019)

Zou M, Dong H, Zhu Z, Zhan Y, Zhang Y, Yue C. 2020. Progress and prospect of treatments and resource utilization of biogas slurry on livestock and poultry farms. *China Poultry* 42: 103–109. https://doi.org/10.16372/j.issn.1004-6364.2020.09.016

Zu B, Liu L, Zu J, Wei S. 2009. Design of fecal sewage treatment project from large-scale duck farm. *China Water and Wastewater* 25: 34–37. http://www.cqvip.com/qk/95430x/200902/29130510.html (accessed on 30 July 2008)

CHAPTER 3: ADSORPTION CHARACTERISTICS OF THREE TYPES OF SOILS ON BIOGAS SLURRY AMMONIUM NITROGEN

This chapter has been published as detailed below:
Wang Z, Zhang L, Sun G, Zhou W, Sheng J, Ye X, Olaniran AO and Kana EBG 2022. Adsorption characteristics of three types of soils on biogas slurry ammonium nitrogen. *Frontiers in Environmental Science* 10:942263. https://doi.org/10.3389/fenvs.2022.942263.

3.1 Abstract

Using farmland to digest biogas slurry is an effective measure to overcome the bottleneck of sewage treatment in livestock and poultry farms. However, there is limited research on the soil adsorption characteristics of biogas slurry ammonium nitrogen (NH_4^+-N). In addition, the maximum adsorption capacity (Q_m) of farm soil is unclear. In this study, three typical farmland tillage layer soils (silty loam, loam, and sandy loam) were used to analyze adsorption characteristics through adsorption kinetics experiments (adsorption for 0.25, 0.5, 1, 2, 4, 6, 12, 18, or 24 h with NH_4^+-N concentrations of 42.90 mg/L) and thermodynamic experiments (adsorption for 3 d with NH_4^+-N concentrations of 54.25, 88.66, 105.85, 133.71, 178.80, 273.54, and 542.87 mg/L). The Q_m value was fitted by models, and its relationship with soil properties was discussed. The results showed the following: (1) the adsorption of biogas slurry NH_4^+-N by the three types of soils was a composite kinetic process that comprised two stages of rapid and slow reactions. Rapid adsorption predominantly occurred within 0–1 h, and the adsorption capacity accounted for 35.24–43.55% of the total adsorption. The ExpAssoc equation produced a good fit for the adsorption kinetic behaviour in the three soil types. (2) The equilibrium adsorption could be described by the Langmuir equation, the Freundlich equation, the PlPlatt model, and the Langevin model isotherm, among which the Langevin model had the best fit, with a coefficient of determination R^2 close to 1. The theoretical saturated Q_m fitting results of NH_4^+-N were 1038.41–1372.44 mg/kg in silty loam, 840.85–1157.60 mg/kg in loam, and 412.33–481.85 mg/kg in sandy loam. The optimal values were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively. (3) The Q_m value was significantly positively correlated with soil organic matter, total nitrogen, available phosphorus, available potassium, cation exchange capacity, and particle content of 0.02–0.002 mm ($P < 0.01$), but significantly negatively correlated with soil pH ($P < 0.05$). This study can provide a reference for the safe application of biogas slurry on farmland.

Keywords: *biogas slurry, wastewater, ammonium nitrogen, soil absorption, kinetics, thermodynamics*

3.2 Introduction

Biogas slurry is the residual liquid substance produced by anaerobic fermentation in biogas engineering using biodegradable organic wastes, such as human and livestock manure or various agricultural and forestry wastes. It is produced together with methane, carbon dioxide, and other gases under certain conditions of water content, temperature, and the action of methane bacteria in closed containers (Han et al., 2014). Biogas production has become an important energy-saving and emission-reduction technology for the harmless treatment and energy utilization of livestock and poultry manure in China. According to recent estimates, the biogas slurry produced by the anaerobic fermentation of livestock and poultry manure is more than 1.3 billion tons each year (Lu et al., 2010; Zhu and Huang, 2010). Returning biogas slurry to farmland soil as fertilizer is an effective method of economical use (Bradford et al., 2008; Ning et al., 2019; Liu et al., 2020). However, unreasonable application will not only reduce the use efficiency of biogas slurry, but it will also cause the environmental pollution of farmland water and the reduction of crop yields (Gao et al., 2011; Chen et al., 2013; Wang et al., 2016). The safe utilization of biogas slurry resources is expected to become an increasingly important topic in agriculture, energy use, and environmental protection and thus urgently needs to be investigated.

Biogas slurry is rich in a variety of nutrients required for plant growth and development, such as nitrogen, phosphorus, potassium, copper, zinc, organic acids, hydrolases, and amino acids. The total nitrogen (TN) content of biogas slurry is 0.53–

3.24 g/kg (Jin et al., 2011; Ni and Zhang, 2017). Many researchers have studied the use of biogas slurry nitrogen as a measurement parameter for farmland reuse and discussed the safe dosage for fertility enhancement, yield, quality improvement, and environmental emission reduction. For example, Wang et al. (2010) found that applying biogas slurry equivalent to 2–3 times the amount of chemical fertilizer could obtain a *Capsicum* spp. yield similar to that of conventional chemical fertilizer treatment, as well as improve *Capsicum* spp. quality, increase the contents of soil organic matter (SOM), TN, available nitrogen, phosphorus, and potassium, and save on fertilizer costs. Yang et al. (2017) showed that compared with chemical fertilizer, the application of an equal amount of biogas slurry nitrogen led to no significant differences in the rice yield, nitrogen utilization rate, or soil residual inorganic nitrogen, while the ammonia volatilization per unit rice yield was significantly reduced by 22.6%. Most of these studies were based on the nitrogen fertilizer required for crop growth and replaced chemical nitrogen fertilizer with different proportions of biogas slurry nitrogen, but they did not consider whether the applied biogas slurry nitrogen exceeded the maximum nitrogen adsorption capacity of the topsoil.

Ammonium nitrogen (NH_4^+-N) is the main component of biogas slurry nitrogen, accounting for 46.42%–92.86% of TN (Ham and DeSutter, 1999; Jin et al., 2012; Ni and Zhang, 2017). In addition to being consumed and retained by ammonia volatilization, biological absorption (Li et al., 2021), and soil adsorption, a considerable portion of NH_4^+-N over-applied to soil can leach into deep soil through nitrification or into the water table along with surface runoff, thus causing nitrogen pollution in groundwater and surface water (Kithome et al., 1998; Wang et al., 2016; He et al., 2021). A large number of studies reported that the nitrate content in the areas adjacent to concentrated animal feeding operations exceeded the safety standards, thereby creating a bottleneck for livestock and poultry feeding development (Ciravolo et al., 1979; Feinerman et al., 2004). Considering the environmental behavior of NH_4^+-N, adsorption is an important process that can block and delay the further migration and transformation of nitrogen in order to inhibit nitrogen loss (Li et al., 2021). Studies of the soil adsorption of NH_4^+-N have focused on the use of a single chemical ammonium salt solution to explore the adsorption mode, deduce the adsorption mechanism, and estimate the adsorption capacity, generally using NH_4Cl solution (Xue et al., 1996; Li et al., 2009; Tian, 2011; Cong et al., 2017). Solutions of NH_4NO_3, $(NH_4)_2SO_4$, and $NH_4H_2PO_4$ have also been used (Dalal, 1975). Furthermore, the soils used in previous research were mostly vermiculitic-type clay loam, kaolinitic sandy soils, and some tropical soils (Dalal, 1975; Lumbanraja and Evangelou, 1994; Wang and Alva, 2000; Kumar and Kothiyal, 2011). There are few studies on the adsorption characteristics of ammonium nitrogen biogas slurry solutions co-existing with complex components (Kumar and Kothiyal, 2012; Zhao et al., 2013), and there is a lack of research on the adsorption characteristics of ammonium nitrogen from biogas slurry in common agricultural production land topsoil.

Studying the adsorption characteristics of biogas slurry ammonium nitrogen in typical farmland soils and predicting the maximum adsorption capacity of the cultivated layer soil are significant for guiding the safe digestion of biogas slurry in farmland. In this study, three types of common farmland soils were collected: silty loam, loam, and sandy loam. Through analyses of adsorption kinetics and adsorption thermodynamics, the adsorption characteristics of these soils for biogas slurry ammonium nitrogen were analyzed, kinetic models were fitted, and the relationships between soil physical and chemical properties and adsorption capacity were explored to provide a scientific basis for the safe application of biogas slurry in farmland and the prevention and control of water pollution.

3.3 Materials and methods

3.3.1 Materials

Biogas slurry was collected from a large pig farm (Jiangsu Yangyu Ecological Agriculture Co., Ltd.) in Xinjie Town of Taixing City, China **(Fig. 3.1)**. The pig farm has 138 standardized brick-and-concrete pens with a structure area of more than 100,000 m^2. The farm produces around 120,000 commercial pigs annually. It has sewage collection tanks of 1,200 m^3, fermentation tanks of 4,000 m^3, oxidation ponds of 35,000 m^3, one sewage treatment system, and a high-efficiency organic fertilizer farm with an annual output of more than 10,000 tons. The biogas slurry sample was generated from pig feces through primary anaerobic fermentation in a continuous stirred tank reactor (CSTR) and a secondary anaerobic fermentation using a black-film-sealed storage process. Once collected, the samples were stored in sealed plastic barrels and were mixed well and filtered through a 0.25-mm mesh screen before the analysis. Samples were then diluted corresponding to the NH_4^+-N concentration with deionized water for backup use. The basic quality indices of the biogas slurry are shown in **Table 3.1**.

Figure 3.1 Site image of manure and sewage treatment facilities in the pig farm.

Table 3.1 Chemical composition of biogas slurry.

	pH	TN (mg/L)	NH_4^+-N (mg/L)	NO_3^--N (mg/L)	TP (mg/L)	TK (mg/L)	COD (mg/L)	EC (mS/cm)	TS (g/L)
Biogas slurry (unfiltered)	7.95	630.29	558.72	42.40	23.97	380	636.67	5.15	2.25
Biogas slurry (filtered through a 0.25-mm mesh screen)	7.97	624.53	550.41	42.36	23.70	375	626.67	5.12	2.24

TN: total nitrogen; NH_4^+-N: ammonium nitrogen; NO_3^--N: nitrate nitrogen; TP: total phosphorus; TK: total potassium; COD: chemical oxygen demand; EC: electrical conductivity; TS: total solid.

The experimental soils were collected from the 0–20 cm plough layer of basic farmland in the plain water network area of the Yangtze River Basin in China. The soil textures were silty loam, loam, and sandy loam. The soils were dried naturally, while stones, plant roots, and other DEBRIS found in the soils were removed. The soils were then crushed with a round wooden stick, sieved through a 2-mm mesh screen, and finally fully mixed and placed into a clean plastic storage box for future use. The particle composition and basic physical and chemical properties of the soils are listed in **Tables 3.2** and **3.3**.

Table 3.2 Soil particle composition of three soils.

Soil number	2–0.2 mm (%)	0.2–0.05 mm (%)	0.05–0.02 mm (%)	0.02–0.002 mm (%)	<0.002 mm (%)	Soil texture	Soil classification system of China	Sampling point
Xinbei	0.64	29.90	22.54	30.39	16.54	Silty loam	Wushan soil	Dongnancun, Xixiashu, Xinbei
Jintan	0.53	34.96	19.70	30.64	14.17	Loam	Permeable paddy soil	Luocun, Xuebu, Jintan
Taixing	0.27	61.56	22.58	10.14	5.45	Sandy loam	High sandy soil	Lidangcun, Xinjie, Taixing

Table 3.3 Physical and chemical characteristics of three soils.

Soil number	pH	SOM (g/kg)	TN (g/kg)	NH_4^+-N (mg/kg)	NO_3^--N (mg/kg)	TP (g/kg)	AP (mg/kg)	AK (mg/kg)	CEC (cmol/kg)	EC (μS/cm)
Xinbei	6.45	29.09	1.16	8.93	56.97	0.57	13.10	122.91	16.27	492.67
Jintan	5.43	19.70	0.79	25.58	26.26	0.31	7.98	126.45	9.57	244.67
Taixing	8.19	5.27	0.16	3.17	10.50	0.54	6.29	65.70	5.83	174.97

SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; CEC: cation exchange capacity; EC: electrical conductivity.

3.3.2 Adsorption kinetics experiments

Soil samples (10 g) were weighed and placed in 250-mL conical bottles. Two hundred millilitres of biogas slurry (NH_4^+-N concentration 42.90±0.66 mg/L) was added to each conical bottle at a soil:water ratio of 1:20, and three drops of toluene were added to inhibit microbial activity. Biogas slurry without soil was used as a blank control. The conical bottles were sealed with a silica gel plug, placed in a thermostatic oscillator (set temperature 25±1°C), and oscillated at 140 r/min for 0.25, 0.5, 1, 2, 4, 6, 12, 18, or 24 h. The conical bottles were taken out for biogas slurry sample collection, and a 20-mL biogas slurry sample was taken each time. The biogas slurry sample was centrifuged at a speed of 3800 r/min for 10 min. The concentration of NH_4^+-N in the supernatant was determined by an automatic flow analyzer (SKALAR SAN^{++}). The above experiments were carried out through destructive sampling. Three batches of experiments were set up. Each batch was set up with nine replicates for each treatment, and one bottle was taken out from the thermostatic oscillator for each round of sampling, which was then discarded after sampling. The average value was taken, and the amount of NH_4^+-N adsorbed onto the biogas slurry was calculated after the blank was deducted according to the difference in NH_4^+-N concentration before and after adsorption.

3.3.3 Adsorption thermodynamic experiments

A 2.5 g soil sample was mixed with 50 mL biogas slurry with initial diluted concentrations of NH_4^+-N of 54.25, 88.66, 105.85, 133.71, 178.80, 273.54, and 542.87 mg/L in a polyethylene centrifuge tube. Two drops of toluene were added to inhibit microbial activity, and different concentrations of biogas slurry without soil samples were used as blank controls. The sealing cover of the centrifuge tube was tightened, and samples were mixed with a vortex oscillator and oscillated at 180 r/min on a thermostatic oscillator (set temperature 25±1°C) for 1 h. Samples were then incubated in a thermostat at the same temperature for 3 d, oscillating twice a day at an interval of 12 h for 1 h each time. After cultivation, the samples were centrifuged at 3800 r/min for 10 min. The concentration of supernatant NH_4^+-N was measured by an automatic flow analyzer (SKALAR SAN^{++}). Each experiment was repeated three times. The amount of NH_4^+-N absorbed by the tested soil was calculated based on the differences between the initial and final NH_4^+-N concentration in the supernatant.

3.3.4 Calculation methods

3.3.4.1 Adsorption capacity calculation formula

$$Q = \frac{(C_0 - C_t) \cdot V}{M}. \quad (1)$$

In the formula, Q is the adsorption capacity of NH_4^+-N (mg/kg); C_0 is the initial concentration (mg/L); C_t is the concentration of the solution at the time of measurement (mg/L); V is the volume of the solution (mL); and M is the soil sample weight (g).

3.3.4.2 Adsorption fitting equations

The fitting equations of adsorption kinetics are shown in **Table 3.4.** Fitting equations for adsorption thermodynamics are shown in **Table 3.5**.

Table 3.4 Four models of soil adsorption kinetics.

Model	Equation
Elovich equation	$Q_t = a + b\ln t$ ....(2)
Parabolic diffusion equation	$Q_t = a + bt^{1/2}$ (3)
First-order reaction equation	$\ln(Q_e - Q_t) = \ln Q_e - kt$ ....(4)
ExpAssoc equation	$Q_t = y_0 + A_1(1 - e^{-t/a}) + A_2(1 - e^{-t/b})$ ....(5)

Q_t is the adsorption capacity of NH_4^+-N at time t (mg/kg); Q_e is the adsorption capacity of NH_4^+-N at adsorption equilibrium (mg/kg); and a, b, k, y_0, A_1, and A_2 are constants used to characterize the adsorption coefficient, where their size indicates the adsorption strength.

Table 3.5 Four thermodynamic models.

Model	Equation	Adjustable model parameters
Langmuir	$\frac{C_e}{Q_e} = \frac{1}{Q_m K_l} + \frac{C_e}{Q_m}$ .... (6)	K_l is a constant used to characterize the adsorption performance of the soil; and MBC = $Q_m \times K_l$, representing the maximum buffer capacity of the soil (mg/kg).
Freundlich	$Q_e = K_f C_e^{1/n}$ .... (7)	K_f is a constant that represents the strength of soil adsorption force; and 1/n represents the heterogeneity factor related to adsorption strength or surface heterogeneity, reflecting the nonlinear degree of adsorption.
Plplatt	$Q_e = Q_m \cdot \tanh\left(\frac{A \cdot C_e}{Q_m}\right)$ .... (8)	A is a constant.
Langevin	$Q_e = a + b \cdot \left(\coth\left(\frac{C_e - k}{s}\right) - \frac{s}{C_e - k}\right)$ ....(9)	a, b, k, and s are constants, $Q_m = a + b$.

Q_e is the adsorption capacity of NH_4^+-N at adsorption equilibrium (mg/kg); C_e is the NH_4^+-N concentration of biogas slurry at adsorption equilibrium (mg/L); and Q_m is the theoretical saturated adsorption capacity of NH_4^+-N per unit soil (mg/kg), representing the capacity factor. MBC: maximum buffer capacity of the soil.

3.3.5 Data processing

Microsoft Office Excel (2010) software was used for test data processing and table drawing, Origin 2017 software was used for drawing and curve fitting, and the significance of Pearson correlations between variables was tested by IBM SPSS Statistics 13.0 version (IBM Corp., NY, USA).

3.4 Results and analysis

3.4.1 Adsorption kinetic characteristics

The adsorption rates of three types of soils on biogas slurry ammonium nitrogen (NH_4^+-N) are shown in **Table 3.6**. The adsorption process of NH_4^+-N from biogas slurry was a composite kinetic process comprising two stages of initial rapid adsorption followed by slow adsorption. The initial rapid adsorption generally occurred within 0–1 h. The ratio of the rapid adsorption amounts to the total amount of adsorption was

35.24–43.55%. After 1 h, the process entered the slow adsorption stage. The total adsorption amounts in order from highest to least were adsorbed onto silty loam, loam, and sandy loam.

Table 3.6 Biogas slurry ammonium nitrogen (NH_4^+-N) adsorption rate of three types of soils.

Soils	Adsorption rate at different stage (mg/(kg•h))								
	0–0.25 h	0.25–0.5 h	0.5–1 h	1–2 h	2–4 h	4–6 h	6–12 h	12–18 h	18–24 h
Silty loam (Xinbei)	279.20	131.04	41.65	18.30	17.68	9.47	5.47	3.47	5.61
Loam (Jintan)	165.65	34.85	53.84	22.23	19.82	7.94	1.54	1.59	3.80
Sandy loam (Taixing)	136.91	81.92	25.40	21.65	9.81	7.90	3.33	1.98	2.67

3.4.2 Adsorption kinetic model fitting

Fig. 3.2A–D shows the fitting results for the adsorption kinetics of NH_4^+-N in the three kinds of soils obtained by the Elovich equation, a parabolic diffusion equation, a first-order reaction equation, and the ExpAssoc equation. The four equations could effectively simulate the dynamic adsorption process. The fit of the ExpAssoc equation with relevant parameters produced a confidence interval for R^2 ($0.9923 < R^2 < 0.9966$) that was better than for the other models **(Table 3.7)**. Therefore, the ExpAssoc equation was used to fit the adsorption kinetics of NH_4^+-N in the three kinds of soils.

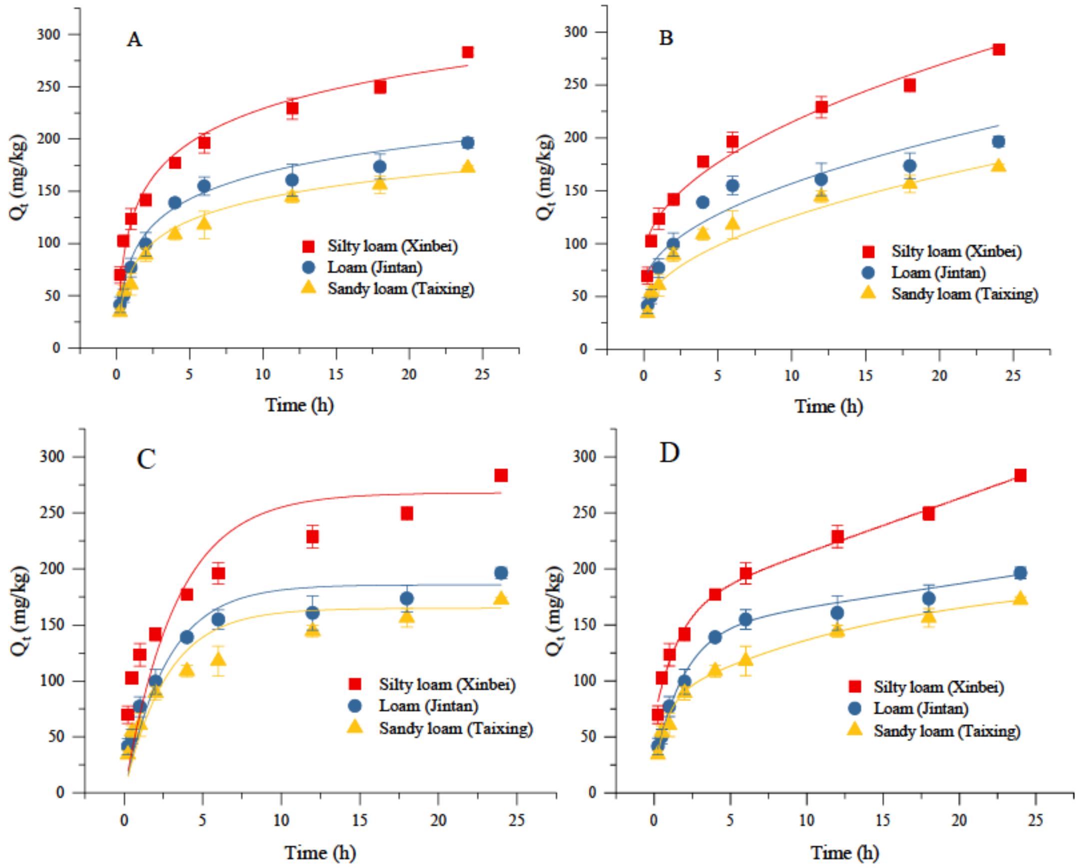


Figure 3.2 Fitting of adsorption kinetics models: (A), (B), (C), and (D) show the fitting results for the adsorption kinetics of NH_4^+-N in the three kinds of soils obtained by the Elovich equation, a parabolic diffusion equation, a first-order reaction equation, and the ExpAssoc equation, respectively.

Table 3.7 Fitted parameters in the adsorption kinetics fitting equations.

Soils	Elovich equation			Parabolic diffusion equation			First-order reaction equation			ExpAssoc equation					
	a	b	R^2	a	b	R^2	Q_e	k	R^2	y_0	A_1	a	A_2	b	R^2
Silty loam (Xinbei)	120.38	108.62	0.97	83.86	41.39	0.97	267.93	0.30	0.78	66.29	8.70	1.79	99.76	1.62	0.99
Loam (Jintan)	84.73	82.49	0.98	57.14	31.51	0.81	185.88	0.37	0.92	23.66	1.23	5.92	121.64	1.93	0.99
Sandy loam (Taixing)	73.17	69.66	0.99	32.74	29.30	0.96	164.82	0.37	0.91	15.73	65.84	0.79	114.37	15.30	1.00

3.4.3 Adsorption thermodynamic characteristics

The isothermal adsorption curves of the three soils for biogas slurry NH_4^+-N at a temperature of 25±1°C are shown in **Fig. 3.3**. With the increase of the initial biogas slurry NH_4^+-N concentration, the adsorption isotherms of three soils on NH_4^+-N increased, primarily due to the increase of initial biogas slurry NH_4^+-N concentration and the increase of the driving force of the soil itself as an adsorbent, an effect that was conducive to the generation of adsorption. When the initial biogas slurry NH_4^+-N concentration was less than 200 mg/L, the NH_4^+-N adsorption capacity of the three soils increased significantly with the increase of initial concentration; when the initial concentration of NH_4^+-N in biogas slurry was greater than 200 mg/L, the NH_4^+-N adsorption capacity increased slowly and tended to balance with the increase of initial concentration. When the initial biogas slurry NH_4^+-N concentration was low, the adsorption sites of the soil itself were not completely occupied. As the initial biogas slurry NH_4^+-N concentration increased, the unused adsorption sites were gradually occupied and thus were unable to be used, ultimately reaching a saturated state so that the soil and the NH_4^+-N solution tended to balance, and the soil adsorption capacity of NH_4^+-N reached its maximum value.

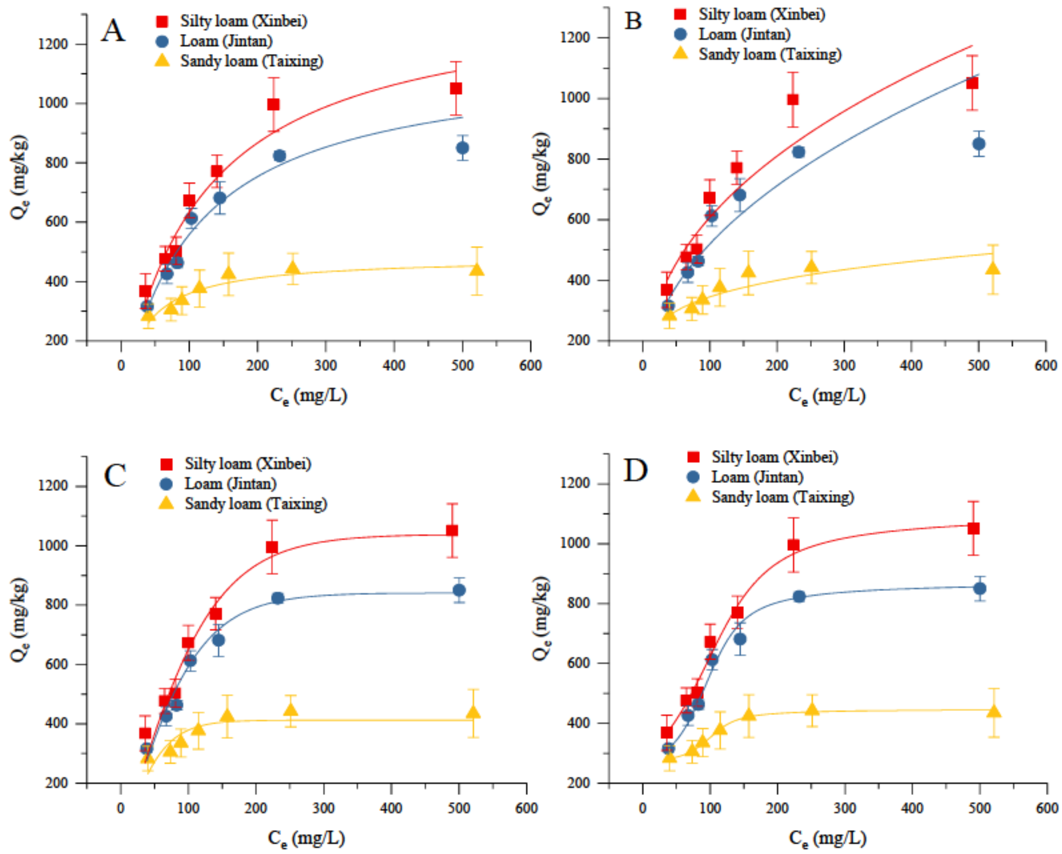


Figure 3.3 Fitting effects of adsorption thermodynamic models: (A), (B), (C), and (D) show the fitting results for the adsorption thermodynamics of NH_4^+-N in the three kinds of soils obtained by

the Langmuir equation, the Freundlich equation, the Plplatt equation, and the Langevin model, respectively, at a temperature of 25±1°C.

3.4.4 Adsorption thermodynamic model fitting

The Langmuir equation and Freundlich equation are classical models used to study the thermodynamic characteristics of soil NH_4^+-N adsorption. The Plplatt equation and the Langevin model were the equations selected in this experiment to achieve better fitting. **Fig. 3.3**A–D shows the fitting results of four equations on the adsorption thermodynamics of biogas slurry NH_4^+-N at a temperature of 25±1°C. When fitting the theoretical saturated maximum adsorption capacity (Q_m) values of biogas slurry NH_4^+-N for the three kinds of soils, the Q_m value fitted by the Langmuir equation was highest, and the Q_m value fitted by the Plplatt equation was closer to the measured average value. From the R^2 values (**Table 3.8**), the adsorption thermodynamic behaviour of biogas slurry NH_4^+-N in this experiment was best fitted by the Langevin Model. The optimal theoretical saturated Q_m values calculated by the sum of the parameters a and b were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively.

Table 3.8 Related parameters in the adsorption thermodynamic fitting equation.

Soils	Langmuir equation				Freundlich equation			Plplatt equation			Langevin Model				
	Q_m	K_l	MBC	R^2	K_f	1/n	R^2	Q_m	A	R^2	a	k	b	s	R^2
Silty loam	1372.44	0.0086	11.79	0.95	90.13	0.41	0.89	1038.41	7.64	0.94	606.06	96.24	502.49	36.31	0.98
Loam	1157.60	0.0093	10.80	0.98	64.25	0.45	0.93	840.85	7.39	0.96	529.26	93.68	345.60	21.83	1.00
Sandy loam	481.85	0.0294	14.18	0.89	131.39	0.21	0.86	412.33	6.52	0.65	352.64	99.99	95.71	16.05	1.00

3.4.5 Correlation between adsorption capacity and soil physical and chemical properties

Correlations between adsorption characteristic parameters and soil properties are shown in **Table 3.9**. The Q_m of the soil for biogas slurry NH_4^+-N was positively correlated with SOM, TN, available phosphorus (AP), available potassium (AK), cation exchange capacity (CEC), and the proportion of 0.02–0.002 mm particles ($P < 0.01$), while it was negatively correlated with soil pH ($P < 0.05$). The adsorption constant K_l

was negatively correlated with SOM, TN, AP, AK, and the content of particles with the particle size of 0.02–0.002 mm (P < 0.01), negatively correlated with soil NH_4^+-N and CEC (P < 0.05), and positively correlated with soil pH (P < 0.01). The maximum buffer capacity (MBC) of the soil was negatively correlated with SOM, NH_4^+-N, AP, AK, and the content of particles with the particle size of 0.02–0.002 mm (P < 0.01), negatively correlated with soil TN (P < 0.05), and positively correlated with soil pH (P < 0.01).

Table 3.9 Correlation between adsorption characteristic parameters and soil properties (r, n = 9).

	pH	SOM	TN	NH_4^+-N	NO_3^--N	TP	AP	AK	CEC	EC	Soil particle size distribution (%)			
											2–0.2 mm	0.2–0.02 mm	0.02–0.002 mm	<0.002 mm
Q_m	−0.763*	0.993**	0.974**	0.558	0.785*	0.081	0.974**	0.951**	0.896**	0.792*	−0.64	−0.335	0.912**	−0.34
K_l	0.877**	−0.952**	−0.917**	−0.713*	−0.644	0.119	−0.909**	−0.994**	−0.791*	−0.654	0.566	0.445	−0.944**	0.377
MBC	0.983**	−0.808**	−0.751*	−0.898**	−0.371	0.423	−0.732**	−0.979**	−0.559	−0.382	0.402	0.581	−0.917**	0.403

SOM: soil organic matter; TN: total nitrogen; TP: total phosphorus; AP: available phosphorus; AK: available potassium; CEC: cation exchange capacity; EC: electrical conductivity. *--P<0.05; **--P<0.01.

3.5 Discussion

3.5.1 Adsorption mechanism

Adsorption can be defined as the accumulation of solutes at the solid–liquid interface. This process includes the transfer of solute molecules from the solution, the removal of solvent molecules from the solid surface, and the process of solute molecules attaching to the solid surface (Stumm, 1992). Farmland soil media are heterogeneous aggregates with complex structures. A large number of organic and inorganic colloids and oxides are interlaced and mixed (Li et al., 2021). There are electric fields and residual force fields on the surface of the media that have extremely high surface energy. They can interact with ions, protons, and molecules in the soil liquid and gas phases, and they have strong adsorption on ammonium nitrogen. There are many kinds of active groups in the media, and all kinds of organic and inorganic groups can interact with ammonium. Therefore, the adsorption behavior of ammonium nitrogen in farmland soil media is complex, and the adsorption behavior in different types of media is significantly different (Krishnamoorthy and Overstreet, 1950). At present, the adsorption mechanism of ammonium nitrogen in soil media is mainly discussed at the macro and micro levels. Most macroscopic research has focused on distinguishing the different active surfaces of soil media using the differences in the extraction capacity of different extractants (Lumbanraja and Evangelou, 1994; Wang and Alva, 2000). Microscopically, the occurrence of ammonium in the medium can be identified at the molecular level using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and other spectral means (Sherman and Smulovitch, 1970; Saruchi and Kumar, 2020). Generally, the adsorption mechanism cannot be accurately described through only a single means. The present study characterized the adsorption characteristics of the three soils, and conducted a preliminary discussion based on the factors affecting the adsorption (Shen et al., 1997), but did not conduct an in-depth study of the adsorption mechanism. This will require further study.

3.5.2 Characteristics of adsorption kinetics

Soil is an important site for nitrogen circulation and transformation, and the only way for nitrogen to enter groundwater (Li et al., 2021; He et al., 2021). The adsorption of NH_4^+-N in the soil shows corresponding regularity with time change, which is one of the important characteristics of soil chemical reaction kinetics. The study of kinetics can reveal the limiting factors and control conditions that affect the adsorption rate. Commonly used adsorption kinetics equations include first-order reaction equations, second-order reaction equations, the Elovich equation, the parabolic diffusion equation, and the ExpAssoc equation. The Elovich equation reflects not only a simple adsorption process but also a complex process involving soil expansion, the activation and deactivation of adsorption sites, and surface diffusion (Sparks and Jardine, 1984). In the present experiment, the coefficient R^2 for the three types of soil adsorption data was the highest for the Elovich equation, indicating that adsorption was a heterogeneous diffusion process. Further analyzing the restrictive factors of the process revealed that the goodness of fit of the parabolic diffusion equation ($0.81 < R^2 < 0.97$) was higher than that of the first-order reaction equation ($0.78 < R^2 < 0.92$) (**Table 3.7**), indicating that the chemical adsorption process was not the rate-limiting step of the process, while the intra-particle diffusion was the main rate-limiting step. Due to the differences in soil media and environmental conditions, the relationship between adsorption capacity and time often differed during the adsorption process. Previous studies have shown that different kinetics models or the same model have different fits with different soils. In the present study, the best fitting models for the soil adsorption of NH_4^+-N were the first-order reaction equation and the Elovich equation (Xue et al., 1996). The adsorption of NH_4^+-N in silty sand, sandy silt, silt, and silty clay of four typical soils primarily occurred during 0–2 h, and the adsorption kinetics conformed to the second-order reaction equation (Tian, 2011). However, the fitting effect of the adsorption kinetics curve with the ExpAssoc equation was the best (Zhao et al., 2013). The results of this study were consistent with those of Zhao et al. (2013).

3.5.3 Adsorption thermodynamic characteristics

The adsorption of NH_4^+-N by soil is a dynamic equilibrium process. Under the same constant temperature, the curve of the adsorption amount (Q) with the equilibrium concentration (C) of the solution is normally referred to as the adsorption isotherm, and the corresponding mathematical expression is called the adsorption isothermal formula. This equation reflects the specific relationship between the adsorbent and the adsorption capacity, as well as the influence of different NH_4^+-N concentrations on the ability of the soil to adsorb NH_4^+-N. At present, the Langmuir equation, the Freundlich equation, the Henry equation, and the Temkin equation are commonly used to describe the adsorption of NH_4^+-N in soil. The Langmuir equation assumes that the medium surface is uniform and the adsorption is performed by single molecules; this model can be used to calculate the corresponding maximum saturated adsorption capacity, adsorption coefficient, and MBC, as well as to evaluate and predict the adsorption of NH_4^+-N in the soil. In this experiment, the Langmuir equation had a high degree of fit, indicating that the isothermal adsorption of NH_4^+-N in the three soils was mainly monolayer adsorption, while multi-molecular layer adsorption was of secondary importance. The Freundlich equation is often used to describe the adsorption of non-uniform surfaces, but the maximum saturated adsorption capacity cannot be calculated. The fitting parameter 1/n of the Freundlich equation in this study was between 0 and 1, indicating that the isothermal adsorption of NH_4^+-N by the three kinds of soils was relatively efficient. The Henry equation is suitable for low concentrations and weak adsorption, while the Temkin equation is only suitable for chemical adsorption. As the latter two models had poor fits to the experimental data, the fitting of these two equations was not presented in this paper. At the same time, in order to further improve the application and evaluation of the fitting results for the maximum saturated adsorption capacity, the analysis screened out the Plplatt equation whose fitting Q_m value was close to the measured average value, and the Langevin model whose fitting curve was more optimal. Although the adaptability of the assumptions that the adsorption model established to soil adsorption characteristics of NH_4^+-N was worthy of further validation, the law summarized by the analysis of the experimental data was basically consistent with the adsorption characteristics reflected by the empirical adsorption isotherm. Therefore, it was effective to use empirical adsorption isotherms to quantitatively describe the thermodynamic behavior of the soil adsorption of NH_4^+-N.

3.5.4 Soil factors affecting adsorption

The NH_4^+-N Q_m of soil is affected by soil texture, environmental temperature and humidity, artificial fertilization, and crop rotation. The Q_m obtained by the Langmuir equation reflected the maximum saturated adsorption capacity of NH_4^+-N in the soil, and the number of soil adsorption sites. Li et al. (2009) found that Q_m was significantly negatively correlated with soil pH and CEC, while it was significantly positively correlated with soil C:N. Research by Cong et al. (2017) showed that Q_m was significantly positively correlated with soil pH and CEC, while it was significantly negatively correlated with SOM and TN content. Wang et al. (2015) reported that the greater the organic matter content, the greater the NH_4^+-N adsorption capacity of albic soil. Xue et al. (1996) found that the adsorption capacity of NH_4^+-N increased with the increase of soil CEC and soil clay content to varying degrees. The results of the present study showed that the Q_m value was significantly negatively correlated with soil pH, consistent with the results of Li et al. (2009). A possible reason was that the biogas slurry was alkaline, and the pH values of weakly acidic soils in Xinbei and Jintan were neutralized, resulting in the release of adsorption sites originally occupied by H^+ and thereby reducing the competition between H^+ and NH_4^+ for adsorption sites. There was a significant positive correlation between the Q_m value and CEC, consistent with the results of Cong et al. (2017), Xue et al. (1996), and Shen et al. (1997). Q_m was positively correlated with SOM, consistent with the results of Li et al. (2009) and Wang et al. (2015). This might be because organic matter had a large number of different functional groups (Liu et al., 2010), a higher CEC, and a larger specific surface area (Acosta et al., 2016; Khorram et al., 2015; Kumar, et al., 2016); these were all factors that could increase the adsorption capacity of NH_4^+-N through surface complexation, ion exchange, and surface precipitation. These results have been verified in many studies aimed at improving soil adsorption of NH_4^+ by biochar (Yao et al., 2012).

Jiang (2004) showed that the finer the soil particles, the lower the percentage of sand powder with a particle size of ≥ 0.01 mm, while the higher the percentage of clay particles with a particle size of < 0.005 mm, the stronger the adsorption. Xue et al. (1996) reported that NH_4^+-N adsorption capacity was mainly affected by clay content, with clay > loam > sandy soil. Cong et al. (2017) showed that the NH_4^+-N adsorption capacity of soil was in the order of light clay > light loam. The results of this study showed that the Q_m value of silty loam > loam > sandy loam was consistent with the above research results. Wan et al. (2004) found that there was a very significant positive correlation between fixed ammonium and clay content < 0.01 mm, with clay content of 0.005–0.01 mm, and with clay content of 0.001–0.005 mm, but there was no significant correlation with clay content < 0.001 mm. The results of this study showed that there was a significant positive correlation between the Q_m value and the content of particles with particle size of 0.02–0.002 mm in the soil. The same trend was observed in the results of Wan et al. (2004). Therefore, it is speculated that the increase of soil fixed ammonium content is a characteristic that can be further verified based on the fact that the fixed ammonium soil content increased with the increase of ammonium ion concentration (Juang et al., 2001; Liang and MacKenzie, 1994). In addition, there was a very significant positive correlation between the Q_m value and soil TN content, as well as a significant correlation with soil nitrate nitrogen. This may be the reason for the positive and negative electrical adsorption, and may be responsible for maintaining the balance between soil new ammonium nitrogen and nitrate nitrogen. The Q_m value was positively correlated with the soil AK. This was because active K^+ ions could provide adsorption sites and solid interlayer localization for NH_4^+ ions in external soil, which was in line with cation exchange theory (Kittrick, 1966; Rich and Black, 1964). The Q_m value was positively correlated with soil AP in this experiment. There were two possible reasons: the positive and negative charge adsorption, and the combination of NH_4^+ ions and PO^{3-} ions to form $[(NH_4)\ PO_4]^{2-}$, subsequently forming complex precipitates $Mg(NH_4)[PO_4]\cdot 6H_2O$ with the Mg^{2+} and Ca^{2+} plasma in the soil, thereby increasing the adsorption of NH_4^+-N. The correlation between the Langmuir equation adsorption constant K_l value, the MBC value, and soil property-related indicators, and the correlation between the Q_m value and soil property-related indicators were opposite (Cong et al., 2017; Li et al., 2009), indicating that the adsorption strength and the adsorption capacity were complementary. In other words, when the adsorption capacity is high, the adsorption strength is low. In addition, the fitted Q_m values of the NH_4^+-N adsorption of the soils in this study were lower than the fitted value of a single chemical ammonium salt solution, thus indicating that the rich complex components of the biogas slurry interfered with the adsorption of ammonium nitrogen in the soil as described in Zhao et al. (2013). While a preliminary demonstration has been achieved in the present research, the specific mechanism of action requires further study.

3.6 Conclusions

The soil adsorption of biogas slurry NH_4^+-N predominantly occurred within 0–1 h, and the adsorption capacity within 0–1 h accounted for 35.24–43.55% of the total adsorption. The ExpAssoc equation produced a good fit for the adsorption kinetic behaviour. The optimal theoretical saturated adsorption capacity (Q_m) values fitted by the Langevin model were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively. The Q_m was significantly positively correlated with SOM, TN, AP, AK, CEC, and particle content of 0.02–0.002 mm, but significantly negatively correlated with soil pH.

3.7 References

Acosta R, Fierro V, Martinez de YA, Nabarlatz D, Celzard A. 2016. Tetracycline adsorption onto activated carbons produced by KOH activation of tyre pyrolysis char. *Chemosphere* 149: 168–176. https://doi.org/10.1016/j.chemosphere.2016.01.093.

Bradford SA, Segal E, Zheng W, Wang Q, Hutchins SR. 2008. Reuse of concentrated animal feeding operation wastewater on agricultural lands. *Journal of Environmental Quality* 37: S–97–S–115. https://doi.org/10.2134/jeq2007.0393.

Chen D, Jiang L, Huang H, Toyota K, Dahlgren RA, Lu J. 2013. Nitrogen dynamics of anaerobically digested slurry used to fertilize paddy fields. *Biology and Fertility of Soils* 49: 647–659. https://doi.org/10.1007/s00374-012-0752-8.

Ciravolo TG, Martens DC, Hallock DL, Collins ER, Kornegay ET, Thomas HR. 1979. Pollutant movement to shallow groundwater tables from anaerobic swine waste lagoons. *Journal of Environmental Quality* 8: 126–130. https://doi.org/10.2134/jeq1979.00472425000800010027x.

Cong R, Zhang L, Lu Y, Huang Q, Shi X, Li X, Ren T, Lu J. 2017. Adsorption-desorption characteristics of soil ammonium under long-term straw returning condition. *Journal of Plant Nutrition and Fertilizer* 23: 380–388. https://doi.org/10.11674/zwyf.16307.

Dalal RC. 1975. Effect of associated anions on ammonium adsorption by and desorption from soils. *Journal of Agricultural and Food Chemistry* 23: 684–687. https://doi.org/10.1021/jf60200a026.

Feinerman E, Bosch DJ, Pease JW. 2004. Manure applications and nutrient standards. *American Journal of Agricultural Economics* 86: 14–25. https://doi.org/10.1111/j.0092-5853.2004.00559.x.

Gao T, Chen N, Li W, Li B, Yuan H. 2011. Effect of highly efficient nutrient solution of biogas slurry on yield and quality of vegetables. *Agricultural science &*

technology 12: 567–570. https://doi.org/10.3969/j.issn.1009-4229-B.2011.04.026.

Ham JM, DeSutter TM. 1999. Seepage losses and nitrogen export from swine‐waste lagoons: a water balance study. *Journal of Environmental Quality* 28: 1090–1099. https://doi.org/10.2134/jeq1999.00472425002800040005x.

Han M, Liu K, Wang S, Qin L, Gao C. 2014. Definition, ingredient, approaches and risks for reuse in biogas slurry. *Journal of Agriculture* 4: 54–57.

He G, Liu X, Cui Z. 2021. Achieving global food security by focusing on nitrogen efficiency potentials and local production. *Global Food Security* 29: 100536. https://doi.org/10.1016/j.gfs.2021.100536.

Jiang G. 2004. Discussion about NH4+-N adsorptive ability in soils. *Journal of Chang an University (Arch. & Envir. Science Edition)* 21: 32–34, 38. https://doi.org/10.3321/j.issn:1673-2049.2004.02.009.

Jin H, Chang Z, Ye X, Ma Y, Jin Z. 2011. Physical and chemical characteristics of anaerobically digested slurry from large-scale biogas project in Jiangsu Province. *Transactions of the Chinese Society of Agricultural Engineering* 27: 291–296. https://doi.org/10.3969/j.issn.1002-6819.2011.01.047.

Jin H, Fu G, Chang Z, Ye X, Chen G, Du J. 2012. Distribution of nitrogen in liquid and solid fraction of pig and dairy manure in anaerobic digestion reactor. *Transactions of the Chinese Society of Agricultural Engineering* 28: 208–214.

Juang TC, Wang M, Chen H, Tan C. 2001. Ammonium fixation by surface soils and clays. *Soil Science* 166: 345–352. https://doi.org/10.1097/00010694-200105000-00005.

Khorram MS, Wang Y, Jin X, Fang H, Yu Y. 2015. Reduced mobility of fomesafen through enhanced adsorption in biochar-amended soil. *Environmental Toxicology and Chemistry* 34: 1258–1266. https://doi.org/10.1002/etc.2946.

Kithome M, Paul JW, Lavkulich LM, Bomke AA. 1998. Kinetics of ammonium adsorption and desorption by the natural zeolite clinoptilolite. *Soil Science Society of America Journal* 62: 622–629. https://doi.org/10.2136/sssaj1998.03615995006200030011x.

Kittrick JA. 1966. Forces involved in ion fixation by vermiculite. *Soil Science Society of America Journal* 30: 801–803. https://doi.org/10.2136/sssaj1966.03615995-003000060040x.

Krishnamoorthy C, Overstreet R. 1950. An expertimental evaluation of ion exchange relationships. *Soil Science* 69: 41-54. https://doi.org/10.1097/00010694-195001000-00003.

Kumar V, Kothiyal NC. 2011. Distribution behavior of polycyclic aromatic hydrocarbons in roadside soil at traffic intercepts within developing cities. *International Journal of Environmental Science &Technology* 8: 63–72. https://doi.org/10.1007/BF03326196.

Kumar V, Kothiyal NC. 2012. Distribution behavior and carcinogenic level of some polycyclic aromatic hydrocarbons in roadside soil at major traffic intercepts within a developing city of India. *Environmental Monitoring and Assessment* 184: 6239–6252. https://doi.org/10.1007/s10661-011-2416-9.

Kumar V, Kothiyal NC, Saruchi. 2016. Analysis of polycyclic aromatic hydrocarbon, toxic equivalency factor and related carcinogenic potencies in roadside soil within a developing city of Northern India. *Polycyclic Aromatic Compounds* 36: 506–526. https://doi.org/10.1080/10406638.2015.1026999.

Li H, Han Y, Cai Z. 2009. Equilibrium of ammonium adsorption in paddy soils of Taihu region of China under different reaction conditions. *Chinese Journal of Soil Science* 40: 89–95. https://doi.org/10.3321/j.issn:0564-3945.2009.01.026.

Li W, Shi Y, Zhu D, Wang W, Liu H, Li J, Shi N, Ma L, Fu S. 2021. Fine root biomass and morphology in a temperate forest are influenced more by the nitrogen treatment approach than the rate. *Ecological Indicators* 130: 108031. https://doi.org/10.1016/j.ecolind.2021.108031.

Li X, Zhang C, Zhang B, Wu D, Zhu D, Zhang W, Ye Q, Yan J, Fu J, Fang C, Ha D, Fu

S. 2021. Nitrogen deposition and increased precipitation interact to affect fine root production and biomass in a temperate forest: Implications for carbon cycling. *Science of the Total Environment* 765: 144497. https://doi.org/10.1-016/j.scitotenv.2020.144497.

Liang B, MacKenzie AF. 1994. Fertilization rates and clay fixed ammonium in two Quebec soils. *Plant and Soil* 163: 103–109. https://doi.org/10.1007/bf00033-946.

Liu C, Chen Y, Li X, Zhang Y, Ye J, Huang H, Zhu C. 2020. Temporal effects of repeated application of biogas slurry on soil antibiotic resistance genes and their potential bacterial hosts. *Environmental Pollution* 258: 113652. https://doi.org/10.1016/j.envpol.2019.113652.

Liu H, Dong Y, Wang H, Liu Y. 2010. Ammonium adsorption from aqueous solutions by strawberry leaf powder: equilibrium, kinetics and effects of coexisting ions. *Desalination* 263: 70–75. https://doi.org/10.1016/j.desal.2010.06.040.

Lu J, Zhu L, Hu G, Wu J. 2010. Integrating animal manure-based bioenergy production with invasive species control: a case study at tongren pig farm in China. *Biomass Bioenergy* 34: 821–827. https://doi.org/10.1016/j.biombioe.2010.0-1.026.

Lumbanraja J, Evangelou VP. 1994. Adsorption-desorption of potassium and ammonium at low cation concentrations in three kentucky subsoils. *Soil Science* 157: 269–278. https://doi.org/10.1097/00010694-199405000-00001.

Ni Z, Zhang M. 2017. Chemical compositions of nitrogen, phosphorus, and potassium in biogas slurry and their bio-availability. *Chinese Journal of Soil Science* 48: 1114–1118. https://doi.org/10.19336/j.cnki.trtb.2017.05.13.

Ning J, Zhou M, Pan X, Li C, Lv N, Wang T, Cai G, Wang R, Li J, Zhu G. 2019. Simultaneous biogas and biogas slurry production from co-digestion of pig manure and corn straw: performance optimization and microbial community shift. *Bioresource Technology* 282: 37–47. https://doi.org/10.1016/j.biortech.-2019.02.122.

Rich CI, Black WR. 1964. Pottasium exchange as affected by cation size, pH, and mineral structure. *Soil Science* 97: 384–390. https://doi.org/10.1097/000106-94-196406000-00004.

Saruchi, Kumar V. 2020. Effective degradation of rhodamine B and Congo red dyes over biosynthesized silver nanoparticles-imbibed carboxymethyl cellulose hydrogel. *Polymer Bulletin* 77: 3349–3365. https://doi.org/10.1007/s00289-019-02920-x.

Shen S, Tu S, Kemper WD. 1997. Equilibrium and kinetic study of ammonium adsorption and fixation in sodium-treated vermiculite. *Soil Science Society of America Journal* 61: 1611–1618. https://doi.org/10.2136/sssaj1997.03615995-006100060011x.

Sherman WF, Smulovitch PP. 1970. Pressure-scanned fermi resonance in the spectrum of NH_4^+ isolated in CsBr. *The Journal of Chemical Physics* 52: 5187–5193. https://doi.org/10.1063/1.1672759

Sparks DL, Jardine PM. 1984. Comparison of kinetic equations to describe potassium-calcium exchange in pure and in mixed systems. *Soil Science* 138: 115–122. https://doi.org/10.1097/00010694-198408000-00004.

Stumm W. 1992. Chemistry of the Solid-Water Interface. New York: John Wiley & Sons.

Tian H. 2011. Ammonia-nitrogen adsorption characteristics onto vadose zone soils in Luanhe Delta. *Chinese Journal of Environmental Engineering* 5: 507–510.

Wan D, Zhang Y, Feng Y, Huang Y. 2004. Fixed ammonium content of soils on cultivated upland in Hunan province and its affecting factors. *Acta Pedologica Sinica* 41: 480–483. https://doi.org/10.3321/j.issn:0564-3929.2004.03.025.

Wang F, Alva AK. 2000. Ammonium adsorption and desorption in sandy soils. *Soil Science Society of America Journal* 64: 1669–1674. https://doi.org/10.2136-/sssaj2000.6451669x.

Wang S, Wang N, Zhang J, Fan C. 2015. Influencing factors of NH_4^+ adsorption characteristics on albic soil. *Soil and Fertilizer Sciences in China* 2: 22–28. https://doi.org/10.11838/sfsc.20150205.

Wang Y, Fu J, Wang Q, Wang J, Ma J, Jiang L. 2010. Effect of biogas slurry farmland disposal and utilization on pepper´s yield, quality and soil fertility. *Acta Agriculturae Zhejiangensis* 22: 859–863. https://doi.org/10.3969/j.issn.1004-1524.2010.06.030.

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2016. Analysis of water environment risk on biogas slurry disposal in paddy field. *Transactions of the Chinese Society of Agricultural Engineering* 32: 213–220. https://doi.org/10.11975/j.issn.1002-6819.2016.05.030.

Xue Q, Wei Q, Gao Y, Shi H, Qu D. 1996. Kinetic characteristics of NH_4^+ adsorption-desorption for five major soils in Shanxi Province. *Acta Pedologica Sinica* 32: 129–136.

Yang R, Sun Q, Zhao H, Zou G, Liu B, Li L. 2017. Precision application of biogas slurry and its environmental effects in paddy fields. *Journal of Agro-Environment Science* 36: 1566–1572. https://doi.org/10.11654/jaes.2016-1617.

Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* 89: 1467–1471. https://doi.org/10.1016/j.chemosphere.2012.06.002.

Zhao W, Li Y, Zhao Q, Ning Z, Zhou C, Wang H, Lu L, Yang P, Zhang K, Wang F, Huang Z, Ouyang Z. 2013. Adsorption and desorption characteristics of ammonium in eight loams irrigated with reclaimed wastewater from intensive hogpen. *Environmental Earth Sciences* 69: 41–49. https://doi.org/10.1007/s-12665-012-1932-4.

Zhu J, Huang T. 2010. New processing technologies in livestock wastewater treatment. Chemical Industry Press, Beijing.

CHAPTER 4: AGING CHARACTERISTICS AND FATE ANALYSIS OF LIQUID DIGESTATE AMMONIUM NITROGEN DISPOSAL IN FARMLAND SOIL

This chapter has been published as detailed below:
Wang Z, Sun G, Zhang L, Zhou W, Sheng J, Ye X, Olaniran AO, Kana EBG, Shao H. 2022. Aging characteristics and fate analysis of liquid digestate ammonium nitrogen disposal in farmland soil. *Water* 14(16):2487. https://doi.org/10.3390/w14162487.

4.1 Abstract

Water environment safety is the focus of engineering measures to eliminate liquid digestate in farmland. It is of great significance to study the aging characteristics of soil absorbing and fate of liquid digestate ammonium nitrogen (NH_4^+-N) to realize safe and efficient disposal. In this paper, simulation experiments of digesting NH_4^+-N (with an application of 0, 120, 180, and 300 kg/hm^2) by static soil column are carried out to study disposal efficiency, migration and transformation characteristics, and fate proportion of NH_4^+-N in saturated water content soil. The result showed that after 3 days of application, the overlying water NH_4^+-N concentration decreased by 63.5– 80.7%, and the reduction rate of total NH_4^+-N was 65.8–82.3%. After 4 days, the NH_4^+- N concentration of pore water in the 0–10 cm soil layer reached the peak value. After 7 days, the NH_4^+-N concentration adsorbed by the 0–10 cm soil layer reached the peak value. After 15 days, the overlying water NH_4^+-N concentration decreased by 97.0–98.7%, the reduction rate was 97.9–99.2%, and the proportion of NH_4^+-N absorbed in the 0–10 cm soil layer accounted for 63.5–76.3%. The disposal is mainly based on soil sorption and pore water migration. A duration of 0–3 days is the rapid disposal period, and 15 days is the completion period of safe digestion.

Keywords: *waste biomass utilization; liquid digestate; ammonium nitrogen; sorption; migration; transformation*

4.2 Introduction

To reduce the environmental pollution of the livestock and poultry breeding industry (Wu et al., 2014), in recent years, the Chinese government has continued to strengthen the construction of biogas projects in livestock and poultry farms, and has continuously promoted the transformation and upgrading of rural biogas projects in combination with the green development of agriculture and the action of replacing chemical fertilizers with organic fertilizers (Song et al., 2021; Li et al., 2022; Zhang et al., 2021b), using the anaerobic fermentation process to dispose of aquaculture excrement, in order to realize the harmless treatment and resource reuse of aquaculture manure (Nasir et al., 2012; Lu et al., 2021). By the end of the year 2020, 128,976 small and medium-sized biogas projects and 10,122 large-scale biogas projects have been built nationwide (Zou et al., 2020). Liquid digestate is a by-product of biogas engineering, accounting for more than 90% of the total fermentation residue (Dong et al., 2021). According to estimates, China produces 1.12 billion tons of liquid digestate annually (Zou et al., 2020). Due to the large amount of liquid digestate produced, high storage and transportation costs, difficult treatment to meet standards, and low commercialization value, there are serious secondary pollution environmental risks (Liang et al., 2013). The treatment and utilization of liquid digestate have become the focus and difficulty of domestic and foreign research (Jiang et al., 2011c; Wang et al., 2014a; Nkoa, 2014; Hagos et al., 2017; He et al., 2017; Fang et al., 2015). The use of farmland soil, crops, and microorganisms living in the soil to absorb liquid digestate is a widely recognized green treatment method (Wang et al., 2016; Manici et al., 2021), but the amount of farmland consumption cannot exceed the limit of land carrying capacity (Feng and Li, 2018); otherwise, it will cause serious pollution to the surrounding soil and water bodies (Monlau et al., 2015; Ternoeven-Urselmans et al., 2009). High ammonia nitrogen (NH_4^+-N) concentration in liquid digestate components is the primary risk factor for environmental pollution (Wang et al., 2016; Zhang et al., 2021a; Zhang et al., 2020). Therefore, it is of great significance to study the aging characteristics of farmland soil to absorb liquid digestate and the fate of NH_4^+-N to realize safe and efficient disposal of liquid digestate in farmland.

According to the soil nitrogen transport theory (Wang et al., 2014b; Tan et al., 2015), after the liquid digestate is applied to the farmland, NH_4^+-N in the unsaturated water content soil completes vertical and horizontal transport with water in convection mode, while the saturated water content soil completes migration from the high-concentration area to the low-concentration area by diffusion infiltration. During the migration process, NH_4^+-N will be rapidly adsorbed and gradually nitrified into nitrate nitrogen (NO_3^--N) (Pote et al., 2001). When local surface runoff is generated, NH_4^+-N and NO_3^--N not adsorbed by soil particles will be lost and leached with water at the same time, thus polluting the surrounding water sources (Lovejoy et al., 1997; Velthof et al., 2005; Paul et al., 1998). Liquid digestate contains relatively more available nitrogen. Therefore, it has been proposed that liquid digestate application will lead to more nitrogen leaching loss than manure application. However, after a two-and-a-half-year corn field experiment, there was no significant difference in nitrogen leaching amount between digestate application and manure and chemical fertilizer application (Svoboda et al., 2013). When liquid digestate is applied by spraying and deepening in the slack season in autumn, there is no risk of NH_4^+-N and NO_3^--N leaching. However, when liquid digestate is applied by injection, there is still a potential risk of NH_4^+-N leaching even when the nitrogen dosage of liquid digestate is 90 kg/(hm^2·d) (Liu et al., 2021). The study on disposal of liquid digestate in paddy fields shows that the concentration of NH_4^+-N in field surface water decreases rapidly 1–4 days after application (Wang et al., 2016; Jiang et al., 2011a). After 8 days of application, the NH_4^+-N concentration in field surface water can basically reach the level of the blank control field. The concentration of NH_4^+-N in groundwater is always lower than that of chemical fertilizer treatment, and does not increase with the increase in liquid digestate application amount (Shi, 2010); meanwhile, the content of NO_3^--N in field surface water and groundwater will not increase significantly (Chen et al., 2013). The increase in ammonia volatilization is considered to be the main negative impact of liquid digestate application on the farmland environment (Jiang et al., 2011a; Huijsmans et al., 2001; Nicholson et al., 2017). After liquid digestate application, the ammonia volatilization is higher than that of the total chemical fertilizer treatment. With the increase in liquid digestate dosage, the ammonia volatilization is increased, and the soil wetting or flooding conditions can reduce the ammonia volatilization (Smith et al., 2000; Hou et al., 2007; Zhou et al., 2009).

The above studies monitored and qualitatively analyzed the changes of nitrogen concentration in farmland water after liquid digestate was applied, but there was a lack of quantitative research on the reduction process of liquid digestate NH_4^+-N. It is a new way to treat liquid digestate by using farmland with saturated water content for disposal, which is different from the fertilizer utilization of liquid digestate. When taking measures to absorb liquid digestate in farmland with saturated water content, farmers are more concerned about the main destination of NH_4^+-N after liquid digestate is applied in farmland and the time required for the discharge of field water quality up to standard. In this paper, the simulation experiment of indoor static soil column is used to study the time-effect of absorbing NH_4^+-N from liquid digestate in saturated water content soil, analyze the migration and transformation characteristics and fate ratio of NH_4^+-N from liquid digestate, and discuss the time required for the discharge of field surface water quality to meet the standard, to provide theoretical basis and technical guidance for the efficient elimination of liquid digestate in farmland under the safety of water environment.

4.3 Materials and methods

4.3.1 Materials

The tested liquid digestate was taken from Jiangsu Yangyu Ecological Agriculture Co., Ltd. (Taizhou, China), which produces around 120,000 commercial pigs annually, and was recognized by the Ministry of Agriculture and Rural Affairs as a “pig standardization demonstration farm”, a provincial key leading enterprise of agricultural industrialization in Jiangsu Province, and a comprehensive demonstration base of circular ecological agriculture of Jiangsu Academy of Agricultural Sciences (Nanjing, China). The liquid digestate was generated from liquid manure and sewage through primary anaerobic fermentation in biogas engineering with a continuous stirred-tank reactor (CSTR) and a secondary anaerobic fermentation using a covered lagoon storage process (**Figure 4.1**). Once taken back to the laboratory, the liquid digestate was stored in sealed plastic barrels and was mixed well. The solid and insoluble matter were filtered out of digestate through a 0.25-mm mesh screen and were not used for the experiment. The average properties of liquid digestate measured before this test are: pH value 8.05 ± 0.06, total nitrogen (TN) 461.63 ± 5.39 mg/L, NH_4^+-N 409.12 ± 6.75 mg/L, NO_3^--N 31.56 ± 0.08 mg/L, total phosphorus (TP) 17.72 ± 0.14 mg/L, total potassium (TK) 279 ± 2.74 mg/L, chemical oxygen demand (COD) 470.11 ± 7.85 mg/L, electrical conductivity (EC) 3.81 ± 0.01 mS/cm, and total solid (TS) 1.63 ± 0.01 g/L.

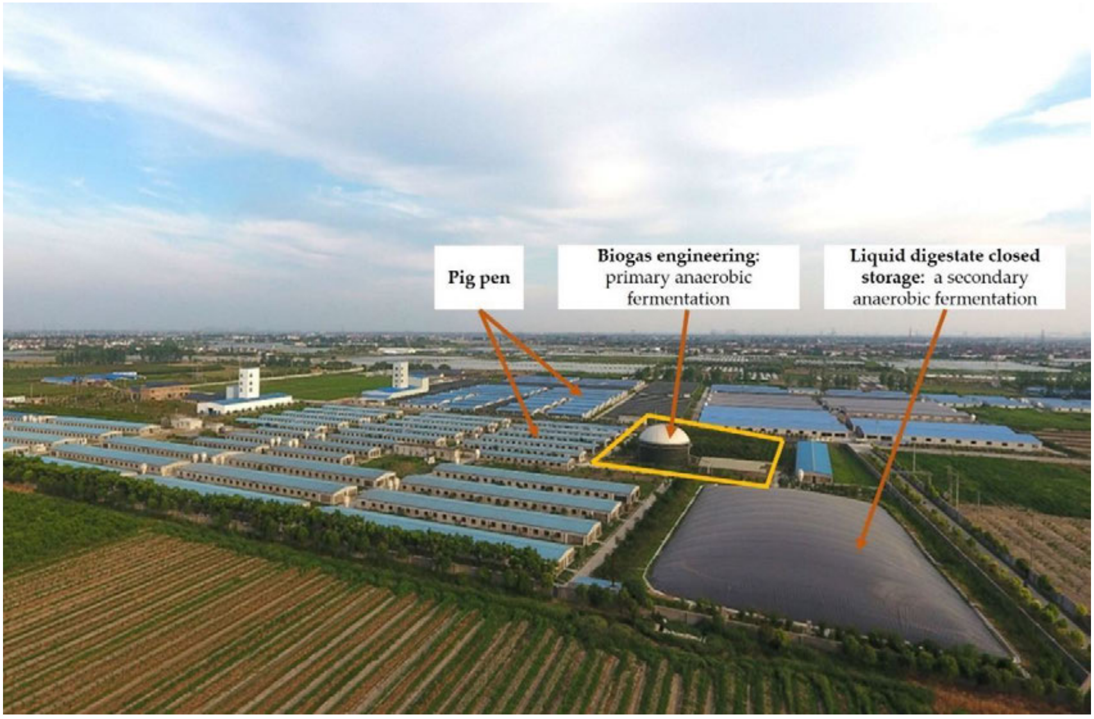


Figure 4.1 Biogas engineering and liquid digestate storage facilities in pig farms.

The experimental soil was collected from the Xinbei District of Changzhou City in the Yangtze River Basin of China. It was 0–20 cm topsoil of permanent basic farmland, and its texture was silty loam. The soil was dried naturally, while stones, plant roots, and other sundries found in the soil were removed. The soil was then crushed with a round wooden stick, sieved through a 2 mm aperture mesh screen, and finally fully mixed into a clean plastic storage box for future use. The basic physical and chemical properties of the soil are: soil organic matter (SOM) 29.09 ± 0.39 g/kg, pH value 6.45 ± 0.04, TN 1.16 ± 0.17 g/kg, NH_4^+-N 8.93 ± 0.57 mg/kg, NO_3^--N 56.97 ± 0.43 mg/kg, TP 0.57 ± 0.02 g/kg, available phosphorus (AP) 13.10 ± 1.47 mg/kg, available potassium (AK) 122.91 ± 13.21 mg/kg, cation exchange capacity (CEC) 16.27± 0.49 cmol/kg, and EC 492.67 ± 19.14 μS/cm. The soil particle group is composed of 30.5% particles with a particle size of 2–0.05 mm, 52.9% particles with a particle size of 0.05–0.002 mm, and 16.5% particles with a particle size less than 0.002 mm.

4.3.2 Static soil column fabrication

An indoor static soil column was used to simulate the experiment (**Figure 4.2**). The manufacturing method for the soil column is as follows: firstly, a flat-bottom glass tube with an inner diameter of 6.0 cm and a height of 30.0 cm is customized, and the cross-sectional surface area of the test tube is 28.26 cm^2. Use a 1% electronic balance to accurately weigh 600 g of the prepared soil into a flat-bottomed tube, shake the tube to make the soil solid (the soil depth is about 20 cm), and then add 369.9 mL of deionized water (the data is the sum of the saturated water content and pore water content of the soil used in the actual test) so that the water content of the soil column reaches the maximum saturated state, and stand for use after standing overnight.

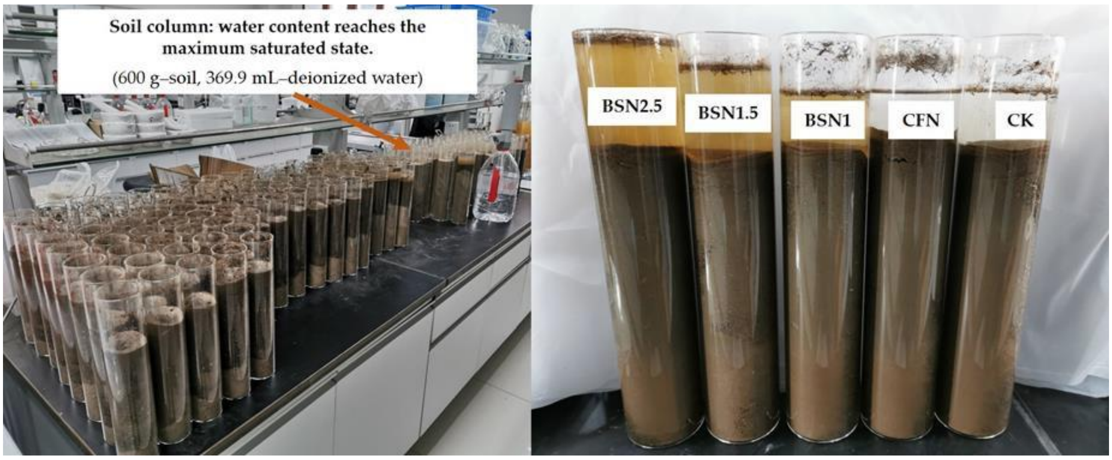


Figure 4.2 Physical photos of static soil column.

4.3.3 Design and setting

There are 5 treatments in the experiment as follows:

Treatment ①: Apply chemical fertilizer NH_4^+-N 120 kg/hm^2. The amount refers to the customary nitrogen fertilizer amount of farmers in the rice panicle fertilizer stage of saturated water content paddy fields, which is recorded as: CFN1. Weigh the pure analytical reagent NH_4Cl and add it into deionized water, then prepare 409 mg/L NH_4^+-N solution with the same concentration as the liquid digestate. Measure 82.9 mL of solution, and add it to the soil column surface.

Treatment ②: Apply liquid digestate NH_4^+-N 120 kg/hm^2, which is 1 times the amount of chemical fertilizer NH_4^+-N in Treatment ①, denoted as: BSN1. Measure 82.9 mL of liquid digestate, and add it to the surface of the soil column.

Treatment ③: Apply liquid digestate NH_4^+-N 180 kg/hm^2, which is 1.5 times the amount of chemical fertilizer NH_4^+-N in Treatment ①, referring to the accustomed nitrogen fertilizer dosage of farmers in the rice base-tiller fertilizer period of saturated water content paddy fields, denoted as: BSN1.5. Measure 124.4 mL of liquid digestate, and add it to the surface of the soil column.

Treatment ④: Apply liquid digestate NH_4^+-N 300 kg/hm^2, which is 2.5 times the amount of chemical fertilizer NH_4^+-N in Treatment ①, with reference to the total nitrogen fertilizer dosage used by farmers in the rice season in paddy fields with saturated water content, recorded as: BSN2.5. Measure 207.3 mL of liquid digestate, and add it to the surface of the soil column.

Treatment ⑤ : No fertilization control, keep the same amount of water as Treatment ①, denoted as CK. Measure 82.9 mL of deionized water, and add it to the soil column surface.

Thirty replicates were set up for each treatment, for a total of 150 soil pillars. Take destructive sampling, take 3 repeated soil columns each time, and discard the soil columns after the measurement.

4.3.4 Sampling and analysis

At 0, 1, 2, 3, 4, 5, 7, 9, 12, and 15 days after the application of liquid digestate, the overlying water was taken from the soil column, and the concentrations of NH_4^+-N and NO_3^--N in the overlying water were measured. After removing the overlying water, excavate 0–10 cm topsoil in the soil column, centrifuge at 4000 r/min for 5 min, and take the supernatant (soil pore water) to measure NH_4^+-N and NO_3^--N concentrations. The soil after centrifugation (Soil Sample 1) was retained, and the soil water content, soil water-soluble NH_4^+-N content (Kowalenko and Yu, 1996), and soil ion-exchanged NH_4^+-N content (Steffens and Sparks, 1997) were determined.

Determination method of soil water-soluble NH_4^+-N content (Zhang, 2017): Take 8.00 g of the centrifuged soil (Soil Sample 1) sample, put it into a centrifuge tube, add 40 mL of deionized water according to the solid–liquid ratio of 1:5, and tighten the sealing cap of the centrifuge tube. Mix thoroughly, shake at 160 r/min for 30 min at 25 °C with a thermostatic oscillator, then centrifuge at 4000 r/min for 20 min, collect the supernatant, and repeat the above operation twice for the soil samples in the centrifuge tube. The supernatants collected three times were mixed for the determination of soil water-soluble NH_4^+-N content. Retain the centrifuge tube and the soil in the tube (Soil Sample 2).

Determination method of ion-exchanged NH_4^+-N content (Zhang, 2017): Add 40 mL of KCl solution with a concentration of 0.5 mol/L to the centrifuge tube where the soil (Soil Sample 2) after extraction of water-soluble NH_4^+-N is located, tighten the sealing cap of the centrifuge tube, and mix well. At 25 °C, shake at 160 r/min for 60 min with a thermostatic oscillator, then centrifuge at 4000 r/min for 10 min, collect the supernatant, and repeat the above operation twice for the soil samples in the centrifuge tube. The supernatants collected three times were mixed and used to determine the ion-exchanged NH_4^+-N content of the soil.

The NH_4^+-N and NO_3^--N contents of all water quality in this experiment were determined by a SKALAR SAN++ full-automatic flow analyzer (Skalar Analytical B.V. Products, Breda, the Netherlands). Daily water evaporation loss of the soil column was measured by using a 1% electronic balance to weigh and calculate the difference with the subtraction method.

4.3.5 Calculation formula

Water evaporation loss of soil column:

$$V_t = \frac{(m_0 - m_t)}{\rho} \tag{1}$$

In the Formula (1): V_t is liquid digestate evaporation loss of overburden water in t day (mL); m_0 is overall mass of soil column on Day 0 (within 8 h) after liquid digestate is applied (g); m_t is the overall mass of soil column on t-day (g); ρ is density of water (g/mL).

Reduction rate of liquid digestate NH_4^+-N in overlying water:

$$R(\%) = \frac{M - C_t \cdot (V_0 - V_t)}{M} \times 100 \tag{2}$$

In Formula (2): M is total application amount of NH_4^+-N (mg); C_t is NH_4^+-N concentration in overlying water on t-day (mg/L); V_0 is initial application volume of liquid digestate (L); V_t is liquid digestate evaporation loss on t-day (L).

Fate of liquid digestate NH_4^+-N:

$$F(\%) = \frac{C_t \cdot V}{M} \times 100 = \frac{\omega_t \cdot m}{M} \times 100 \tag{3}$$

In Formula (3): M is total application amount of NH_4^+-N (mg); C_t is NH_4^+-N, NO_3^--N concentration in overlying water or in soil pore water on t-day (mg/L); V is residual volume of overlying water or pore water volume (L); ω_t is the concentration of NH_4^+-N and NO_3^--N adsorbed by the soil on t-day (mg/kg); m is soil mass (kg).

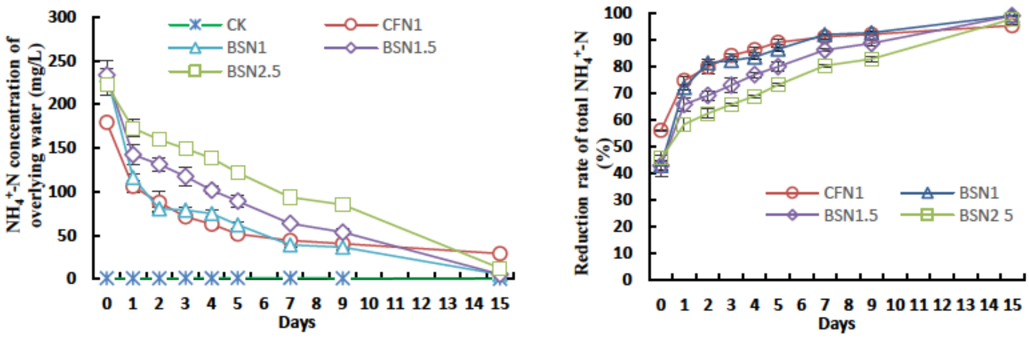
4.3.6 Data analysis

Microsoft Office Excel (2016) software was used for the summary, analysis, and graphing of experimental data, and IBM SPSS Statistics (22) software was used for one-way ANOVA and Duncan's method for analysis of variance and multiple comparisons ($\alpha = 0.05$). Data in the graph are mean ± standard deviation.

4.4 Results

4.4.1 Variation characteristics of NH_4^+-N concentration and NH_4^+-N reduction rate in overlying water

The dynamic change process of liquid digestate NH_4^+-N consumption and the reduction rate in overlying water with saturated water content farmland soil are shown in **Figure 4.3**. After liquid digestate was applied to the soil surface with saturated water content, the concentration of NH_4^+-N in the overlying water decreased gradually with the extension of time, and the reduction rate of the total amount of NH_4^+-N gradually increased. Among them, 0–3 days is the rapid digestion period. During this period, the concentration of NH_4^+-N in the overlying water drops rapidly, the decline range is 63.5–80.7% (**Figure 4.3a**), and the total reduction rate of NH_4^+-N reaches 65.8–82.3% (**Figure 4.3b**).



(a) (b)

Figure 4.3 Digestion characteristics (a) and reduction rate (b) of liquid digestate NH_4^+-N in the overlying water.

Compared with CFN1 treatment, under the condition of equal NH_4^+-N, the NH_4^+-N concentration in overlying water of BSN1 treatment increased significantly ($p < 0.05$) and then decreased rapidly after 0 days of liquid digestate application (the sampling time was within 8 h after liquid digestate application). On the third day after application, the NH_4^+-N concentration of the overlying water decreased to 78.88 mg/L, which was lower than the discharge concentration of 80 mg/L, specified in the emission standard of pollutants for the livestock and poultry breeding industry (GB18596-2001) (General Administration of Environmental Protection of the People's Republic of China, 2003), and lower than that of the CFN1 treatment, but the difference was not significant. The

NH_4^+-N concentration rebounded slightly after application for 3–7 days and remained lower than that of CFN1 treatment after application for 7 days. After 15 days, the NH_4^+-N concentration in the overlying water of BSN1 treatment decreased to 5.16 mg/L, which was significantly lower than that of CFN1 treatment ($p < 0.05$). The NH_4^+-N concentration decreased by 98.7%, and the total reduction rate of NH_4^+-N reached 99.2%. However, with high ammonium nitrogen treatment of BSN1.5 and BSN2.5, the NH_4^+-N concentration in the overlying water was significantly higher than that of CFN1 treatment from 0 to 9 days after application, but after 15 days, the NH_4^+-N concentration decreased to 5.18 mg/L and 12.32 mg/L, respectively, which were significantly lower than that of CFN1 treatment ($p < 0.05$). The NH_4^+-N concentration of the two treatments decreased by 98.7% and 97.0%, and the total reduction rate of NH_4^+-N was 99.0% and 97.9%.

4.4.2 Migration and soil sorption characteristics of liquid digestate NH_4^+-N

Figure 4.4a shows the change of NH_4^+-N concentration in soil pore water in the 0–10 cm soil layer. After the application of liquid digestate, the NH_4^+-N in the overlying water diffused and migrated downward, and the NH_4^+-N concentration in soil pore water increased rapidly. The larger the amount of liquid digestate applied, the higher the NH_4^+-N concentration in soil pore water in the 0–10 cm soil layer. On the fourth day after application, the NH_4^+-N content in the pore water reached a peak value and then decreased slowly. The NH_4^+-N concentration of BSN1, BSN1.5, and BSN2.5 treatments were 24.41 mg/L, 27.40 mg/L, and 28.91 mg/L, which were significantly higher than those of CFN1 treatment by 16.4%, 30.7%, and 37.9%, respectively ($p < 0.05$).

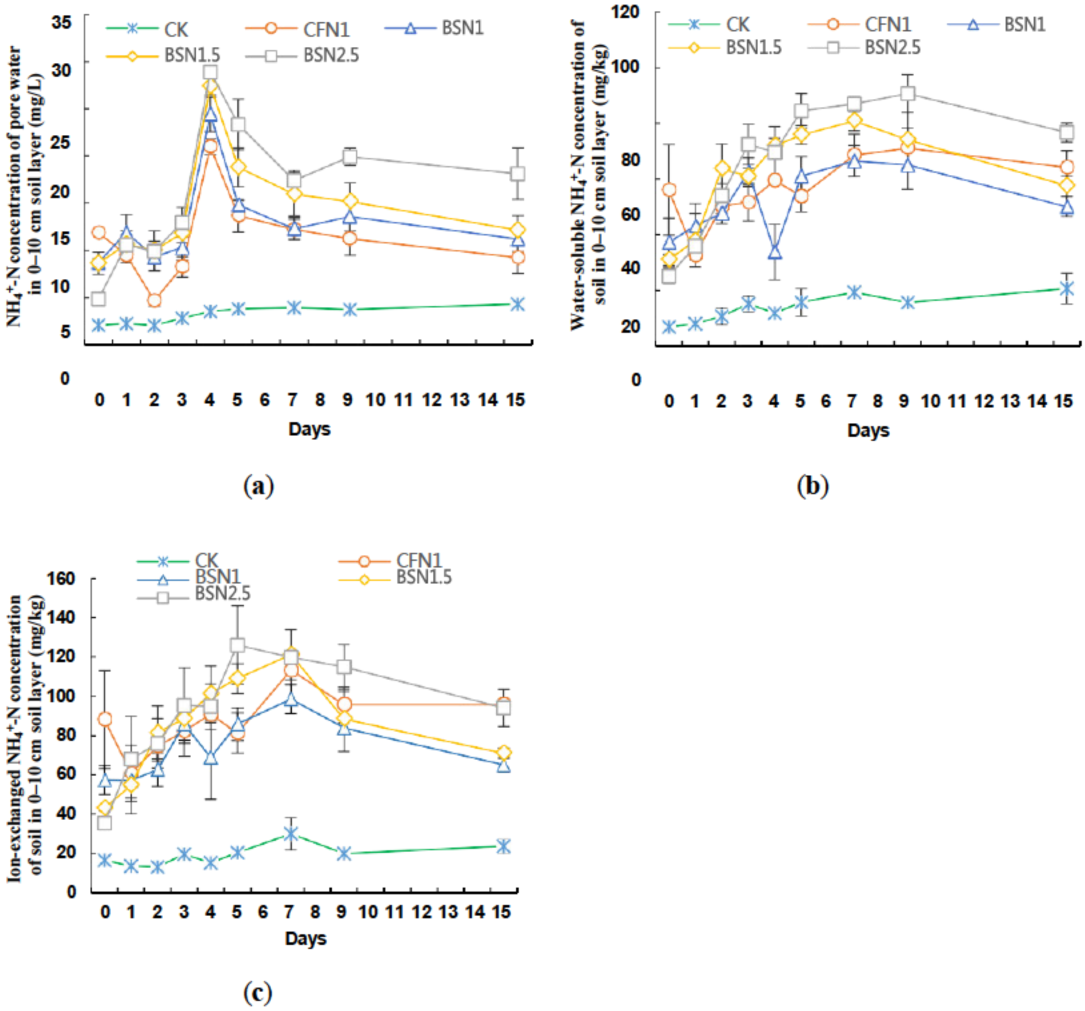
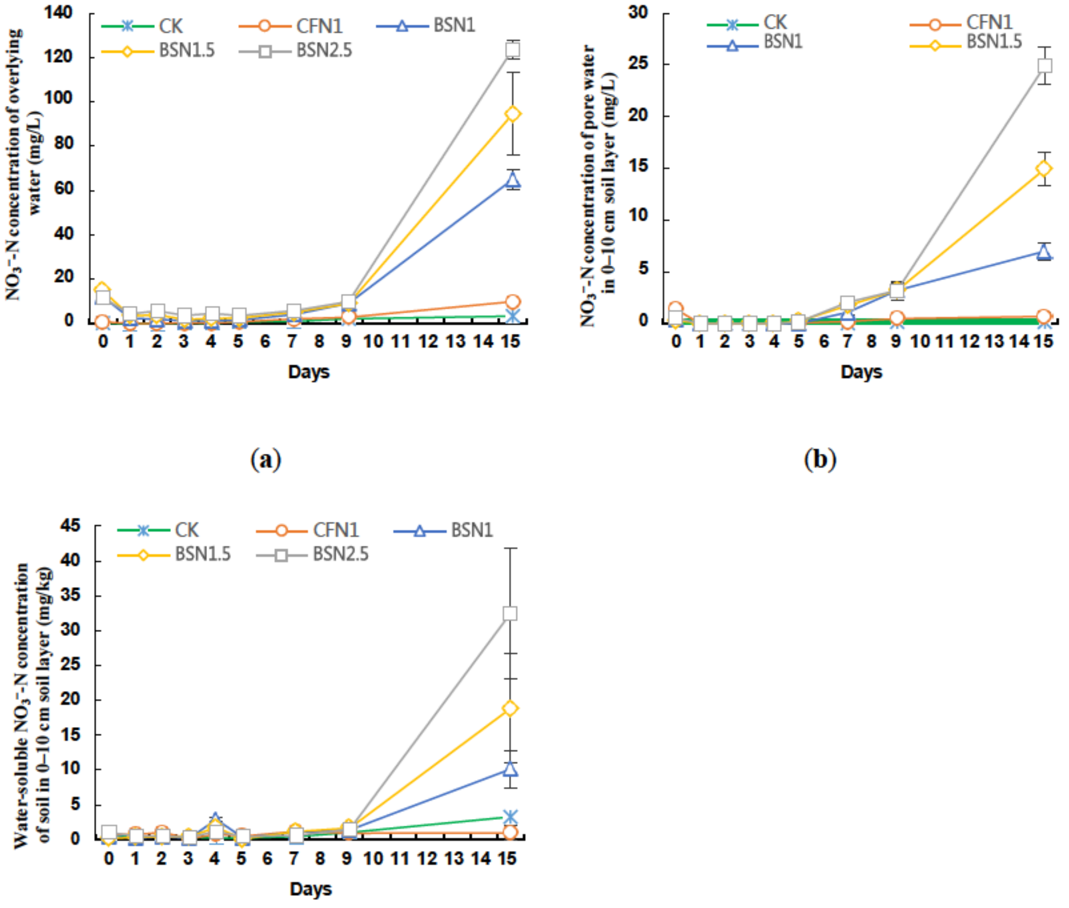


Figure 4.4 Migration of NH_4^+-N in soil pore water (a) and changes of NH_4^+-N adsorbed by soil (b,c).

Figure 4b,c shows the changes of soil water-soluble NH_4^+-N and ion-exchanged NH_4^+-N in the 0–10 cm soil layer. After the liquid digestate was applied, the increase in NH_4^+-N concentration in soil pore water created a good environment for soil particles to adsorb NH_4^+-N. The soil water-soluble NH_4^+-N concentration and ion-exchange NH_4^+-N concentration increased first and then decreased, and the more liquid digestate applied, the higher the soil water-soluble NH_4^+-N concentration and the ion-exchanged NH_4^+-N concentration. Under the condition of equal NH_4^+-N content, the soil water-soluble NH_4^+-N concentration and ion-exchange NH_4^+-N concentration of BSN1 treatment reached the peak value on the seventh day after liquid digestate application, but they were 3.0% and 13.1% lower than those of CFN1 treatment respectively, and the difference between treatments was not significant. With the high ammonium nitrogen content BSN1.5 treatment, on the seventh day, the soil water-soluble NH_4^+-N concentration and ion-exchange NH_4^+-N concentration reached the peak, which were significantly higher than that of CFN1 treatment by 17.9% and 7.0%, respectively ($p < 0.05$). The concentration of ion-exchange NH_4^+-N in BSN2.5 treatment reached the peak on the fifth day, but the concentration of water-soluble NH_4^+-N reached the peak on the ninth day, which was significantly higher than that in BSN1 treatment. After the NH_4^+-N sorption (Pourret et al., 2022) reached the peak, desorption and transformation gradually appeared. On the 15th day, the concentration of water-soluble NH_4^+-N and the concentration of ion-exchange NH_4^+-N in BSN1 and BSN1.5 treatments were lower than that in CFN1 treatment, and the difference of ion-exchange NH_4^+-N concentration reached a significant level ($p < 0.05$).

4.4.3 Characteristics of liquid digestate NH_4^+-N converted to NO_3^--N

The concentration changes of liquid digestate NH_4^+-N converted to NO_3^--N was shown in **Figure 4.5**. The change trends of NO_3^--N in overlying water (**Figure 4.5a**), pore water (**Figure 4.5b**), and soil water-soluble (**Figure 4.5c**) are basically the same. NO_3^--N concentrations were consistently low and there were no significant differences between treatments. Since the seventh day, the NO_3^--N concentrations in overlying water, pore water, and soil water-soluble NO_3^--N of treatments BSN1, BSN1.5, and BSN2.5 all increased significantly compared with those of CFN1 and CK treatments ($p < 0.05$). The greater the amount of liquid digestate application, the greater the increase in NO_3^--N.



(a) (b)

(c)

Figure 4.5 Concentration changes of NO_3^--N in overlying water (a), pore water (b), and soil water-soluble (c).

4.4.4 Fate analysis of farmland absorbing liquid digestate NH_4^+-N

Figure 4.6 is the analysis of the fate of NH_4^+-N in BSN1, BSN1.5, and BSN2.5 treatments on the 15th day of liquid digestate application. The disposal of liquid digestate NH_4^+-N is mainly based on soil particle sorption and conversion, but with the increase in liquid digestate application, the proportion of NH_4^+-N absorbed by soil decreases. The proportions of nitrogen (sum of NH_4^+-N and NO_3^--N) in soil sorption and pore water storage in the 0–10 cm soil layer of treatments BSN1, BSN1.5, and BSN2.5 accounted for 76.3%, 67.1%, and 63.5% of the total applied NH_4^+-N, respectively. The residual proportions of overlying water were 0.9%, 1.1%, and 2.4%, respectively, and the proportions of other destinations (including migration to deeper soil layers, transformation, and volatilization loss of overlying water, etc.) were 22.8%, 31.8%, and 34.1%, respectively. Among them, BSN1, BSN1.5, and BSN2.5 treatments accounted for 62.8%, 49.7%, and 44.7% of the total applied NH_4^+-N by soil sorption in the 0–10 cm soil layer, respectively, and the NH_4^+-N adsorbed by soil ion-exchange state was greater than that adsorbed by water-soluble state. The proportion of nitrogen contained in pore water is 7.5%, 8.3%, and 8.4%, which are higher than the corresponding residual amount of overlying water, indicating that the diffusion and migration of liquid digestate NH_4^+-N from overlying water to interstitial water in the 0–10 cm soil layer has been completed after 15 days of liquid digestate application, and the more application, the more migration. The proportion of water-soluble NO_3^--N in soil accounts for 6.1%, 9.2%, and 10.3%, indicating that the liquid digestate NH_4^+-N has been transformed into NO_3^--N in the 0–10 cm soil layer after 15 days of application, and the more amount of liquid digestate applied, the greater the quantity of the transformation.

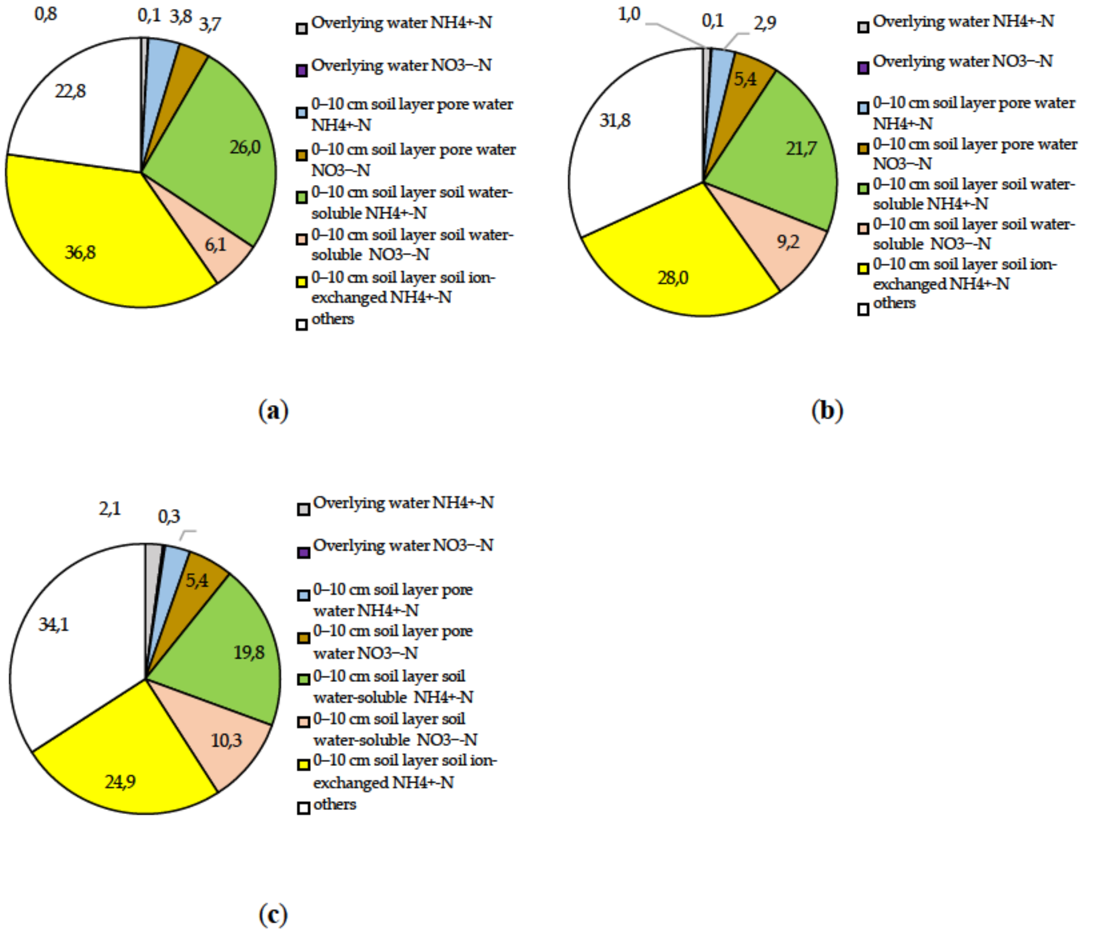


Figure 4.6 Fate analysis of liquid digestate NH_4^+-N in treatments of BSN1 (a), BSN1.5 (b), and BSN2.5 (c).

4.5 Discussion

4.5.1 Time node of liquid digestate NH_4^+-N removal in farmland

Saturated water content farmland has the self-regulation function of the soil-microbial complex system and the comprehensive purification ability of pollutants, and has great liquid digestate disposal potential. The safe bearing capacity of farmland soil and the frequency of digestion (Shi, 2010; Jiang et al., 2011b) are important parameters for determining the area configuration of liquid digestate in land-consumption farms in the combined planting and breeding system. Research on the engineering measures for disposal of liquid digestate in paddy fields shows that the NH_4^+-N concentration in field water is affected by the digested amount of liquid digestate. At the beginning of application, it increased with the increase in liquid digestate and decreased significantly with time. The NH_4^+-N concentration decreased by 47.52%–85.27% after 3 days of liquid digestate application (Wang et al., 2016), and the concentration of NH_4^+-N in field water is stably lower than the emission concentration of 80 mg/L specified in the emission standard of pollutants for the livestock and poultry breeding industry (GB18596-2001). It can be stably lower than 40 mg/L after 5 days of application (Jiang et al., 2011a). The results of this study are slightly different from the above reports in the digestion time of NH_4^+-N in liquid digestate. After 3 days of application, only the NH_4^+-N concentration in the overlying water of BSN1 treatment decreased to less than 80 mg/L. After 7 days of application, BSN1 and BSN1.5 treatments can stabilize below 80 mg/L, of which BSN1 treatment is lower than 40 mg/L. The reason might be that the static soil column used in this study is a soil-microbial composite system, which lacks the participation of farmland plants, so the digestion speed and aging are slightly delayed.

In addition, by monitoring the change of NH_4^+-N concentration in field water, we can predict the water environment pollution risk and water quality standard discharge time node of farmland disposal liquid digestate engineering measures (Wang et al., 2016; Jiang et al., 2011a; Wang et al., 2015a; Wang et al., 2015b). However, it is impossible to distinguish whether the main reason for the decrease in NH_4^+-N concentration is farmland digestion or farmland irrigation water dilution, which has been questioned in production practice. This study further quantifies the reduction rate of NH_4^+-N in the liquid digestate. From the perspective of reduction of NH_4^+-N input, it is verified again that the first three days after liquid digestate application is a rapid reduction period, during which the prohibition of runoff plays an important role in preventing environmental pollution of surrounding water bodies. After 15 days of application, under the condition of an equal amount of NH_4^+-N, the total amount of NH_4^+-N in the overlying water of liquid digestate treatment decreased by 99.2%, significantly lower than that of fertilizer NH_4^+-N treatment, which proved that the purpose of disposal liquid digestate NH_4^+-N had been achieved, and 15 days could be used as the time node for the end of the first digestion cycle.

4.5.2 Migration and transformation characteristics of NH_4^+-N in farmland consuming liquid digestate

In this study, under the condition of applying the same amount of NH_4^+-N, the NH_4^+-N concentration in the overlying water of the liquid digestate treatment was lower than that of the chemical fertilizer NH_4^+-N treatment on the third day, but it rebounded from 4 to 7 days, mainly due to the NH_4^+-N accounts for 88.6% of the total nitrogen in the liquid digestate, and other nitrogen-containing organic substances in the liquid digestate components are oxidized and decomposed by microorganisms, which increases the NH_4^+-N content of the overlying water. The concentration of NH_4^+-N in overlying water treated with liquid digestate for 0 days (the sampling time in this study is within 8 h after application) is significantly higher than that of fertilizer NH_4^+-N treatment, but the concentration of NH_4^+-N in pore water and the concentration of NH_4^+-N adsorbed by soil are lower than that of fertilizer NH_4^+-N treatment. This is because there is a competitive and mutually exclusive relationship between other cations (Song et al., 2021) and NH_4^+-N ions in liquid digestate, thus delaying the molecular diffusion rate of NH_4^+-N in pore water, it also reduces the dominant sorption of NH_4^+-N on soil particles (Zhao et al., 2013). The abnormal value of BSN1 treatment on the fourth day of application may be related to the operation error of the destructive test, and the value at this point can be regarded as the missing value. After 7 days of application, the NO_3^--N concentration in overlying water, pore water, and soil with the liquid digestate NH_4^+-N treatment was significantly higher than that of the fertilizer NH_4^+-N treatment, which may be that the organic active substances in the liquid digestate components promoted the reproduction of nitrifying microorganisms (Chen et al., 2020), thus promoting the conversion of NH_4^+-N to NO_3^--N.

4.5.3 Fate of farmland disposal liquid digestate NH_4^+-N

Using farmland to consume liquid digestate is a widely recognized and effective treatment method, and the environmental pollution risk related to this measure has always been the focus of attention (Lovejoy et al., 1997; Velthof et al., 2005; Paul et al., 1998). The total nitrogen in liquid digestate is mainly NH_4^+-N. There is no clear report on the final whereabouts of NH_4^+-N when a large amount of liquid digestate is applied to farmland. Some scholars believe that liquid digestate NH_4^+-N might enter the underlying soil through leaching and then pollute the groundwater (Wang et al., 2015b), but many experimental studies have shown that the application of liquid digestate in dryland (Svoboda et al., 2013), and in paddy fields (Wang et al., 2016; Chen et al., 2013) has not significantly increased the NH_4^+-N and NO_3^--N in groundwater. The results of this study showed that the concentration of NH_4^+-N in the pore water of 0–10 cm soil layer reached the peak value after 4 days of liquid digestate application, and the NH_4^+-N sorption by soil particles reached the peak after 7 days, indicating that the NH_4^+-N in overlying water was gradually migrating to the soil layer over time. The proportion of liquid digestate nitrogen (including NH_4^+-N, NO_3^--N transformed from NH_4^+-N) absorbed by soil and contained in pore water in the 0–10 cm soil layer accounted for 76.3% of the total NH_4^+-N after being applied for 15 days, indicating that the disposal of liquid digestate NH_4^+-N in farmland was mainly soil sorption and transformation. However, with the increase in liquid digestate application, the proportion of NH_4^+-N adsorbed by soil in the 0–10 cm soil layer decreases, which is due to the limit value of soil sorption capacity of 1108.55 mg/kg (Wang et al., 2022). When the sorption limit value is exceeded, NH_4^+-N will migrate to the 10–20 cm soil layer. Only when the amount of NH_4^+-N applied exceeds the sorption limit value of 0–20 cm cultivated soil layer, there will be the risk of polluting groundwater.

Ammonia volatilization loss was once considered as one of the main ways to reduce NH_4^+-N in field water (Jiang et al., 2011a; Huijsmans et al., 2001), but the ammonia volatilization process is very complex and affected by many factors, so it is very difficult to accurately estimate its loss under natural conditions. Some studies have shown that soil wetting or flooding conditions can reduce ammonia volatilization (Hou et al., 2007; Zhou et al., 2009). The standing test of liquid digestate showed that the removal rate of ammonium nitrogen was only 53% under natural conditions for 100 days (Shi, 2010). In this study, the other fate of liquid digestate NH_4^+-N in the BSN1, BSN1.5, and BSN2.5 treatments accounts for 22.8%, 31.8%, and 34.1%, including the migration of NH_4^+-N to deeper soil layer (Wang et al., 2014b; Tan et al., 2015), transformation (Pote et al., 2001) and ammonia volatilization loss of overlying water. Some scholars believe that the key period of ammonia volatilization is within 7 days after liquid digestate application. The ammonia volatilization loss rates of 1 N liquid digestate, 2 N liquid digestate, 4 N liquid digestate, and 1 N chemical fertilizer treatment are 18.8%, 14.3%, 9.9%, and 6.6%, respectively (Shi, 2013). In this experiment, the other directions of liquid digestate NH_4^+-N were not subdivided, so the proportion of ammonia volatilization loss in other directions could not be determined. Therefore, it cannot be proved that ammonia volatilization loss is one of the main ways to reduce liquid digestate NH_4^+-N in overlying water. However, at the beginning of liquid digestate application, the concentration of NH_4^+-N in overlying water maintained a high level, decreased rapidly within 7 days, and gradually transformed into NO_3^--N after 7 days. Therefore, it is speculated that if ammonia volatilization really exists, then the critical period of ammonia volatilization should be within 7 days, but the proportion of ammonia volatilization loss will not be too high.

4.6 Conclusions

The use of saturated water content farmland soil for disposal of liquid digestate ammonium nitrogen is mainly based on soil sorption and pore water migration. With the extension of time, the ammonium nitrogen concentration in the overlying water gradually decreases, and the reduction rate of the total ammonium nitrogen gradually increases. However, the reduction speed and rate showed a downward trend with the increase in the application amount of the ammonium nitrogen in the liquid digestate. The application of 0–3 d is the rapid consumption period for preventing and controlling the pollution of surrounding water bodies, and the application of 15 d is the completion period of one-time safety consumption.

4.7 References

Chen D, Jiang L, Huang H, Toyata K. 2013. Nitrogen dynamics of anaerobically digested slurry used to fertilize paddy fields. *Biology and Fertility of Soils* 49: 647–659.

Chen Z, Wang Q, Ma J, Chapman S, Zou P, Ye J, Yu Q, Sun W, Lin H, 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: 15–25. https://doi.org/10.1007/s10333-019-00761-y.

Dong Y, Liang D, Li D, Jin H. 2021. Characteristic analysis of main nutrient content in biogas slurry. *Jiangsu Journal of Agricultural Science* 37: 1206–1214. http://qikan.cqvip.com/Qikan/Article/Detail?id=7105949915 (accessed on 9 January 2020).

Fang C, Zhang T, Li P, Jiang R, Wu S, Nie H, Wang Y. 2015. Phosphorus recovery from biogas fermentation liquid by Ca-Mg loaded biochar. *Journal of Environmental Sciences* 29: 106–114. https://doi.org/10.1016/j.jes.2014.08.019.

Feng Z, Li P. 2018. The genesis and evolution of the concept of carrying capacity: A view of natural resources and environment. *Journal of Natural Resources* 33: 1475–1489. https://doi.org/10.31497/zrzyxb.20170967.

General Administration of Environmental Protection of the People's Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China. 2003. Discharge Standard of Pollutants for Livestock and Poultry Breeding. National Standards of the People's Republic of China, GB 18596-2001. https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/shjbh/swrwpfbz/200301/t200301 01_66550.shtml (accessed on 1 January 2003).

Hagos K, Zong J, Li D, Liu C, Lu X. 2017. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. *Renewable and Sustainable Energy Reviews* 76: 1485–1496. https://doi.org/10.1016/j.rser.2016.11.184.

He X, Zhang T, Ren H, Li G, Ding L, Pawlowski L. 2017. Phosphorus recovery from biogas slurry by ultrasound/H_2O_2 digestion coupled with HFO/biochar adsorption process. *Waste Management* 60: 219–229. https://doi.org/10.1016/j.wasman.2016.08.032.

Hou H, Zhou S, Hosomi M, Toyota K, Yosimura K, Mutou Y, Nisimura T, Takayanagi M, Motobayashi T. 2007. Ammonia emissions from anaerobically-digested slurry and chemical fertilizer applied to flooded forage rice. *Water, Air, and Soil Pollution* 183: 37–48. https://doi.org/10.1007/s11270-007-9353-9.

Huijsmans JFM, Hol JMG, Hendriks MMWB. 2001. Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland. *NJAS: Wageningen Journal of Life Sciences* 49: 323–342. https://doi.org/10.1016/s1573-5214(01)80021-x.

Jiang L, Wang Q, Chen D, Li A, Qian S, Fu J, Wang J. 2011a. Effects of paddy field disposal of biogas slurry on the rice production, soil quality and environmental safety. *Journal of Agro-Environment Science* 30: 1328–1336. http://www.cnki.com.cn/Article/CJFDTotal-NHBH201107013.htm (accessed on 6 January 2011).

Jiang L, Wang Q, Li A, Qian S, Fu J, Ma J, Ye J, Wang J. 2011b. The ecological effects of fallow paddy field disposal biogas slurry and its impact on the following rice safety production. *Journal of Agro-Environment Science* 30: 2483–2490. http://www.cqvip.com/QK/92252A/201112/40459055.html (accessed on 17 May 2011).

Jiang X, Sommer SG, Christensen KV. 2011c. A review of the biogas industry in China. *Energy Policy* 39: 6073–6081. https://doi.org/10.1016/j.enpol.2011.07.007.

Kowalenko CG, Yu S. 1996. Solution, exchangeable and clay-fixed ammonium in south coast British Columbia soils. *Canadian Journal of Soil Science* 76: 473–483. https://doi.org/10.4141/cjss96-059.

Li H, Zhang T, Shaheen SM, Abdelrahman H, Ali EF, Bolan NS, Li G, Rinklebe J. 2022. Microbial inoculants and struvite improved organic matter humification and stabilized phosphorus during swine manure composting: Multivariate and multiscale investigations. *Bioresource Technology* 351: 126976.

Liang Y, Guan Y, Wu H, Wang Z. 2013. Study on measures and policies to reduce pollution in raising livestock and poultry in Jiangsu Province. *Asian Agricultural Research* 10: 93–96. http://qikan.cqvip.com/Qikan/Article/Detail?id=6565718-25048495149484850 50 (accessed on 1 August 2013).

Liu C, Zhang Y, Liu S, Liu Q, Yan L. 2021. Effects of biogas slurry application on nitrogen loss soil in black soil area during the autumn fallow period. *Journal of Agro-Environment Science* 40: 2528–2536. https://doi.org/10.11654/jaes.-2021-1022.

Lovejoy SB, Lee JG, Randhir TO, Engel BA. 1997. Research needs for water quality management in the 21st century: A spatial decision support system. *Journal of Soil Water Conservation* 52*:* 18–22. https://agris.fao.org/agrissearch/sea-rch.do?recordID=US9708000 (accessed on 15 February 1996).

Lu G, Yang F, Chen H, Du T. 2021. Research progress on application of biogas slurry. *Soil and Fertilizer Sciences in China* 1: 339–345. https://doi.org/10.11838/-sfsc.1673-6257.19611.

Manici LM, Caputo F, Cappelli GA, Ceotto E. 2021. Can repeated soil amendment with biogasdigestates increase soil suppressiveness toward non-specific soil-borne pathogensin agricultural lands? *Renewable Agriculture and Food Systems* 36: 353–364. https://doi.org/10.1017/S1742170520000393.

Monlau F, Sambusiti C, Ficara E, Aboulkas A, Barakat A, Carrere H. 2015. New opportunities for agricultural digestate valorization: Current situation and perspectives. *Energy & Environmental Science* 8: 2600–2621. https://doi.org/10.1039/c5ee01633a.

Nasir IM, Mohd Ghazi TI, Omar R. 2012 Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Engineering in Life Sciences* 12: 258–269. https://doi.org/10.1002/elsc.201100150.

Nicholson F, Bhogal A, Cardenas L, Chadwick D, Misselbrook T, Rollett A, Taylor M, Thorman R, Williams J. 2017. Nitrogen losses to the environment following food-based digestate and compost applications to agricultural land. *Environmental Pollution* 228: 504–516. https://doi.org/10.1016/j.envpol.201-7.05.023.

Nkoa R. 2014. Agricultural benefits and environmental risks of soil fertilization with anaerobic digestates: A review. *Agronomy for Sustainable Development* 34: 473–492. https://doi.org/10.1007/s13593-013-0196-z.

Paul JW, Dinn NE, Kannangara T, Fisher LJ. 1998. Protein content in dairy cattle diets affects ammonia losses and fertilizer nitrogen value. *Journal of Environmental Quality* 27: 528–534. https://doi.org/10.2134/jeq1998.00472-425002700030008x.

Pote D, Reed BA, Daniel TC, Nichols DJ. 2001. Water-quality effects of infiltration rate and manure application rate for soils receiving swine manure. *Journal of Soil Water Conservation* 56: 32–37.

Pourret O, Bollinger JC, Hursthouse A, Hullebusch ED. 2022. Sorption vs adsorption: The words they are a-changin', not the phenomena. *Science of the Total Environment* 838: 156545. https://doi.org/10.1016/j.scitotenv.2022.156545.

Shi Y. 2010. The Potential Capacity for Paddy Field Ecosystem to Decontaminate Biogas Slurry and its Risks Assessment. PhD. Thesis, Zhejiang University, Hangzhou, China.

Smith KA, Jackson DR, Misselbrook TH, Pain BF, Johnson RA. 2000. Reduction of ammonia emission by slurry application techniques. *Journal of Agricultural and Engineering Research* 77: 277–287. https://doi.org/10.1006/jaer.2000.0-604.

Song Y, Wang G, Li R, Chen G. 2021. Research progress of biogas slurry treatment and resource utilization. *Transactions of the CSAE* 37: 237–250. https://doi.org/10.11975/j.issn.1002-6819.2021.12.028.

Steffens D, Sparks DL. 1997. Kinetics of nonexchangeable ammonium release from soils. *Soil Science Society of America Journal* 61: 455–462. https://doi.org-/10.2136/sssaj1997.03615995006100020012x.

Svoboda N, Taube F, Wienforth B, Kluß C, Kage H, Herrmann A. 2013. Nitrogen leaching losses after biogas residue application to maize. *Soil and Tillage Research* 130: 69–80. https://doi.org/10.1016/j.still.2013.02.006.

Tan X, Shao D, Gu W, Liu H. 2015. Field analysis of water and nitrogen fate in lowland paddy fields under different water managements using HYDRUS-1D. *Agricultural Water Management* 150: 67–80. https://doi.org/10.1016/j.agwat.-2014.12.005.

Ternoeven-Urselmans T, Scheller E, Raubuch M, Ludwig B, Joergensen RG. 2009. CO_2 evolution and N mineralization after biogas slurry application in the field and its yield effects on spring barley. *Applied Soil Ecology* 42: 297–302. https://doi.org/10.1016/j.apsoil.2009.05.012.

Velthof GL, Nelemans JA, Oenema O, Kuikman PJ. 2005. Gaseous nitrogen and carbon losses from pig manure derived from different diets. *Waste Management* 34: 698–706. https://doi.org/10.2134/jeq2005.0698.

Wang X, Chen Y, Sui P, Gao W, Qin F, Wu X, Xiong J. 2014a. Efficiency and sustainability analysis of biogas and electricity production from a large-scale biogas project in China: An emergy evaluation based on LCA. *Journal of Cleaner Production* 65: 234–245. https://doi.org/10.1016/j.jclepro.2013.09.0-01.

Wang Z, Guan Y, Sheng J, Liang Y, Wu H, Chen L, Zheng J. 2015a. Effects of biogas slurry application on paddy field water nitrogen content at tillering stage. *Chinese Journal of Eco-Agriculture* 23: 1544–1551. https://doi.org/10.1393-0/j.cnki.cjea.150687.

Wang Z, Li J, Li Y. 2014b. Simulation of nitrate leaching under varying drip system uniformities and precipitation patterns during the growing season of maize in the North China Plain. *Agricultural Water Management* 142: 19–28. https://doi.org/10.1016/j.agwat.2014.04.013.

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2015b. Effects of biogas slurry degradation on nitrogen content in paddy field water of panicle fertilizer stage. *Journal of Soil and Water Conservation* 29: 246–251. https://doi.org/10.13870/j.cnki.stbcxb.2015.06.043.

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2016. Analysis of water environment risk on biogas slurry disposal in paddy field. *Transactions of the CSAE* 32: 213–220. https://doi.org/10.11975/j.issn.1002-6819.2016.05.030.

Wang Z, Zhang L, Sun G, Zhou W, Sheng J, Ye X, Olaniran AO, Kana EBG. 2022. Adsorption characteristics of three types of soils on biogas slurry ammonium nitrogen. *Frontiers in Environmental Science* 10: 942263. https://doi.org/1-0.3389/fenvs.2022.942263.

Wu H, Wang Z. 2014. Discussions and recommendations about establishing agro-ecological compensation mechanism in Jiangsu Province. *Asian Agricultural Research* 6: 108–111. https://doi.org/10.22004/AG.ECON.169074.

Zhang L, Sun G, Wang Z, Zong J, Zhou W, Sheng J. 2021a. Analysis of rice seedling growth restriction factors under biogas slurry application. *Journal of Agro-Environment Science* 40: 2537–2543. https://doi.org/10.11654/jaes.2021-1025.

Zhang T, Wu X, Shaheen SM, Zhao Q, Liu X, Rinklebe J, Ren H. 2020. Ammonium nitrogen recovery from digestate by hydrothermal pretreatment followed by activated hydrochar sorption. *Chemical Engineering Journal* 379: 122254. https://doi.org/ 10.1016/j.cej.2019.122254.

Zhang T, Wu X, Shaheen SM, Rinklebe J, Bolan NS, Ali EF, Li G, Tsang DCW. 2021b. Effects of microorganism-mediated inoculants on humification processes and phosphorus dynamics during the aerobic composting of swine manure. *Journal of Hazardous Materials.* 416: 125738. https://doi.org/10.1016/j.jhazmat.2021.125738.

Zhang Y. 2017. Ammonia forms and adsorption / desorption behavior in soils from the downstream of informal landfill. Master’s Thesis, Chongqing University, Chongqing, China.

Zhao W, Li Y, Zhao Q, Ning Z, Zhou C, Wang H, Lu L, Yang P, Zhang K, Wang F, Huang Z, Ouyang Z. 2013. Adsorption and desorption characteristics of ammonium in eight loams irrigated with reclaimed wastewater from intensive hogpen. *Environmental Earth Science* 69: 41–49. https://doi.org/10.1007/s-12665-012-1932-4.

Zhou S, Nishiyama K, Watanabe Y, Hosomi M. 2009. Nitrogen budget and ammonia volatilization in paddy fields fertilized with liquid cattle waste. *Water, Air, and Soil Pollution* 201: 135–147. https://doi.org/10.1007/s11270-008-9933-3.

Zou M, Dong H, Zhu Z, Zhan Y, Zhang Y, Yue C. 2020. Progress and prospect of treatments and resource utilization of biogas slurry on livestock and poultry farms. *China Poultry* 42: 103–109. https://doi.org/10.16372/j.issn.1004-6364.2020.09.016.

CHAPTER 5: ASSESSMENT OF BIOGAS SLURRY PRETREATMENT ON SOIL PROPERTIES, SOIL MICROFLORA AND GROWTH OF *CAPSICUM* SPP.

5.1 Abstract

This study reports the effects of pretreated biogas slurry on farm soil properties, microflora and growth of *Capsicum* spp. The split zone approach was adopted for the experiment, with untreated soil as the control (CK). This was investigated under various process conditions. The saturated water content, clean water (W) (495 m^3/hm^2), low biogas slurry (LBS) (495 m^3/hm^2) and high biogas slurry (HBS) (990 m^3/hm^2) were used in the soil pretreatment. In addition, the four treatments (CKM, WM, LBSM, HBSM) were set up with film mulching as the sub zone. The responses of soil properties, microorganisms and *Capsicum* spp. growth to biogas slurry pretreated soil were determined. Biogas slurry pretreatment of protected soil increases the soil total nitrogen (0.15–0.32 g/kg), total phosphorus (0.13–0.75 g/kg), available phosphorus (102.62–190.68 mg/kg), available potassium (78.94–140.31 mg/kg), organic carbon content (0.67–3.32 g/kg) and soil pH value, while the population, diversity and distribution of soil bacteria, fungi, actinomycetes, and fusarium were significantly affected. Interestingly, soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were highly correlated to the population of bacteria and fungi present in the pretreated soil. The soil with biogas slurry pretreatment of 495 m^3/hm^2 favoured the growth, seedlings survival rate, flowering rate and fruit-bearing rate of *Capsicum* spp. and significantly reduced the rate of rigid seedlings. The application of biogas slurry to pretreat protected soil has achieved the multi-goals of biogas slurry valorization, soil biofertilization, preventing and controlling soil-borne microbial diseases. These findings are of significant importance for safe and environmental-friendly application of biogas slurry for soil pretreatment.

Keywords: *liquid digestate, biogas slurry, ammonium nitrogen, soil microorganisms, Capsicum*

5.2 Introduction

The extensive application of acidic or physiologically acidic fertilizers, pesticides and high-intensity single planting mode in protected vegetable cultivation can easily cause continuous cropping obstacles such as soil quality degradation, soil-borne diseases, soil acidification, secondary salinization and nutrient imbalance (Pérez-Brandán et al., 2014). These usually result in a sharp decline in vegetable yield, sustainable vegetable cultivation and seriously affect the economic income of farmers (Zhu et al., 2013). It is reported that the losses caused by pathogenic bacteria in vegetable industry around the world are up to US $1 billion every year (Lamour et al., 2012). Research on the effective methods of preventing and controlling soil degradation as well as soil-borne diseases in protected lands has become imperative and important for promoting sustainable agricultural development.

Soil-borne diseases are caused by plant pathogenic fungi, bacteria, nematodes and viruses in the soil. The microbes can be proliferate when the conditions are suitable, infecting the roots and stems of crops (Cai and Huang, 2016). Among them, the root rot disease of protected land vegetables caused by pathogenic fungi is more serious, and the yield can be reduced by more than 60%. Additionally, soil acidification provides a suitable living environment for the growth of pathogenic fungi. The accumulation of phenolic acid allelochemicals in soil affects the permeability of root cell membranes, which is the main reason for the autotoxic effect of continuous cropping of vegetables, hence, providing pathogenic fungi with carbon source and energy for growth (Xie et al., 2014). Efforts have been made to mitigate soil-borne diseases such as Reductive Soil Disinfestation (RSD). The RSD method has proven to be a very strong method of "curing" the infection of soil-borne pathogens (Butler et al., 2012; Momma et al., 2013; Cai et al., 2015). The core method is to apply a large amount of easily decomposed organic materials, irrigate and mulch to prevent air from diffusing into the soil, creating a strong soil reduction state in a short time, and thus, killing soil- borne pathogens.

As a by-product of biogas production, biogas slurry is weakly alkaline, this can be used to alleviate soil acidification. Also, biogas slurry is rich in organic carbon and nutrient elements, which can provide rich carbon sources and energy for microbial growth. Hence, the application of biogas slurry to soil could significantly influence the population, community structure and activity of soil microorganisms (Tao et al., 2014). Biogas slurry treatment has been found to increase the population of bacteria such as *Pseudomonas fluorescens* and *Trichoderma*, fungi, actinomycetes, in the rhizosphere soil as well as improve the diversity index of soil bacteria and fungi (Cao et al., 2013). In another related study, Sui et al. (2016), showed that the population of soil actinomycetes and fungi increased by 72.4% and 61.6%, respectively, while the number of soil bacteria decreased by 18.4% when biogas slurry drip irrigation was used in solar greenhouse. Moreover, biogas slurry has a certain inhibitory effect on a variety of crop pathogenic fungi (Tao et al., 2011). Li et al. (2013), reported a significant inhibitory effect on *Rhizoctonia solani*, *Fusarium nivalea*, *F. oxysporum*, and *Fusarium solani*, with an inhibition rate of 70%, 40%, 68%, and 70%, respectively when biogas slurry was used for the treatment of farmland. Similarly, biogas slurry of 21 different large-scale biogas projects in Jiangsu Province of China had different degrees of inhibitory effect on the growth of strawberry Fusarium wilt when applied to farmland. In addition, the stage of obtaining the biogas slurry had a significant effect on its antibacterial effect (Ma et al., 2011). Although, there have been different application of biogas slurry on farmland as potential biofertilizers and pesticides, there is a scarcity of knowledge on the use of biogas slurry to pretreat degraded protected soil. Similarly, there is a dearth of information on preventing and controlling soil-borne diseases of protected farmland using biogas slurry. Knowledge of multiple potential usage of biogas slurry, the impact of biogas slurry on soil and its operating mechanism provides a theoretical basis and technical approach to biogas slurry farmland application, thereby improving resource utilization of biogas slurry.

Furthermore, studies have shown that the application of biogas slurry can improve the physical and chemical properties of farmland (Möller, 2015; Niyungeko et al., 2020; Tang et al., 2021) while effectively valorizing the biogas slurry (Chen et al., 2015).

Treatment of farmland with biogas slurry has a direct positive effect on improving soil organic matter, soil structure, and fertility (Xu et al., 2013; Liu et al., 2018; Yu et al., 2018). Overall, pretreatment of farmland with biogas slurry have multiply benefits to the soil and cultivated crops. Thus, it is imperative to study the dual benefits of biogas slurry on soil physiochemical properties and growth performance of cultivated crop.

Hence, the present study assessed the application of biogas slurry to pretreat the degraded protected soil to achieve the dual goals of preventing and controlling soil-borne pathogens in the protected farmland. Also, the efficiency of biogas slurry absorption per unit area of farmland was evaluated through field experiments. The changes in soil properties, soil microbial community and the growth of *Capsicum* spp. following the application of biogas slurry was also analysed, based on the RSD method.

5.3 Materials and methods

5.3.1 Study site and soil properties

The experiment was carried out in a *Capsicum* spp. greenhouse in Sihe Township, Sihong County, China. *Capsicum* spp. was planted continuously for more than 5 years in the greenhouse. The basic soil properties of the greenhouse after the harvest of the previous crop were organic carbon (OC) 8.92±0.61g/kg, pH 7.40±0.02, total nitrogen (TN) 1.49±0.15 g/kg, ammonium nitrogen (NH_4^+-N) 49.37±1.67mg/kg, nitrate nitrogen (NO_3^--N) 351.87±13.81 mg/kg, total phosphorus (TP) 1.09±0.02 g/kg, available phosphorus (AP) 21.15±2.78 mg/kg, available potassium (AK) 242.35±11.12 mg/kg. Soil culturable microbial indicators: bacteria (3.20±0.19) $\times 10^6$ cfu/g, fungi (1.00±0.06) $\times 10^4$ cfu/g, actinomycetes (2.84±0.09) $\times 10^6$ cfu/g, fusarium (1.08±0.14) $\times 10^3$ cfu/g.

Biogas slurry properties

The biogas slurry tested was obtained from anaerobic digester using pig farm manure and sewage from adjacent farm. The average properties of biogas slurry are TN 628.34±103.22mg/L, NH_4^+-N 519.89±96.83mg/L, NO_3^--N 65.64±8.58mg/L, TP 339.72±96.13mg/L, total potassium (TK) 423.47±81.67mg/L, COD 1060±35mg/L, pH 8.14±0.31. The experimental *Capsicum* spp. variety was Moxiu No. 8.

5.3.2 Design and setting

A split-plot experimental design was adopted in the application of the biogas slurry. Four main farmland plots were implemented: the blank control without any treatment (CK); the clean water treatment-W (applying clean water of 495 m^3/hm^2), the low concentration biogas slurry treatment-LBS (applying biogas slurry of 495 m^3/hm^2) and the high concentration biogas slurry treatment-HBS (applying 990 m^3/hm^2 of biogas slurry). The W, LBS and HBS treatments were brought to soil saturated water content by watering 450 m^3/hm^2 a day to prior applying the biogas slurry on the farmland. Two additional subplots were set up, one with the black mulch and another without the black mulch. Thus, a total of eight treatments namely CK, W, LBS, HBS, CKM, WM, LBSM and HBSM were implemented. Each experimental treatment was repeated three times. The area of each plot is 35m^2 (length 7m, width 5m), underground depth of 80cm, reserved height above ground of 20cm with black PE impermeable membrane buried around the plot. The biogas slurry was extracted by a mud pump, and then applied using a flow meter.

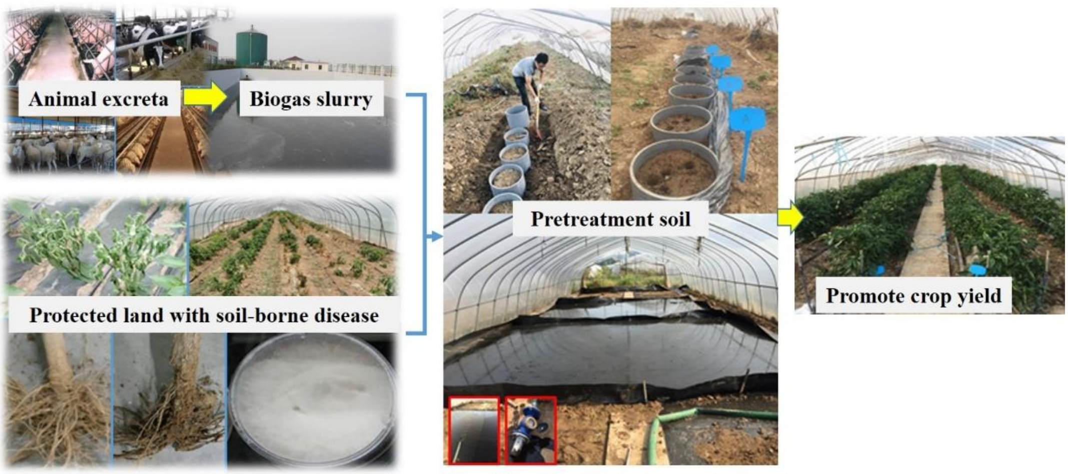


Figure 5.1 Graphical abstract.

After application of biogas slurry, the facility greenhouse was closed for 20 days, then the covering film was removed, and the greenhouse was further kept ventilated for 7 days, after which the land was ploughed and aired for another 14 days. The *Capsicum* spp. seedlings were transplanted after 51 days seedling period using local farmer transplanting density (approximate 21,975 plants per ha). During the *Capsicum* spp.

planting, 45% of nitrogen and potassium fertilizer was used as base fertilizer, 30% as topdressing at flowering stage, and 25% as topdressing at fruit stage. The daily management of pest control, weeding and water irrigation was carried out using conventional methods.

5.3.3 Sampling and analysis

5.3.3.1 Determination content

Soil samples were taken at 5, 10, 15 and 20 days after biogas slurry application to determine the soil properties. The soil properties analysed were TN, NH_4^+-N, NO_3^--N, TP, AP, AK, OC, pH, soil culturable bacteria, fungi, actinomycetes and fusarium population. Also, microbial community diversity using 16S rDNA V3+V4 area/fungal ITS rDNA ITS2 area sequencing was carried out.

The growth of *Capsicum* spp. in each treatment was measured 50 days after transplanting. Data on the total number of transplanted *Capsicum* spp., seedlings survival rate, rate of hardened seedlings, rate of flowering plants, rate of fruit-bearing plants, and plant height were obtained using Equations 1 to 4

$$Survival\ rate\ seedlings\ (\%) = \frac{Survival\ seedling\ number}{Total\ number\ of\ transplanted} \times 100 \qquad (1)$$

$$Rigid\ seedlings\ rate\ (\%) = \frac{Hardened\ seedlings\ number}{Survival\ seedlings\ number} \times 100 \qquad (2)$$

$$Flowering\ plants\ rate\ (\%) = \frac{Flowering\ plants\ number}{Survival\ seedlings\ number} \times 100 \qquad (3)$$

$$Fruit - bearings\ rate\ (\%) = \frac{Fruit{-}bearing\ plants\ number}{Survival\ seedlings\ number} \times 100 \qquad (4)$$

5.3.3.2 Soil sample collection methods

The multi-point sampling method was used for the soil sampling analysis. The soil was collected from 0–10 cm soil layer with an undisturbed soil drill. The fresh soil sample was spread on clean paper and mixed evenly. Then 30g of finely crushed fresh soil was stored in a ziplock PE bag at 4 ℃ thereafter used to enumerate microorganisms present in the soil. Another 5g of fine fresh soil was wrapped in an Aluminum foil then stored in liquid nitrogen for the determination of microbial community diversity. The remaining soil sample was dried, sieved and used for the determination soil properties.

5.3.3.3 Soil properties determination

The chemical properties of the soil were determined using standard methods for chemical analysis of soil and agriculture (Lu, 2000). First, the soil sample was digested with concentrated sulfuric acid and the content of TN and TP were determined with an automatic flow analyzer (SKALAR SAN++, Holland). Then the contents of NH_4^+-N and NO_3^--N in the soil were extracted with 2mol/L KCl solution (ratio of 2mol/L KCl solution to the soil was 5:1), and determined with SKALAR SAN++ (Holland) analyzer. Moreover, AP content was obtained by sodium bicarbonate leaching-molybdenum antimony anti-spectrophotometry (HJ 704-2014), while AK content was determined by ammonium acetate extraction flame photometer method (NY/T 889-2004) (Gao et al., 2020). The OC was determined using the potassium dichromate volumetric method (Cesarano et al., 2017). Lastly, the pH value was measured by Thunder Magnetic PHS-3C pH meter (Sadaf et al., 2017; Yao et al., 2022).

5.3.3.4 Soil microbial community determination

The gradient dilution plate coating counting method was used to determine the culturable bacteria, fungi, actinomycetes, and fusarium. The beef extract peptone agar medium, Martin's medium, modified Komada's No. 1 medium, and modified Komada's selective media were employed for the culturable microorganisms (Yao et al., 2016). This was achieved by weighing 10g of soil into 90ml of sterile water, incubated for 1h at 28 ℃ constant temperature oscillation. Then it was diluted according to 10 times gradient and coated with specific culture medium at corresponding dilution times (coating was carried out 330ul per plate). This was repeated three times, and enumerated after 2–5 days of incubation (Zhou, 2015).

Soil microbial community diversity was determined using high-throughput sequencing. The specific steps are as follows:

①**DNA extraction and quality control.** The FastDNA® SPIN Kit (Mpbio, USA) was used to extract the total microbial DNA in the soil (Miller et al., 1999). The specific experimental steps were carried out according to the manufacturing instructions. 1% agarose gel electrophoresis was used to detect the degradation and impurities of the extracted DNA samples. Nano Drop nucleic acid protein analyzer was used to detect the sample concentration and total amount of DNA, and the PCR pre-amplification to test whether the sample is qualified.

②**16S/ITS rDNA library preparation.** Ten nanogram (10ng) of DNA template was used to carry out PCR amplification of target region; bacterial 16S rDNA V3+V4 region amplification primers were 338F (5'-ACTCCTACGGGAGGCAGCA-3') and 806R (5'-GGACTACHVGGGTWTCTAAT-3'), fungal ITS rDNA ITS2 region amplification primers are ITS3F (5'-GCATCGATGAAGAACGCAGC-3 ') and ITS4R (5'-TCCTCCGCTTATTGATATGC-3') (Essel et al., 2018; Wang et al., 2021). The PCR amplification was divided into two steps: first, specific primers to amplify the target fragment with the EX *Taq* enzyme of TaKaRa to ensure amplification efficiency and accuracy. The target fragment was purified and recovered by Novozen AMPure XP magnetic beads, and then the recovered product was used as a template for secondary PCR amplification. The connectors, sequencing primers and barcodes required for sequencing on the Illumina platform were added to both ends of the target fragment. After the library was constructed using Qubit2.0 Flurometer for preliminary quantification and diluting the library to 1ng/μL, Agilent2100 was used to detect the insert size of the library. After the desired insert size was obtained, a Thermo 2720 fluorescence quantitative PCR instrument StepOnePlus (Thermo-Life Company) was used to perform a QPCR to accurately quantify the effective concentration of the library.

③**Computer sequencing:** Paired-end sequencing was performed on the Illumina Hiseq platform for qualified libraries using the PE250 sequencing strategy.

④**Sequencing analysis:** The data filtering is completed by removing low-quality bases, Ns, and linker contamination sequences to obtain credible target sequences for subsequent analysis.

The corresponding Read1 and Read2 (Read1 and Read2 refer to sequence fragments obtained from 5 'and 3' directions respectively) sequenced at both ends were spliced using the sequence splicing method PEAR (Zhang et al., 2014). Then, the spliced sequence was analyzed using software QIIME version 1.8.0, including OTUs extraction for OTUs analysis and alpha diversity analysis (Caporaso et al., 2010; Edgar 2010; Vasileiadis et al., 2012; Quast et al., 2013; Adler et al., 2013). And the canonical correspondence analysis (CCA) was performed using the Canoco windows 4.5 to find the most significant environmental variables.

5.3.4 Data analysis

Using Office Excel 2016 software and OriginPro 2017 were used analyze and map soil traits, soil microorganisms and *Capsicum* spp. plant growth data. One-way ANOVA and Duncan's method were further used for analysis of variance and multiple comparisons (α=0.05) using IBM SPSS Statistics (22).

5.4 Results and analysis

5.4.1 Effect of biogas slurry pretreatment on soil properties

The impact of biogas slurry on soil properties is shown in **Figure 5.2**. After 20 days of biogas slurry treatment of the soil, compared with CK treatment, LBS, HBS, LBSM treatment increased in TN content by 25.3%, 11.7%, 19.0%, respectively (Fig. 5.2A). The HBS, LBSM and HBSM treatments significantly increased the content of NH_4^+-N by 24.6%, 33.1% and 86.8%, respectively while LBS significantly reduced the content of ammonium nitrogen by 14.2% (Fig. 5.2B). On the other hand, all the treatments significantly reduced NO_3^--N content with LBS, HBS, LBSM, HBSM and WM treatments reduced NO_3^--N content by 47.8%, 52.2%, 51.3%, 55.9% and 84%, respectively (Fig. 5.2C). Moreover, the LBS, HBS, LBSM and HBSM treatments increased the TP content by 79.2%, 55.8%, 65.2% and 14.2%. LBS, HBS and LBSM treatments increased the TP content significantly ($P<0.05$) (Fig. 5.2D). Similarly, the LBS, HBS, LBSM and HBSM treatments increased the content of available phosphorus and potassium in the treated soil. The content of available phosphorus increased by 1378.5%, 1355.9%, 778.6% and 741.9% (Fig. 5.2E), while, the content of available potassium increased by 87.7%, 84.8%, 61.0% and 108.4% respectively (Fig. 5.2F). Likewise, the LBS, HBS, LBSM and HBSM treated soil increased in soil organic carbon content by 38.7%, 27.4%, 40.3% and 8.1% (organic carbon content in LBS, HBS and LBSM treatments was observed to increased significantly (P<0.05)) (Fig. 5.2G). Also, the pH value in the HBS, LBSM and HBSM treated soil increased significantly by 0.8%, 2.2% and 2.5% respectively (Fig. 5.2H).

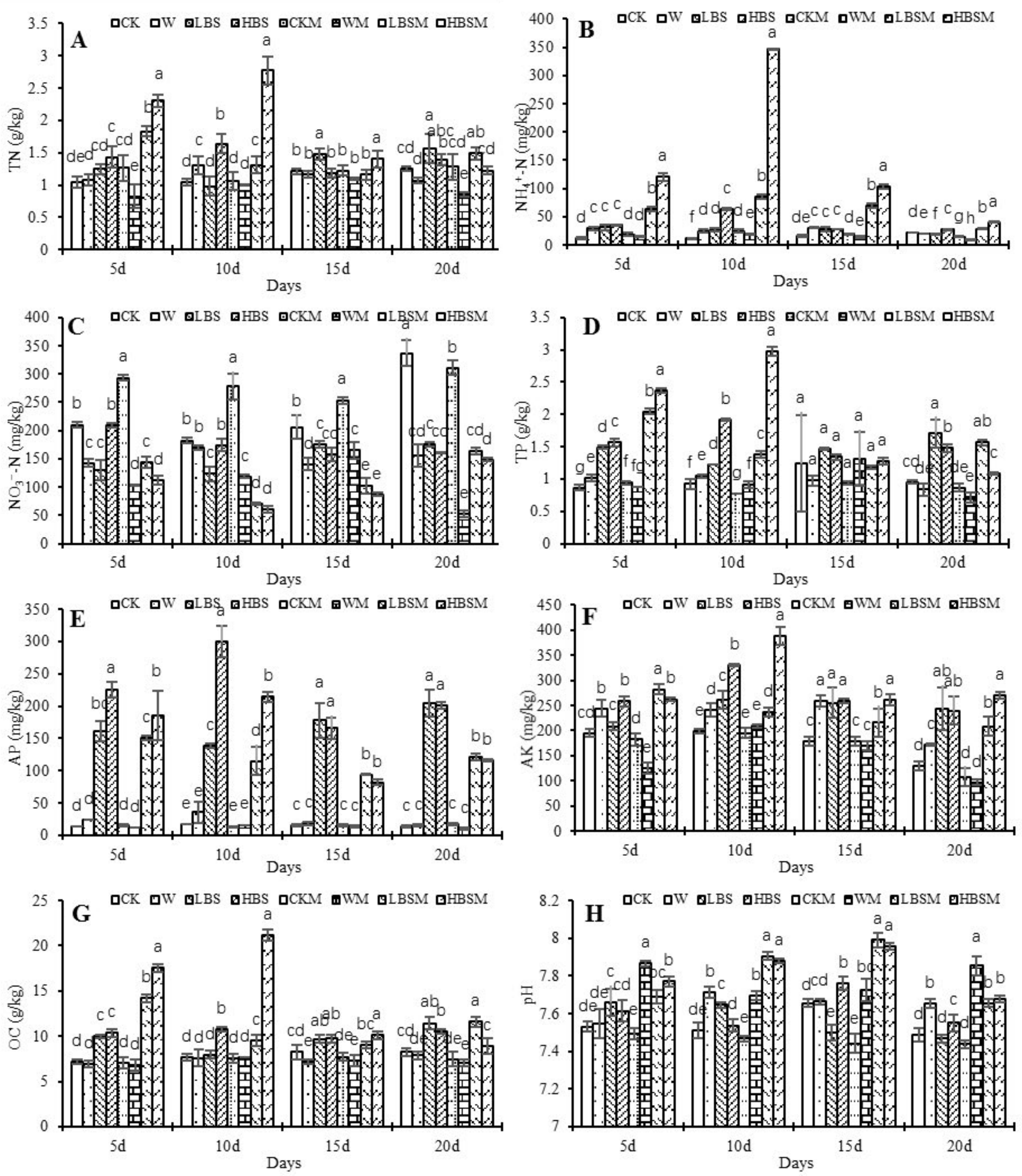


Figure 5.2 Changing trend of soil properties following biogas slurry pretreatment.

5.4.2 Effect of biogas slurry pretreatment on soil microorganisms

5.4.2.1 Soil culturable microorganisms

Shown in **Figure 5.3** is the impact of different pretreatment measures on culturable bacteria, fungi, actinomycetes and fusarium. The results obtained showed that the soil pretreatment for 15 days significantly reduced the number of culturable bacteria in soil (Fig. 5.3A). There was an increase in the population of culturable bacteria in soil after the biogas slurry application when compared with the control (CK treatment) while, the difference in the population of culturable bacteria between treatments decreases with the increase in pretreatment time. After the cultivation period of 20 days, the number of culturable bacteria in LBSM treatment reduced compared to CK treatment (33.3%). Similarly, the fungi load of culturable fungi in the soil increased first and then decreased after 20 days of pretreatment (Fig. 5.3B). On the other hand, comparing LBS and HBS treatment to CK treatment, LBS and HBS treatment increased the number of culturable fungi by 130.1% and 30.1%, while LBSM and HBSM treatment resulted in the decreased in the fungi load of culturable fungi by 41.0% and 13.0%, respectively, without observable significant difference ($P<0.05$).

Moreover, in Fig 5.3C, a gradual increased in the actinomyces population was observed, although the cultivation period was extended there was no substantial effect on the population of actinomyces. On the 20th day, the number of actinomycetes decreased by 31.1%, 54.5%, 42.6% and 52.9% for LBS, HBS, LBSM and HBSM treatment, respectively. The reduction in actinomyces was found to be significant within treatment and in comparison, with control ($P<0.05$).

Furthermore, biogas slurry pretreatment of farmland reduced the population of cultivable fusarium in the soil (Fig. 5.3D). The LBS treated soil showed fusarium population initially increase (1.19×10^2 cfu/g at day 5, 7.90×10^2 cfu/g at day 10, and 1.02×10^3 cfu/g at day 15) and then decreased (1.20×10^2 cfu/g at day 20) as the treatment period extended. LBSM treatment showed a decreasing trend in fusarium population while, HBS and HBSM treated soil showed an initial decrease in fusarium population, then increasing to later decrease. When these are compared to CK treatment, LBS, HBS, LBSM and HBSM treatment significantly decreased the number of cultivable fusarium in soil by 16.4%, 48.4%, 77.9% and 70.5% respectively after the 15th day of treatment. On the 20th day, the population of cultivable fusarium in each treatment decreased less than that in CK treatment, but there was no significant difference in the population of cultivable fusarium between LBS, LBSM and CK treatment.

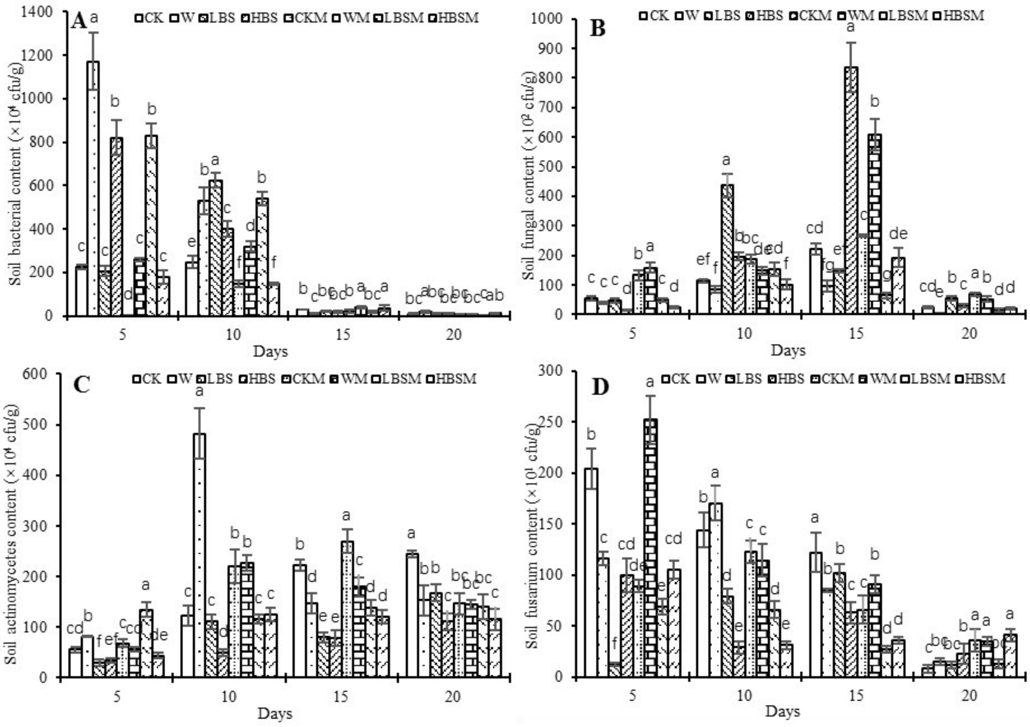


Figure 5.3 Profile of culturable bacteria, fungi, actinomycetes and fusarium in biogas slurry pretreated soil.

5.4.2.2 Changes in soil microbial community diversity

Figure 5.4 shows the OTU cluster analysis and annotation results of high-throughput sequencing of bacterial 16S and fungal ITS in different soil treatments. Compared with CK treatment, the number of soil bacterial OTU in BS (LBS+HBS) and BSM (LBSM+HBSM) treatment decreased by 12.9% and 49.3% respectively. Moreover, the population of fungi OTU in BS (LBS+HBS) treatment decreased by 4.2%, but the number of fungi OTU in BSM (LBSM+HBSM) treatment increased by 14.4%. The OUT-annotation results showed that the number of bacteria and fungi in each treatment changed to varying degrees in terms of kingdom, phylum, class, order, family, genus and species. **Table 5.1** represent the α diversity analysis of the sample. The Chao1 index of bacteria and fungi in the BS treatment compared with the CK treatment decreased by 14.5% and 5.4%, respectively, while the BSM treatment decreased by 46.8% and 34.5%. This is an indication that BS and BSM treatment reduced the population of species in soil bacterial and fungal communities. Similarly, the Shannon index and Simpson index of bacteria and fungi in BS and BSM treatments were lower than those in CK treatments, indicating that BS and BSM treatments led to the decrease in the diversity of bacteria and fungi communities in soil. Also, BS and BSM treatments resulted in the uniformity of species distribution in microbial communities.

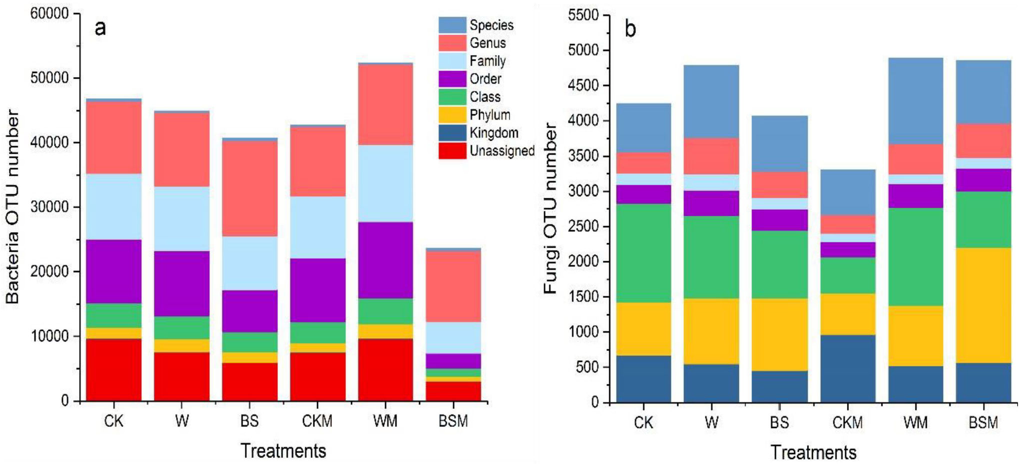


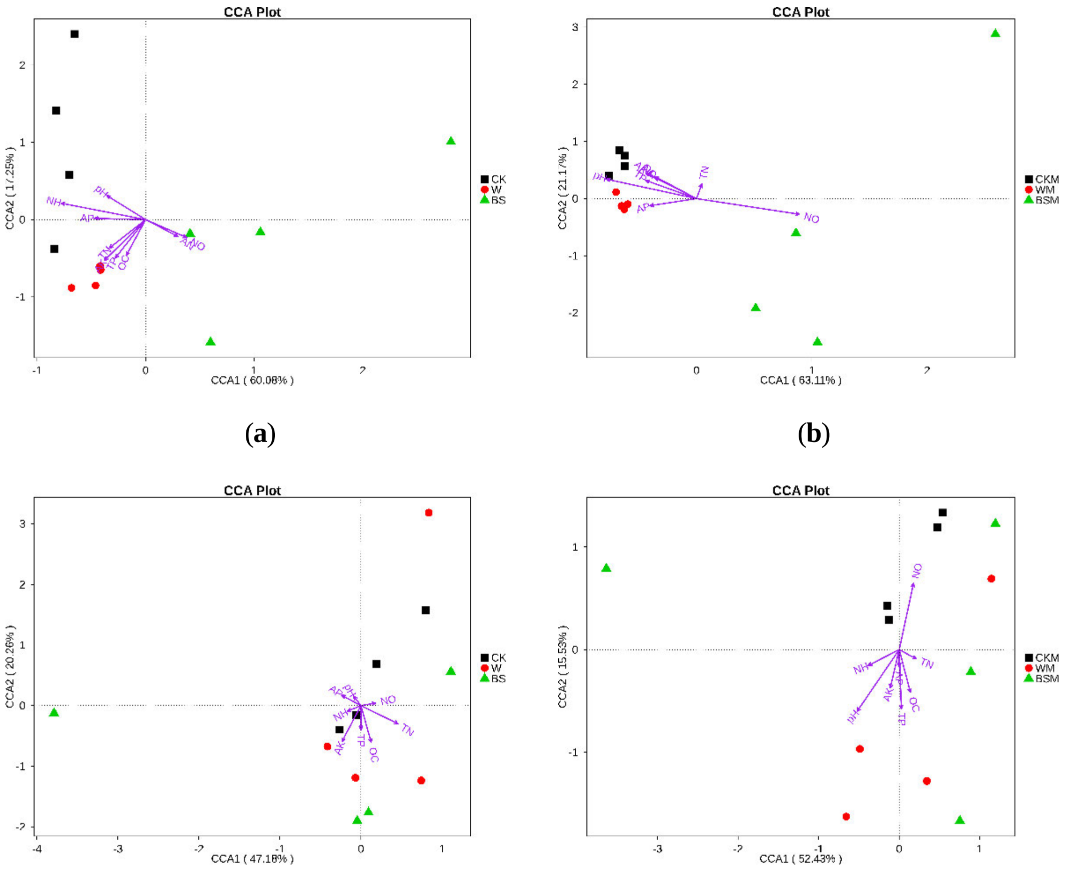
Figure 5.4 OTU cluster analysis and annotation results of soil bacteria and fungi in pretreated soil.

Table 5.1 Change in α diversity indices of bacteria and fungi under different treatments

Type	Sample name	Shannon	Simpson	Chao1	Goods coverage
Bacteria	CK	11.14±0.61ab	0.99±0.00a	19238.07±5150.93ab	0.93±0.03ab
	W	11.44±0.34ab	1.00±0.00a	19913.37±5801.58ab	0.93±0.03ab
	BS	10.51±0.27b	0.99±0.00a	16453.05±2047.63ab	0.94±0.01a
	CKM	11.30±0.73ab	1.00±0.00a	31899.50±23013.83a	0.88±0.05bc
	WM	11.91±0.28a	1.00±0.00a	27582.11±7239.36a	0.87±0.03c
	BSM	8.11±1.43c	0.95±0.05b	10236.63±3830.54b	0.95±0.02a
Fungi	CK	6.59±0.14a	0.97±0.00a	1956.38±514.75ab	0.99±0.00a
	W	6.09±0.24a	0.95±0.02a	1630.31±387.41b	1.00±0.00a
	BS	6.17±0.85a	0.96±0.02a	1851.14±606.25ab	1.00±0.00a
	CKM	6.54±0.16a	0.97±0.00a	2494.80±756.80a	0.99±0.00a
	WM	6.23±0.43a	0.95±0.02a	1868.95±146.70ab	1.00±0.00a
	BSM	3.45±2.82b	0.55±0.39b	1281.76±118.88b	1.00±0.00a

5.4.2.3 Canonical correspondence analysis (CCA)

The CCA analysis shows that the content of NH_4^+-N in soil was the main contributory factor to the observed inhibition of the growth of bacteria without mulching (Figure 5.5a/b), while the soil pH was mainly responsible for the inhibition of the growth of bacteria and fungi in soil with mulching (Figure 5.5c/d). In addition, soil NO_3^--N was positively correlated with the proliferation of bacteria and fungi, and soil OC was positively correlated with the proliferation of fungi, but negatively correlated with the reproduction of bacteria.



(a) (b)

(c) (d)

Figure 5.5 Canonical correspondence analysis (CCA) between soil bacteria (a, b), fungi (c, d) and soil properties

5.4.3 Effect of biogas slurry pretreatment on the growth of *Capsicum* spp.

Figure 5.6 shows the growth performance of *Capsicum spp*. on biogas slurry treated soil after 50 days. The survival rate of *Capsicum* spp. pretreated with biogas slurry LBS, HBS, LBSM and HBSM was significantly increased ($P<0.05$). Comparing the LBS, HBS, LBSM and HBSM with CK treatment, the survival rate of *Capsicum* spp. was increased by 71.3%, 76.2%, 76.2% and 76.2% respectively. Similarly, comparing these treatments with CKM treatment, an increase of 46.7%, 50.9%, 50.9% and 50.9%, respectively was obtained. When these treatments were also compared with W treatment, the growth performance increased by 1.2%, 4.1%, 4.1% and 4.1% respectively (Fig. 5.6a). The rate of rigid seedlings in WM treatment was the highest, reaching 32.5%, followed by W treatment, which was 29.0%. Both treatments were significantly higher than that obtained from CK, CKM, LBS, HBS, LBSM, HBSM ($P<0.05$). Moreover, comparing CK treatment to LBS, HBS, LBSM and HBSM treatment, the rate of rigid seedlings was observed to reduce by 63.2%, 52.6%, 42.1% and 84.2% respectively. Similarly, when W treatment was compared with LBS, HBS, LBSM and HBSM treatment the rate of rigid seedlings was significantly (($P<0.05$)) reduced by 90.4%, 87.7%, 84.9% and 95.9% respectively ($P<0.05$) (Fig. 5.6b). Furthermore, the soil pretreated with biogas slurry significantly increased the plant height of *Capsicum* spp. plants and when this was compared with CK treatment, the plant height of *Capsicum* spp. plants treated with LBS, HBS, LBSM and HBSM increased by 113.1%, 83.6%, 96.7% and 50.8% respectively (Fig. 5.6c). Also, population of flowering *Capsicum* spp. and the percentage of fruit-bearing *Capsicum* spp. were substantially improved. Comparing CK treatment to other treatments (LBS, HBS, LBSM and HBSM), an increase (98.8%, 82.9%, 86.5% and 81.7%) in the population of flowering *Capsicum* spp. was observed. This was 35.82, 30.08, 31.38 and 29.65 times higher than CK treatments, and 1.64, 1.37, 1.43 and 1.35 times higher than W treatments, respectively (Fig. 5.6d). The highest (47.8%) population of fruit-bearing *Capsicum* spp. was observed with LBS treatment. This was 47.8%, 17.32, 2.31, 19.66 and 5.92 times of CK, W, CKM and WM, respectively (Fig. 5.6e).

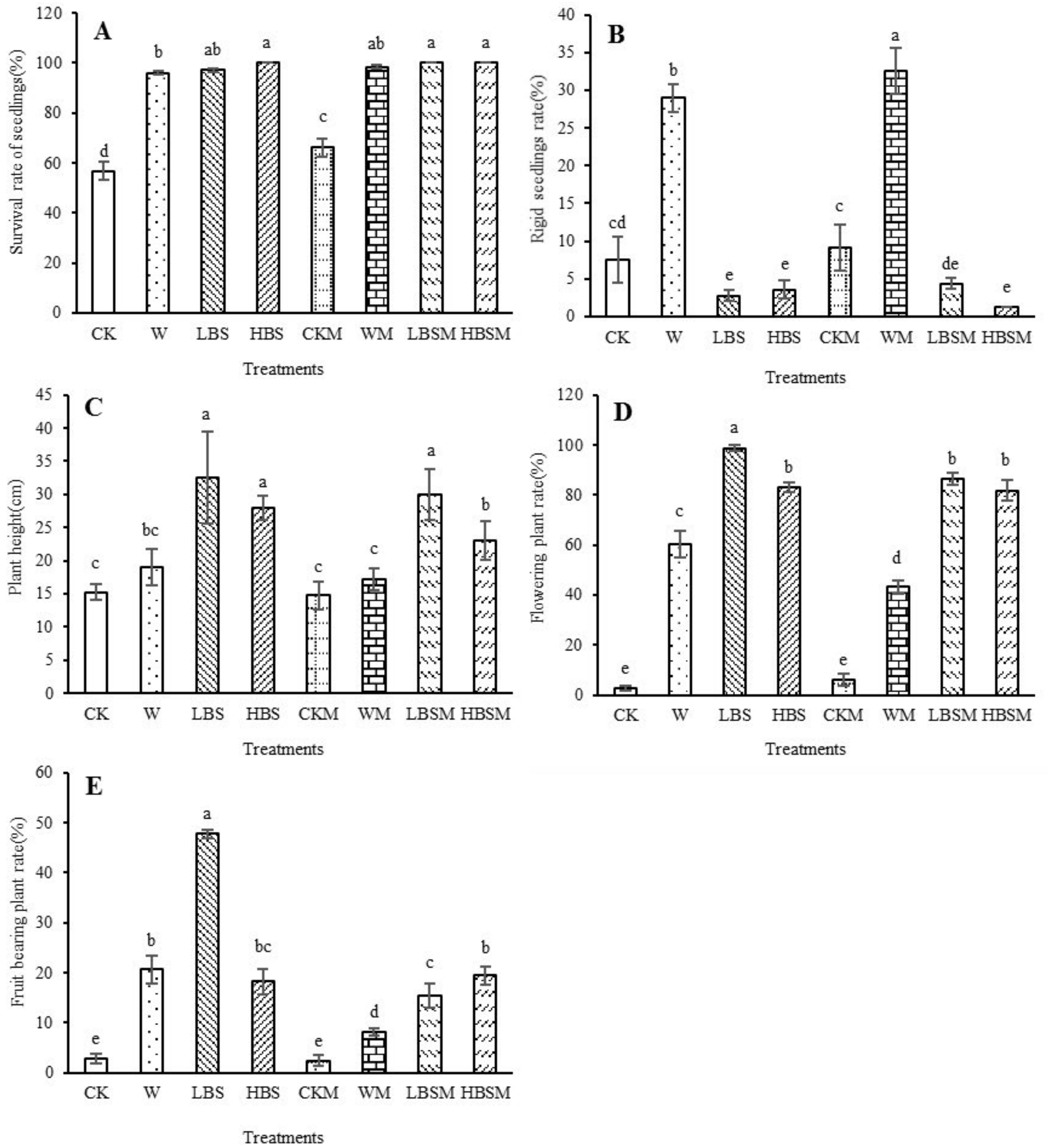


Figure 5.6 Growth of *Capsicum* spp. under different biogas slurry pretreatments.

5.5 Discussion

5.5.1 Effect of biogas slurry pretreatment on soil properties

This study shows that biogas slurry pretreatment of protected soil improved the physical and chemical properties of the soil (Niyungeko et al., 2020; Tang et al., 2021). Effective adjustment in the proportion of each nutrient content such as soil organic carbon in the soil (Yan et al., 2019), and the pH value (Xu et al., 2019). It has a direct positive effect on soil fertility (Yu et al., 2018). Studies have shown that under similar nitrogen condition, the TN, NH_4^+-N, NO_3^--N, AP, AK and pH of soil increased to varying degrees after soil was treated with pig manure biogas slurry to soil, while the OC content of the soil was not significantly impacted (Li et al., 2021). Similarly, Lai et al. (2018), reported controlling the concentration of swine manure biogas slurry applied in three years within the range of 546.25–626.00×10^3 kg/hm^2 significantly increase soil available potassium, phosphorus, and alkaline hydrolyzable nitrogen as well as reducing the risk of soil acidification. In another related study, the TN, NH4-N, TP, AP, AK and OC content of paddy field treated with continuous application of biogas slurry for four years were significantly higher than those of no biogas slurry application (Dong et al., 2021). The authors also observed an increase in the soil organic matter content which was directly proportional to the amount of biogas slurry applied (Liu et al., 2021). The effects of biogas slurry pretreatment on soil TN, TP, AP, AK, and OC in this study were consistent with the results of previous studies. Soil NH_4^+-N content decreased in low-volume biogas slurry pretreatment (LBS treatment), which may be related to soil microbial activity, while the relative increase in soil TN was higher in the same treatment. The reduction of NO_3^--N content in the treatments may be ascribed to the downward leaching of NO_3^--N in surface soil caused by irrigation that keeps the soil saturated before pretreatment. The pH value of soil treated with LBS decreased slightly, indicating that low application of biogas slurry could not prevent soil acidification, while high application of biogas slurry fully neutralized soil acids (Xie et al., 2014), as well as inhibited the growth and proliferation of acidobacteria, thus, reducing soil acidification (Wang et al., 2021).

5.5.2 Effect of biogas slurry pretreatment on soil microorganisms

Appropriate application of biogas slurry can promote the growth and enrichment of soil dominant bacteria, microbial alpha diversity (Lv et al., 2011; Abubaker et al., 2013; Cao et al., 2013; Xu et al., 2013; Wentzel and Joergensen, 2016), and help prevent and control soil-borne diseases of crops (Cao et al., 2016; Li et al., 2021). Studies showed that the application of biogas slurry could increase the culturable number of soil bacteria (Feng et al., 2014; Chai et al., 2019), fungi (Tang et al., 2021) and actinomycetes (Yu et al., 2010) to a certain extent. Although nitrogen input is the key factor to increase soil microbial nitrogen energy (Möller, 2015), a large amount of ammonium nitrogen in biogas slurry may play a role in inhibiting microbial growth in the short term. Some studies found that the population of bacteria in the soil decreased (Cao et al., 2013), the main fungi in the soil decreased by 55.03% (Yang et al., 2017), and *Fusarium oxysporum* decreased significantly (Cao et al., 2015) after the application of biogas slurry. The relative abundance of actinomycetes increased with the increase of biogas slurry concentration, but the further increase of biogas slurry concentration would inhibit the growth of actinomycetes (Xu et al., 2019).

Furthermore, when the biogas slurry was applied at 180 m^3/hm^2, the richness and diversity of bacteria were increased, when the Chao1 index and Shannon index were high, which the diversity of fungi decreased with low Chao1 index and Shannon index (Wang et al., 2021). In this study, the biogas slurry pretreatment of protected soil showed reduction in culturable number of soil microorganisms, decrease in the richness and diversity of soil microorganisms, and altered the soil dominant microorganisms. These alterations in the microbial compositions through biogas slurry treatment is not only related to the complex factors of closed greenhouse, high temperature, mulching film, soil moisture and other supporting technologies, but also closely related to the change of soil properties.

5.5.3 Effect of biogas slurry pretreatment on the growth of crops

Biogas slurry pretreatment measures can promote the growth and development of subsequent crops through fertilization and elimination of soil borne pathogenic microorganisms, with no risk of affecting crop growth. On the other hand, high NH_4^+-N (Zhang et al., 2021), electrical conductivity (Tigini et al., 2016), and chemical oxygen demand (Wang et al., 2019; Gao et al., 2019) in biogas slurry can result in plant roots' adversity stress leading to plant growth retardation. In this study, the plant height and flowering rate of *Capsicum* spp. with low amount of biogas slurry (LBS) were better than those of high amount of biogas slurry (HBS and HBSM), which buttresses the aforementioned observations. The application of biogas slurry can significantly reduce plant disease index (Wang et al., 2021). For instance, a study by Cao et al. (2016), showed watermelon fusarium wilt was significantly inhibited, and disease index was reduced by 36.4%. Moreover, in this study, the survival rates of *Capsicum* spp. with clean water (W, WM) and biogas slurry (LBS, HBS, LBSM, HBSM) were higher than that of the blank control (CK, CKM). This is an indication that soil moisture played an important role in improving the survival rate of *Capsicum* spp. plants. Also, the rigid seedling rate of clean water treatment (W, WM) is significantly higher than those of biogas slurry treatment (LBS, HBS, LBSM, HBSM). This substantiates the role of biogas slurry in promoting the growth of crops in biogas slurry pre-treatment soil. This might be related to the nutrient richness of biogas slurry and its potential in the reduction of soil-borne pathogens, but more in-depth research might be needed to substantiate and elucidate this.

5.6 Conclusions

This study has demonstrated the potential of biogas slurry pretreatment of protected soil to improve soil fertility, alleviating continuous cropping obstacles and promoting plant growth for high productivity. Soil pretreatment with biogas slurry dosage of 495 m^3/hm^2 and 990 m^3/hm^2 increased soil total nitrogen, total phosphorus, available phosphorus, available potassium, organic carbon and soil pH, while inhibiting the growth of soil bacteria, fungi, actinomycetes and fusarium. It also reduced the soil microbial flora as well as the evenness of species distribution. Moreover, the soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were closely correlated to the growth and proliferation of soil bacteria and fungi. Interestingly, biogas slurry dosage of 495 m^3/hm^2 improved the growth of *Capsicum* spp., which significantly improved the survival rate of *Capsicum* spp. seedlings, the plant height, the flowering rate and the fruit-bearing rate. In addition, the rate of rigid seedlings was substantially reduced. These findings demonstrate that biogas slurry which is usually disposed unfriendly to the environment can be an excellent sustainable source for improving soil fertility and crop productivity.

5.7 References

Abubaker J, Cederlund H, Arthurson V, Pell M. 2013. Bacterial community structure and microbial activity in different soils amended with biogas residues and cattle slurry. *Applied Soil Ecology* 72: 171−180. https://doi.org/10.1016/-j.apsoil.2013.07.002

Adler CJ, Dobney K, Weyrich LS, Kaidonis J, Walker AW, Haak W, Bradshaw CJA, Townsend G, Soltysiak A, Alt KW, Parkhill J, Cooper A. 2013. Sequencing ancient calcified dental plaque shows changes in oral microbiota with dietary shifts of the Neolithic and industrial revolutions. *Nature Genetics* 45(4): 450−455. https://doi.org/10.1038/ng.2536

Butler DM, Kokalis-Burelle N, Muramoto J, Shennan C, McCollum TG, Rosskopf EN. 2012. Impact of anaerobic soil disinfestation combined with soil solarization on plant-parasitic nematodes and introduced inoculum of soilborne plant pathogens in raised-bed vegetable production. *Crop Protection* 39(8): 33−40. https://doi.org/10.1016/j.cropro.2012.03.019

Cai Z, Huang Q. 2016. Soil-borne pathogens should not be ignored by soil science. *Acta Pedologica Sinica* 53: 305–310. https://doi.org/10.11766/trxb201511190489

Cai Z, Zhang J, Huang X, Zhu T, Wen T. 2015. Application of reductive soil disinfestation to suppress soil-borne pathogens. *Acta Pedologica Sinica* 52: 469–476. https://doi.org/10.11766/trxb201411040554

Cao Y, Chang Z, Ma Y, Yang H, Fu G. 2013. Effects of application of anaerobically digested slurry on suppression of pepper (*Capsicum frutescens* L.) blight and soil biological characteristics. *Scientia Agricultura Sinica* 46: 507−516. https://doi.org/10.3864/j.issn.0578-1752.2013.03.007

Cao Y, Wang J, Wu H, Yan S, Guo D, Wang G, 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. https://doi.org/10.1016-/j.apsoil.2016.05.010

Cao Y, Wu H, Guo D, Wang Q, Yan S, Wang G, Ma Y. 2015. Effect of biogas slurry application on incidence of fusarium wilt, fruit yield and quality of watermelon. *Soils* 47: 904–910. https://doi.org/10.13758/j.cnki.tr.2015.05.015

Caporaso JG, Kuczynski J, Stombaugh J, Bittinger K, Bushman FD, Costello EK, Fierer N, Peña AG, Goodrich JK, Gordon JI, Huttley GA, Kelley ST, Knights D, Koenig JE, Ley RE, Lozupone CA, McDonald D, Muegge BD, Pirrung M, Reeder J, Sevinsky JR, Turnbaugh PJ, Walters WA, Widmann J, Yatsunenko T, Zaneveld J, Knight R. 2010. QIIME allows analysis of high-throughput community sequencing data. *Nature Methods* 7(5): 335−336. https://doi.org/10.1038/nmeth.f.303

Cesarano G, Filippis FD, Storia AL, Scala F, Bonanomi G. 2017. Organic amendment type and application frequency affect crop yields, soil fertility and microbiome composition. *Applied Soil Ecology* 120:254−264. https://doi.org/10.1016/j.apsoil.2017.08.017

Chai Y, Huang L, Dong Y, Li Y, Wang Z, Shan S, Ping L, Zhang W. 2019. Effects of biogas slurry application rates on soil physical and chemical properties and carbon storage of bamboo forest. *Transactions of the Chinese Society of Agricultural Engineering* 35: 214−220. https://doi.org/10.11975/j.issn.1002-6819.2019.08.025

Chen S, Yu W, Zhang Z, Luo S. 2015. Soil properties and enzyme activities as affected by biogas slurry irrigation in the Three Gorges Reservoir areas of China. *Journal of Environmental Biology* 36: 513−520. http://jeb.co.in/journal_issues/201503_-mar15/paper_26.pdf (accessed on 29 September 2014)

Dong Y, Zhou X, Ye B, Liu Y. 2021. Effect of long-term biogas slurry application in rice field on soil chemical properties and C-N-P stoichiometry. *Journal of Zhejiang Agricultural Sciences* 62: 2398−2401 https://doi.org/10.16178/j.issn.-0528-9017.20212829

Edgar RC. 2010. Search and clustering orders of magnitude faster than BLAST.*Bioinformatics* 26(19): 2460−2461. https://doi.org/10.1093/bioinfor-matics/btq461.

Essel E, Li L, Deng C, Xie J, Zhang R, Luo Z, Cai L. 2018. Evaluation of bacterial and fungal diversity in a long-term spring wheat-field pea rotation field under different tillage practices. *Canadian Journal of Soil Science* 98(4): 619−637. https://doi.org/10.1139/cjss-2017-0155

Feng D, Wu J, Yang G, Zhang L, Zhang Y, Wang J. 2014. Influence of long-term applications of biogas slurry on microbial community composition and enzymatic activities in surface soil under rice-rape rotation. *Journal of Agro-Environment Science* 33: 1644–1651. https://doi.org/10.11654/jaes.2014.08.-025

Gao M, Wang D, Wang Y, Wang X, Feng Y. 2019. Opportunities and challenges for biogas development: a review in 2013-2018. *Current Pollution Reports* 5: 25–35. https://doi.org/10.1007/s40726-019-00106-7

Gao X, Zhang S, Zhao X, Long H. 2020. Evaluation of potassium application on tomato performance and rhizosphere bacterial communities under negative pressure irrigation of greenhouse-grown. *Journal of Plant Nutrition* 43(3): 317−326. https://doi.org/10.1080/01904167.2019.1683862

Lai X, Wu J, Wang J, Xu M, Mao X, Li Y. 2018. The long-term effects of biogas slurry on soil properties and potential risks of heavy metals in soils. *Journal of Soil and Water Conservation* 32: 359–364. https://doi.org/10.13870/j.cnki.stbcxb.-2018.06.052

Lamour KH, Stam R, Jupe J, Huitema E. 2012. The oomycete broad-host-range pathogen Phytophthora capsici. *Molecular plant pathology* 13(4): 329−337. https://doi.org/10.1111/j.1364-3703.2011.00754.x

Li W, Fan J, Li W, Yuan H. 2013. Antibacterial mechanism of cow manure biogas slurry on Rhizoctonia solani. *Transactions of the Chinese Society of Agricultural Engineering* 29: 207–212. http://qikan.cqvip.com/Qikan/Article/Detail?id=4496-4505 (accessed on 12 October 2012)

Li Y, Xu J, Liu B, Sun Q, Li J, Liu J, Lang Q, Sun R, Jin H. 2021. Effects of different biogas slurries on soil microbial carbon metabolism. *Chinese Journal of Eco-Agriculture* 29: 1921−1930. https://doi.org/10.12357/cjea.20210274

Liu C, Zheng Y, Liu S, Liu Q, Yan L. 2021. Effects of biogas slurry application on nitrogen loss soil in black soil area during the autumn fallow period. *Journal of Agro-Environment Science* 40: 2528–2536. https://doi.org/10.11654/jaes.-2021-1022

Liu X, Wang L, Wu D, Luo X, Dong R, Shao L. 2018. Effects of long-term application of biogas slurry on soil and products. *China Biogas* 36: 87–91. https://doi.org/10.3969/j.issn.1000-1166.2018.02.015

Lu R. 2000. Methods for chemical analysis of soil and agriculture. Beijing: China Agricultural Science and Technology Press.

Lv W, Wu J, Gou S, Yang G, Wang L, Chen J. 2011. The research of biogas slurry on yield and safety. *Applied Mechanics and Materials* 71-78: 3142−3146. https://doi.org/10.4028/www.scientific.net/AMM.71-78.3142

Ma Y, Li H, Chang Z, Xu Y, Zhang J. 2011. Biocontrol effect and mechanism of biogas slurry on plant disease I: primary study of growth inhibition effects and mechanism on phytopathogen fungi. *Journal of Agro-Environment Science* 30: 366–374. http://qikan.cqvip.com/Qikan/Article/Detail?id=36846607 (accessed on 26 May 2010)

Miller DN, Bryant JE, Madsen EL, Ghiorse WC. 1999. Evaluation and optimization of DNA extraction and purification procedures for soil and sediment samples. *Applied and Environmental Microbiology* 65(11): 4715−4724. https://-doi.org/10.1128/aem.65.11.4715-4724.1999

Momma N, Kobara Y, Uematsu S, Kita N, Shinmura A. 2013. Development of biological soil disinfestations in Japan. *Applied Microbiology and Biotechnology* 97(9): 3801−3809. https://doi.org/10.1007/s00253-013-4826-9

Möller K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development* 35: 1021−1041. https://doi.org/10.1007/s13593-015-0284-3

Niyungeko C, Liang X, Liu C, Zhou J, Chen L, Lu Y, Tiimub BM, Li F. 2020. Effect of biogas slurry application on soil nutrients, phosphomonoesterase activities, and phosphorus species distribution. *Journal of Soils and Sediments* 20:

900−910. https://doi.org/10.1007/s11368-019-02435-y

Pérez-Brandán C, Huidobro J, Grumberg B, Scandiani MM, Luque AG, Meriles JM, Vargas-Gil S. 2014. Soybean fungal soil-borne diseases: a parameter for measuring the effect of agricultural intensification on soil health. *Canadian Journal of Microbiology* 60(2): 73−84. https://doi.org/10.1139/cjm-2013-0792.

Quast C, Pruesse E, Yilmaz P, Gerken J, Schweer T, Yarza P, Peplies J, Glöckner FO. 2013. The SILVA ribosomal RNA gene database project: improved data processing and web-based tools. *Nucleic acids research* 41(D1): D590−D596.

Sadaf J, Shah GA, Shahzad K, Ali N, Shahid M, Ali S, Hussain RA, Ahmed ZI, Traore B, Ismail IMI, Rashid MI. 2017. Improvements in wheat productivity and soil quality can accomplish by co-application of biochars and chemical fertilizers. *Science of the Total Environment* 607/608:715−724. https://doi.org/10.1016/-j.scitotenv.2017.06.178.

Sui H, Chen X, Qin N, Wang G, Xu K, Ai P. 2016. Effects of drip irrigation with biogas slurry on yield and quality of tomato and physical and chemical properties of soil. *Shandong Agricultural Sciences* 48: 80–84. https://doi.org/10.14083/-j.issn.1001-4942.2016.02.019

Tang Y, Luo L, Carswell A, Misselbrook T, Shen J, 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: 143786. https://doi.org/10.1016/j.scitotenv.2020.143786

Tao L, Chu X, Liu T, Tang C, Li J, Liang Y. 2014. Impacts of organic manure partial substitution for chemical fertilizer on cotton yield, soil microbial community and enzyme activities in mono-cropping system in drip irrigation condition. *Acta Ecologica Sinica* 34: 6137–6146. https://doi.org/10.5846/stxb201301-290184

Tao X, Dong H, Shang B, Chen Y, Huang H. 2011. Comparison of inhibiting effects between fresh effluents of anaerobically digested piggery waste and anaerobically digested dairy waste on plant pathogenic fungi. *Journal of*

Agro-Environment Science 30:1443–1449. http://qikan.cqvip.com/Qikan/Article/Detail?id=38607940 (accessed on 09 September 2010)

Tigini V, Franchino M, Bona F, Varese GC. 2016. Is digestate safe? A study on its ecotoxicity and environmental risk on a pig manure. *Science of The Total Environment* 551-552: 127–132. https://doi.org/10.1016/j.scitotenv.2016.02.004

Vasileiadis S, Puglisi E, Arena M, Cappa F, Cocconcelli PS, Trevisan M. 2012. Soil bacterial diversity screening using single 16S rRNA gene V regions coupled with Multi-million read generating sequencing technologies. *PLoS One* 7(8): e42671. https://doi.org/10.1371/journal.pone.0042671

Wang L, Wang G, Wang H, Zhou G, Zhao C, Wang P, Jiang S. 2021. Effects of applying biogas slurry instead of chemical fertilizer on the growth of melon and soil microorganism. *Journal of Southern Agriculture* 52: 2498−2506. https://doi.org/10.3969/j.issn.2095-1191.2021.09.020

Wang Z, Wang X, Zhang Y, Guo Z, Sheng J, Zheng J. 2019. COD in biogas slurry: effects on cucumber seedling growth and soil environmental factors. *Chinese Agricultural Science Bulletin* 35: 15–22. http://www.cqvip.com/qk/91831x/20194/7000000000000000000000000000.html (accessed on 04 June 2018)

Wentzel S, Joergensen RG. 2016. Effects of biogas and raw slurries on grass growth and soil microbial indices. *Journal of Plant Nutrition and Soil Science* 179: 215−222. https://doi.org/10.1002/jpln.201400544

Xie X, Chen Y, Bu Y, Dai C. 2014. A review of allelopathic researches on phenolic acids. *Acta Ecologica Sinica* 34: 6417–6428. https://doi.org/10.5846/stxb201302210285

Xu C, Tian Y, Sun Y, Dong L. 2013. Effects of biogas slurry irrigation on growth, photosynthesis, and nutrient status of *Perilla frutescens* seedlings. *Communications in Soil Science and Plant Analysis* 44: 3381–3390. https://doi.org/10.1080/00103624.2013.847447

Xu M, Xian Y, Wu J, Gu Y, Yang G, Zhang X, Peng H, Yu X, Xiao Y, 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: 2534–2542. https://doi.org/10.1007/s11368-019-02258-x

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

Yang Z, Chen W, Wang W, Li W, He X, Yang X. 2017. Effects of biogas slurry on soil microbial characteristics of broccoli. *Chinese Agricultural Science Bulletin* 29: 112–115 http://www.cqvip.com/QK/91831X/201729/673598109.html (accessed on 21 March 2017)

Yao Y, Xue Z, Hong C, Zhu F, Chen X, Wang W, Cai Z, Huang N, Yang X. 2016. Efficiency of different solarization-based ecological soil treatments on the control of Fusarium wilt and their impacts on the soil microbial community. *Applied Soil Ecology* 108: 341−351. https://doi.org/10.1016/j.apsoil.2016.09.-015

Yao Y, Zhu W, Ding J, Hong L, Hong C, Wang W, Zhu F, He W, Hong H. 2022. Investigation and analysis of continuous cropping obstacle and soil environment in large-scale vegetable bases in Zhejiang Province, China. *Acta Agriculturae Zhejiangensis* 34(7): 1474−1484. https://doi.org/10.3969/j.issn.-1004-1524.2022.07.15

Yu D, Wen Z, Li X, Song X, Wu H, Yang P. 2018. Effects of straw return on bacterial communities in a wheat-maize rotation system in the North China Plain. *PLoS One* 13: e0198087. https://doi.org/10.1371/journal.pone.0198087

Yu F, Luo X, Song C, Zhang M, Shan S. 2010. Concentrated biogas slurry enhanced soil fertility and tomato quality. *Acta Agriculturae Scandinavica. Section B – Soil and Plant Science* 60: 262−268. https://doi.org/10.1080/0906471090289-3385

Zhang J, Kobert K, Flouri T, Stamatakis A. 2014. PEAR: a fast and accurate Ilumine Paired-End reAd mergeR. *Bioinformatics* 30(5): 614−620 https://doi.org/10.1093/bioinformatics/btt593

Zhang L, Sun G, Wang Z, Zong J, Zhou W, Sheng J. 2021. Analysis of rice seedling growth restriction factors under biogas slurry application. *Journal of Agro-Environment Science* 40: 2537–2543. https://doi.org/10.11654/jaes.2021-1025

Zhu T, Meng T, Zhang J, Cai Z. 2013. Effects of strong reductive approach on remediation of degraded facility vegetable soil. *Chinese Journal of Applied Ecology* 24: 2619–2624. http://qikan.cqvip.com/Qikan/Article/Detail?id-=47125669 (accessed on 01 July 2013)

Zhou K. 2015. Anaerobic soil disinfestation, an effective way to control watermelon Fusarium wilt caused by *Fusarium Oxysporum f. sp*. niveum. *Jiangsu Journal of Agricultural Sciences* 31(5): 1006−1011. https://doi.org/10.3969/j.issn.-1000-4440.2015.05.010

CHAPTER 6: GENERAL DISCUSSION AND CONCLUSION

6.1 Research in perspective

In the present study, the coefficient R^2 for the three types of soil adsorption data was the highest for the Elovich equation, an indication that the adsorption was a heterogeneous diffusion process. Further probing into the restrictive factors of the process revealed that the goodness of fit of the parabolic diffusion equation ($0.81< R^2 < 0.97$) was higher than that of the first-order reaction equation ($0.78< R^2 < 0.92$) (**Table 3.7**). The high R^2 for the parabolic diffusion equation suggests that the chemical adsorption process was not the rate-limiting step of the process, while the intra-particle diffusion was the main rate-limiting step. At present, the adsorption mechanism of ammonium nitrogen in soil media is mainly reported at the macro and micro levels. Most macroscopic research has focused on distinguishing the different active surfaces of soil media using the differences in the extraction capacity of different extractants (Wang and Alva, 2000). Microscopically, the occurrence of ammonium in the medium can be identified at the molecular level using X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and other spectral means (Saruchi and Kumar, 2020). Generally, the adsorption mechanism cannot be accurately described using a single approach. Hence, this study used different kinetic approaches to lay a groundwork for research into the ammonium adsorption mechanism. The adsorption characteristics of the three soils (silty loam, loam, and sandy loam), provided a baseline data on the factors affecting the adsorption process (Shen et al., 1997). Since, soil is an important unit for nitrogen circulation and transformation (He et al., 2021). The adsorption of NH_4^+-N in the soil shows corresponding regularity with time change, which is one of the important characteristics of soil chemical reaction kinetics. Due to the differences in soil media and environmental conditions, the relationship between adsorption capacity and time often differed during the adsorption process. Previous studies have shown that different kinetics models or the same model have different fits with different soils (Xue et al., 1996). In the present study, the best fitting models for the soil adsorption of NH_4^+-N were the first-order reaction equation and the Elovich equation. The adsorption of NH_4^+-N in silty sand, sandy silt, silt, and silty clay of four typical soils primarily occurred during 0–2 h, and the adsorption kinetics conformed to the second-order reaction equation (Tian, 2011).

Moreover, model equations were used to reflect the relationship between the soil adsorbent and the adsorption capacity, as well as the influence of different NH_4^+-N concentrations on the ability of the soil to adsorb NH_4^+-N. In the current study, the Langmuir equation had a high degree of fit, indicating that the isothermal adsorption of NH_4^+-N in the three soils was mainly monolayer adsorption, while multi-molecular layer adsorption was of secondary importance. The fitting parameter 1/n of the Freundlich equation in this study was between 0 and 1. This shows that the isothermal adsorption of NH_4^+-N by the three kinds of soils was relatively efficient. At the same time, in order to further improve the application and evaluation of the fitting results, for the maximum saturated adsorption capacity, the analysis screened out the Plplatt equation that has fitting Q_m value that was close to the measured average. However the adaptability of the model assumptions to the soil adsorption characteristics of NH_4^+-N was worthy of further validation. The validation results were basically consistent with the adsorption characteristics reflected by the empirical adsorption isotherm. Therefore, it was effective to use empirical adsorption isotherms to quantitatively describe the thermodynamic behavior of the soil adsorption of NH_4^+-N.

Furthermore, the NH_4^+-N Q_m of soil is affected by soil texture, environmental temperature and humidity, artificial fertilization, and crop rotation. The Q_m obtained by the Langmuir equation reflected the maximum saturated adsorption capacity of NH_4^+-N in the soil at the prevailing experimental conditions. The observations in this study showed that the Q_m value was significantly negatively correlated with the soil pH. A possible reason was that the biogas slurry was alkaline, and the pH values of weakly acidic soils in Xinbei and Jintan were neutralized, resulting in the release of adsorption sites originally occupied by H^+ and thereby reducing the competition between H^+ and NH_4^+ for adsorption sites. Moreover, there was a significant positive correlation between the Q_m value and cation exchange capacity. Also, the Q_m was positively correlated with soil organic matter. This might be ascribed to the large number of different functional groups present in the organic matter and high cation exchange capacity. These factors could increase the adsorption capacity of NH_4^+-N through surface complexation, ion exchange, and surface precipitation (Acosta et al., 2016). These results on soil adsorption of NH_4^+ are consistent with many studies in literature (Yao et al., 2012). For instance, Li et al. (2009) found that Q_m was significantly negatively correlated with soil pH and cation exchange capacity, while it was significantly positively correlated with soil carbon-nitrogen (C:N) ratio. Similarly, Cong et al. (2017) showed that Q_m was significantly positively correlated with soil pH and cation exchange capacity, while it was significantly negatively correlated with soil organic matter and total nitrogen content. Likewise, Wang et al. (2015) reported that the greater the organic matter content, the greater the NH_4^+-N adsorption capacity of albic soil. In other related study, Xue et al. (1996) found that the adsorption capacity of NH_4^+-N increased with the increase of soil cation exchange capacity and soil clay content to varying degrees.

The Q_m value of silty loam > loam > sandy loam was consistent with the other reports. For instance, Xue et al. (1996) reported that NH_4^+-N adsorption capacity was mainly affected by clay content, with clay > loam > sandy soil. Similarly, Cong et al. (2017) showed that the NH_4^+-N adsorption capacity of soil was in the order of light clay > light loam. Moreover, the there was a significant positive correlation between the Q_m value, the content of the soil and the particle size of the soil. Likewise, Wan et al. (2004) found that there was a very significant positive correlation between fixed ammonium and clay content < 0.01 mm, with clay content of 0.005–0.01 mm, and with clay content of 0.001–0.005 mm, but there was no significant correlation with clay content < 0.001 mm. In addition, there was a very significant positive correlation between the Q_m value and the soil TN content, as well as a significant correlation with soil nitrate nitrogen. This may be the reason for the positive and negative electrical adsorption and may be responsible for maintaining the balance between soil ammonium nitrogen and nitrate nitrogen. The Q_m value was also positively correlated with the soil available potassium and available phosphorus. This was because active K^+ ions could provide adsorption sites and interlayer solid localization for NH_4^+ ions in external soil, which was in line with cation exchange theory (Kittrick, 1966). There were two possible reasons: the positive and negative charge adsorption, and the combination of NH_4^+ ions and PO_4^{3-} ions to form $[(NH_4)\ PO_4]^{2-}$, subsequently forming complex precipitates $Mg(NH_4)[PO_4]\cdot 6H_2O$ with the Mg^{2+} and Ca^{2+} in the soil, thereby increasing the adsorption of NH_4^+-N. The correlation between the Langmuir equation adsorption constant K_l value, the MBC value, and the correlation between the Q_m value and soil property-related indicators were opposite (Cong et al., 2017). This indicates that the adsorption strength and the adsorption capacity were complementary. In other words, when the adsorption capacity is high, the adsorption strength is low. In addition, the fitted Q_m values of the NH_4^+-N adsorption of the soils in this study were lower than the fitted value of a single chemical ammonium salt solution, thus signifying the rich complex components of the biogas slurry interfering with the adsorption of ammonium nitrogen in the soil (Zhao et al., 2013). The soil adsorption of biogas slurry NH_4^+-N predominantly occurred within 0–1 h, and the adsorption capacity within 0–1 h accounted for 35.24–43.55% of the total adsorption. The ExpAssoc equation produced a good fit for the adsorption kinetic behavior. The optimal theoretical saturated adsorption capacity (Q_m) values fitted by the Langevin model were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively. The Q_m was significantly positively correlated with soil organic matter, total nitrogen, available phosphorus, available potassium, cation exchange capacity, and particle content of 0.02–0.002 mm, but significantly negatively correlated with soil pH.

The safe bearing capacity of farmland soil and the frequency of digestion (Jiang et al., 2011b) are important parameters for determining the area configuration of biogas slurry in land-consumption farms in the combined planting and breeding system. Previous report showed that the disposal of biogas slurry in paddy fields revealed that NH_4^+-N concentration in field water was affected by the digested amount of biogas slurry. The report also showed that NH_4^+-N concentration increased with the increase in biogas slurry and decreased significantly with time. The NH_4^+-N concentration decreased by 47.52%–85.27% after 3 days of biogas slurry application (Wang et al., 2016), and the concentration of NH_4^+-N in field water is stably lower than the discharge concentration of 80 mg/L specified in the discharge standard of pollutants for the livestock and poultry breeding industry (GB18596-2001). It can be stably lower than 40 mg/L after 5 days of application (Jiang et al., 2011a). The results of this study were slightly different from the above reports in the digestion time of NH_4^+-N in biogas slurry. After 3 days of application, only the NH_4^+-N concentration in the overlying water of BSN1 treatment decreased to less than 80 mg/L. After 7 days of application, BSN1 and BSN1.5 treatments stabilized below 80 mg/L, of which BSN1 treatment is lower than 40 mg/L. The reason might be that the static soil column used in this study is a soil-microbial composite system, which lacks the participation of farmland plants, so the digestion speed and aging are slightly delayed.

In addition, by monitoring the change of NH_4^+-N concentration in field water, we can predict the water environment pollution risk and water quality standard discharge time node of farmland disposal biogas slurry (Wang et al., 2016). However, it is impossible to distinguish whether the main reason for the decrease in NH_4^+-N concentration is farmland digestion or farmland irrigation water dilution, which has been questioned in production practice. This study further quantifies the reduction rate of NH_4^+-N in the biogas slurry. From the perspective of reduction of NH_4^+-N input, it was demonstrated again that the first three (3) days after biogas slurry application was the rapid reduction period during which the prohibition of runoff plays an important role in preventing environmental pollution of surrounding water bodies. After 15 days of application, under the condition of an equal amount of NH_4^+-N, the total amount of NH_4^+-N in the overlying water of biogas slurry treatment decreased by 99.2%. This was significantly lower than that of the fertilizer NH_4^+-N treatment, which underscore the use of disposal biogas slurry NH_4^+-N. Thus, 15 days could be used as the time node for the end of the first digestion cycle.

Furthermore, under the same application condition with the same amount of NH_4^+-N, the NH_4^+-N concentration in the overlying water of the biogas slurry treatment was lower than that of the chemical fertilizer NH_4^+-N treatment on the third day. But it rebounded from 4 to 7 days, mainly due to the NH_4^+-N accounts for 88.6% of the total nitrogen in the biogas slurry. And other nitrogen-containing organic substances in the biogas slurry components are oxidized and decomposed by microorganisms, which increases the NH_4^+-N content of the overlying water. The concentration of NH_4^+-N in overlying water treated with biogas slurry for 0 days (the sampling time in this study is within 8 h after application) is significantly higher than that of fertilizer NH_4^+-N treatment, but the concentration of NH_4^+-N in pore water and the concentration of NH_4^+-N adsorbed by soil are lower than that of fertilizer NH_4^+-N treatment. This is because there is a competitive and mutually exclusive relationship between other cations (Song et al., 2021) and NH_4^+-N ions in biogas slurry, thus delaying the molecular diffusion rate of NH_4^+-N in pore water, it also reduces the dominant sorption of NH_4^+-N on soil particles (Zhao et al., 2013). The abnormal value of BSN1 treatment on the fourth day of application might be due to the operational error of the destructive test, and the value at this point can be regarded as the missing value. After 7 days of application, the NO_3^--N concentration in overlying water, pore water, and soil with the biogas slurry NH_4^+-N treatment was significantly higher than that of the fertilizer NH_4^+- N treatment, which might be that the organic active substances in the biogas slurry components promoted the reproduction of nitrifying microorganisms (Chen et al., 2020), thus promoting the conversion of NH_4^+-N to NO_3^--N. The concentration of NH_4^+-N in the pore water of 0–10 cm soil layer reached the peak value after 4 days of biogas slurry application, and the NH_4^+-N sorption by soil particles reached the peak after 7 days, indicating that the NH_4^+-N in overlying water was gradually migrating to the soil layer over time. The proportion of biogas slurry nitrogen absorbed by soil and contained in pore water in the 0–10 cm soil layer accounted for 76.3% of the total NH_4^+- N after 15 days application, signifying that the disposal of biogas slurry NH_4^+-N in farmland was mainly soil sorption and transformation. However, with the increase in biogas slurry application, the proportion of NH_4^+-N adsorbed by soil in the 0–10 cm soil layer decreases, which is due to the limit value of soil sorption capacity of 1108.55 mg/kg (Wang et al., 2022). When the sorption limit value is exceeded, NH_4^+-N will migrate to the 10–20 cm soil layer. Only when the amount of NH_4^+-N applied exceeds the sorption limit value of 0–20 cm cultivated soil layer, there will be the risk of polluting groundwater. Ammonia volatilization loss was once considered as one of the main ways to reduce NH_4^+-N in field water (Huijsmans et al., 2001), but the ammonia volatilization process is very complex and affected by many factors, so it is very difficult to accurately estimate its loss under natural conditions. Some studies have shown that soil wetting or flooding conditions can reduce ammonia volatilization (Zhou et al., 2009). The test of biogas slurry showed that the removal rate of ammonium nitrogen was only 53% under natural conditions for 100 days (Shi, 2010). In this study, the other fate of biogas slurry NH_4^+-N in the BSN1, BSN1.5 and BSN2.5 treatments accounts for 22.8%, 31.8%, and 34.1%, respectively, including the migration of NH_4^+-N to deeper soil layer, transformation and ammonia volatilization loss of overlying water (Tan et al., 2015). Some scholars believe that the key period of ammonia volatilization is within 7 days after biogas slurry application. The ammonia volatilization loss rates of 1 N biogas slurry, 2 N biogas slurry, 4 N biogas slurry, and 1 N chemical fertilizer treatment are 18.8%, 14.3%, 9.9%, and 6.6%, respectively (Shi, 2010). In this study, the other directions of biogas slurry NH_4^+-N were not subdivided, therefore, the proportion of ammonia volatilization loss in other directions could not be determined. Therefore, it cannot be proved that ammonia volatilization loss is one of the main ways to reduce biogas slurry NH_4^+-N in overlying water. However, at the beginning of biogas slurry application, the concentration of NH_4^+-N in overlying water maintained a high level, decreased rapidly within 7 days, and gradually transformed into NO_3^--N after 7 days.

The use of saturated water content farmland soil for disposal of biogas slurry ammonium nitrogen is mainly based on soil sorption and pore water migration. With the extension of time, the ammonium nitrogen concentration in the overlying water gradually decreases, and the reduction rate of the total ammonium nitrogen gradually increases. Nevertheless, the reduction speed and reduction rate showed a downward trend with the increase in the application amount of the ammonium nitrogen in the biogas slurry. The application of 0–3 d is the rapid consumption period for preventing and controlling the pollution of surrounding water bodies, and the application of 15 d is the completion period of one-time safety consumption.

The results of the biogas slurry pretreatment of protected soil improved the physical and chemical properties of the soil (Tang et al., 2021). Effective positive adjustment in the proportion of each nutrient content such as soil organic carbon in the soil (Yan et al., 2019) and the pH value (Xu et al., 2019) were observed, with a direct positive effect on soil fertility (Yu et al., 2018). Studies have shown that under similar nitrogen condition, the total nitrogen, NH_4^+-N, NO_3^--N, available phosphorus, available potassium and pH of soil increased to varying degrees after soil was treated with pig manure biogas slurry to soil, while the organic carbon content of the soil was not significantly impacted (Li et al., 2021). Soil NH_4^+-N content decreased in low- volume biogas slurry pretreatment (LBS treatment), which may be related to soil microbial activity, while the relative increase in soil total nitrogen was higher in the same treatment. The reduction of NO_3^--N content in the treatments may be ascribed to the downward leaching of NO_3^--N in surface soil caused by irrigation that keeps the soil saturated before the biogas slurry pretreatment of the soil. The pH of the soil treated with LBS decreased slightly, suggesting that low application of biogas slurry could not prevent soil acidification, while high application of biogas slurry fully neutralized soil acids (Xie et al., 2014), as well as inhibited the growth and proliferation of acidobacteria, thus, reducing soil acidification (Wang et al., 2021).

The biogas slurry pretreatment of protected soil showed significant reduction in culturable number of soil microorganisms, as well as a decrease in the richness and diversity of soil microorganisms. These could alter the soil dominant microorganisms. Alterations in the soil microbial compositions through biogas slurry treatment is not only related to the complex factors of closed greenhouse, high temperature, mulching film, soil moisture and other supporting factors, but also closely related to the changes in soil properties. The CCA analysis shows that the content of NH_4^+-N in soil was the main contributory factor to the inhibition of the growth of bacteria without mulching (**Figure 5.4a/b**), while the soil pH was mainly responsible for the inhibition of the growth of bacteria and fungi in soil with mulching (**Figure 5.4c/d**). In addition, soil NO_3^--N was positively correlated with the proliferation of bacteria and fungi, while soil organic carbon was positively correlated with the proliferation of fungi, but negatively correlated with the reproduction of bacteria. Appropriate application of biogas slurry can promote the growth and enrichment of soil dominant bacteria (microbial alpha diversity) (Wentzel and Joergensen, 2016), and thus, help prevent and control soil-borne diseases of crops (Li et al., 2021). Although nitrogen input is the key factor to increase soil microbial nitrogen energy (Möller, 2015), a large amount of ammonium nitrogen in biogas slurry could play a role in inhibiting microbial growth in the short-term. Some studies reported that the population of bacteria, fungi and *Fusarium oxysporum* in the soil decreased significantly after the application of biogas slurry (Cao et al., 2013; Cao et al., 2015; Yang et al., 2017). The increase in biogas slurry concentration till optimal concentration resulted in the relative increase of actinomycetes, while further increment in the concentration of biogas slurry inhibits the growth of actinomycetes (Xu et al., 2019). Furthermore, when the biogas slurry was applied at 180 m^3/hm^2, with high Chao1 and Shannon index the richness and diversity of bacteria increased, while the diversity of fungi decreased with low Chao1 index and Shannon index (Wang et al., 2021).

Biogas slurry pretreatment of soil can promote the growth and development of subsequent crops through fertilization and elimination of soil-borne pathogenic microorganisms, with no risk of affecting crop growth. On the other hand, high NH_4^+-N (Zhang et al., 2021), electrical conductivity (Tigini et al., 2016), and chemical oxygen demand (Wang et al., 2019) in biogas slurry can result in plant roots' adversity stress leading to plant growth retardation. In this study, the plant height and flowering rate of *Capsicum* spp. with low amount of biogas slurry (LBS) were better than those with high amount of biogas slurry (HBS and HBSM), which buttresses the aforementioned observations. Appropriate application of biogas slurry to the soil can significantly reduce plant disease index (Wang et al., 2021). For instance, a study by Cao et al. (2016), showed watermelon fusarium wilt was significantly inhibited, and disease index was reduced by 36.4%. Moreover, in this study, the survival rates of *Capsicum* spp. with clean water (W, WM) and biogas slurry (LBS, HBS, LBSM, HBSM) were higher than that of the blank control (CK, CKM). This is an indication that soil moisture played an important role in improving the survival rate of *Capsicum* spp. plants. Also, the rigid seedling rate of clean water treatment (W, WM) is significantly higher than those of biogas slurry treatment (LBS, HBS, LBSM, HBSM). This substantiates the role of biogas slurry in promoting the growth of crops in biogas slurry pretreatment soil. This might be related to the nutrient richness of biogas slurry and its potential in the reduction of soil-borne pathogens, but more in-depth research might be needed to substantiate and elucidate this. Soil pretreatment with biogas slurry dosage of 495 m^3/hm^2 and 990 m^3/hm^2 increased soil total nitrogen, total phosphorus, available phosphorus, available potassium, organic carbon and soil pH. But both of them inhibited the growth of soil bacteria, fungi, actinomycetes and fusarium, and reduced the soil microbial flora as well as the evenness of species distribution. Moreover, with the soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were closely related to the growth and proliferation of soil bacteria and fungi. Interestingly, biogas slurry dosage of 495 m^3/hm^2 improved the growth of *Capsicum* spp., which significantly improve the survival rate of *Capsicum* spp. seedlings, the plant height, the flowering rate, the fruit- bearing rate and the reduced the rigid seedling rate substantially.

6.2 Concluding Remarks

The need for safe digestion or treatment of biogas slurry has received serious attention and requires an urgent solution. This will help to reduce unfriendly environmental disposal of livestock and poultry waste pollution in China. The use of biogas slurry as fertilizer meets the requirements for sustainable environmental development. Present field application of biogas slurry discharged from intensive large-scale livestock and poultry farms as well as biogas projects have exceeded the bearing capacity of adjacent farmland. Also, the maximum farmland fertilizer requirement and agricultural seasonality have been greatly affected. It is therefore necessary to further explore alternative treatment options for this biogas slurry as well as improve biogas slurry waste efficient utilization. Also, there is a significant knowledge gap on the adsorption mechanism and kinetics of biogas slurry ammonium nitrogen in the soil. Hence, this study uses waste biogas slurry pretreatment continuous cropping obstacle soil in facilities protected land to diversify biogas slurry application. And uses semi-pilot field trials to understand the synergistic combination measures. It needed to achieve the multiple goals of efficient biogas slurry digestion per unit area of farmland, improvement of soil fertility and productivity as well as the prevention and control of soil-borne diseases in facility protected land.

Three typical farmland ploughing layer soils (silty loam, loam and sandy loam) were selected for the adsorption kinetics and thermodynamic studies. The adsorption characteristics of the three types of soils on biogas slurry ammonium nitrogen were analyzed, and the optimal model was selected to fit the maximum adsorption value to explore the relationship between soil physicochemical properties and adsorption capacity. The theoretical saturated adsorption capacity of biogas slurry ammonium nitrogen were 1038.41–1372.44 mg/kg in silty loam, 840.85–1157.60 mg/kg in loam, and 412.33–481.85 mg/kg in sandy loam. The optimal values were 1108.55 mg/kg, 874.86 mg/kg, and 448.35 mg/kg for silty loam, loam, and sandy loam, respectively. The value was significantly positively correlated with soil organic matter, total nitrogen, available phosphorus, available potassium, cation exchange capacity, and particle content of 0.02–0.002 mm, but significantly negatively correlated with soil pH. The maximum adsorption capacity of three types of soil (silty loam = 1108.55 mg/kg, loam = 874.86 mg/kg, sandy loam = 448.35 mg/kg) to ammonium nitrogen in biogas slurry were determined, providing the safe dosage/concentration for biogas slurry pretreatment of protected soil.

The disposal of biogas slurry ammonium nitrogen in farmland soil with saturated water content is mainly based on soil sorption and pore water migration. A duration of 0–3 days was established as rapid disposal period with the overlying water ammonium nitrogen concentration decrease of 63.5–80.7%, while the reduction rate of total ammonium nitrogen was 65.8–82.3%. Also, 15 days was established as the completion period for safe digestion of the biogas slurry, resulting in 97.0–98.7% decrease in the overlying water ammonium nitrogen concentration and a , the reduction rate of 97.9–99.2%, while the proportion of ammonium nitrogen absorbed in the 0–10 cm soil layer accounted for 63.5–76.3%.

Moreover, through the static soil column simulation experiment, the speed and efficiency of biogas slurry ammonium nitrogen disposed by the saturated water content soil were studied. Also, evaluated was the migration, transformation characteristics and the fate ratio of the biogas slurry ammonium nitrogen alongside the time point of the discharge when the field surface water quality reached the standard. The safe cycle (15 days) of absorbing biogas slurry in saturated water content soil and the final fate of ammonium nitrogen in biogas slurry were established, to provide theoretical support for the safe consumption of biogas slurry pretreatment protected soil.

Semi-pilot split-plot studies on the application of waste biogas slurry were carried out to understand the impacts of biogas slurry on soil properties, microorganisms and crop growth on the field (facility protected soil). The use of biogas slurry to pretreat facility protected soil noticeably increased the soil total nitrogen, total phosphorus, available phosphorus, available potassium, organic carbon content and soil pH. During biogas slurry pretreatment of the soil, soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were closely related to the growth and development of soil bacteria and fungi. The effect of biogas slurry pretreatment on the growth of crops was elucidated, and the response effect on soil microorganisms and soil properties to biogas slurry pretreatment were determined. The relationship of soil properties, microorganisms and *Capsicum* spp. growth to biogas slurry pretreated soil were dose-based responses. The biogas slurry soil pretreatment with a dosage of 495 m^3/hm^2 was most beneficial to the growth of the *Capsicum* spp., which significantly improved the survival rate of *Capsicum* spp.

seedlings, the flowering plants rate, the fruit-bearing plants rate and the plant height, and substantially reduce the rate of rigid seedlings. The soil with biogas slurry pretreatment of 495 m^3/hm^2 favoured the health and growth of *Capsicum* spp. by preventing and controlling soil-borne microbial diseases.

Moreover, the use of biogas slurry to pretreat protected soil increases the soil total nitrogen, total phosphorus, available phosphorus, available potassium, organic carbon content and soil pH value, while the population, diversity and distribution of soil microbes were significantly influenced. Interestingly, soil ammonium nitrogen, soil pH, and soil nitrate nitrogen were highly correlated to the population of bacteria and fungi present in the pretreated soil.

6.3 Recommendations

The safe application of biogas slurry to pretreat continuous cropping obstacle soil in protected land still is critical. Findings from this study has provided baseline data on the adsorption kinetics and thermodynamic of biogas slurry ammonium in the soil, significant impacts of biogas slurry application on soil physiochemical properties, soil microorganisms, and *Capsicum* spp. health and growth. A semi-plot field application of waste biogas slurry was also demonstrated. In the future, based on the environmental safety requirements, there are many biogas slurry contents and their implications in the environments that need to be further studied. Such studies should include:

i characterization of adsorption, migration, and transformation of different components of biogas slurry in a specific soil type as well as in different soil types. Similarly, the complex and varied components of biogas slurry, soil texture and plough layer properties, crop types and continuous cropping conditions need to be considered;

ii analysis of the correlation coefficient between soil properties and the adsorption process of biogas slurry components; and,

iii determination of the interaction between the components of biogas slurry during adsorption, migration and transformation.

iv assessment of the inhibitory effect of biogas slurry on specific soil pathogens.

Using biogas slurry to pretreat continuous cropping obstacle soil in protected land involves the intersection of resources, environment, and soil microorganisms. An in-depth study of biogas slurry pretreatment of continuous cropping obstacle soil in protected land is also important to provide the interlink among different disciplines such as agronomy, microbiology, soil science and chemistry.

In addition, it is particularly necessary to develop corresponding matching combination technologies according to local conditions. The effect of high temperature, high humidity, greenhouse sealing, film mulching, and other factors on the biogas slurry pretreatment also need to be studied.

References

Acosta R, Fierro V, Martinez de YA, Nabarlatz D, Celzard A. 2016. Tetracycline adsorption onto activated carbons produced by KOH activation of tyre pyrolysis char. *Chemosphere* 149: 168–176. https://doi.org/10.1016/j.chemosphere.2016.01.093.

Cao Y, Chang Z, Ma Y, Yang H, Fu G. 2013. Effects of application of anaerobically digested slurry on suppression of pepper (*Capsicum frutescens* L.) blight and soil biological characteristics. *Scientia Agricultura Sinica* 46: 507−516. https://doi.org/10.3864/j.issn.0578-1752.2013.03.007

Cao Y, Wang J, Wu H, Yan S, Guo D, Wang G, 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. https://doi.org/10.1016/-j.apsoil.2016.05.010

Cao Y, Wu H, Guo D, Wang Q, Yan S, Wang G, Ma Y. 2015. Effect of biogas slurry application on incidence of fusarium wilt, fruit yield and quality of watermelon. *Soils* 47: 904–910.https://doi.org/10.13758/j.cnki.tr.2015.05.015

Chen Z, Wang Q, Ma J, Chapman S, Zou P, Ye J, Yu Q, Sun W, Lin H, 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: 15–25. https://doi.org/10.1007/s10333-019-00761-y.

Cong R, Zhang L, Lu Y, Huang Q, Shi X, Li X, Ren T, Lu J. 2017. Adsorption-desorption characteristics of soil ammonium under long-term straw returning condition. *Journal of Plant Nutrition and Fertilizer* 23: 380–388. https://doi.org/10.11674/zwyf.16307.

He G, Liu X, Cui Z. 2021. Achieving global food security by focusing on nitrogen efficiency potentials and local production. *Global Food Security* 29: 100536. https://doi.org/10.1016/j.gfs.2021.100536.

Huijsmans JFM, Hol JMG, Hendriks MMWB. 2001. Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland. *NJAS: Wageningen Journal of Life Sciences* 49: 323–342. https://doi.org/10.1016/s1573-5214(01)80021-x.

Jiang L, Wang Q, Chen D, Li A, Qian S, Fu J, Wang J. 2011a. Effects of paddy field disposal of biogas slurry on the rice production, soil quality and environmental safety. *Journal of Agro-Environment Science* 30: 1328–1336. http://www.cnki.com.cn/Article/CJFDTotalNHBH201107013.htm (accessed on 6 January 2011).

Jiang L, Wang Q, Li A, Qian S, Fu J, Ma J, Ye J, Wang J. 2011b. The ecological effects of fallow paddy field disposal biogas slurry and its impact on the following rice safety production. *Journal of Agro-Environment Science* 30: 2483–2490. http://www.cqvip.com/QK/92252A/201112/40459055.html (accessed on 17 May 2011).

Kittrick JA. 1966. Forces involved in ion fixation by vermiculite. *Soil Science Society of America Journal* 30: 801–803. https://doi.org/10.2136/sssaj1966.03615995-003000060040x.

Li H, Han Y, Cai Z. 2009. Equilibrium of ammonium adsorption in paddy soils of Taihu region of China under different reaction conditions. *Chinese Journal of Soil Science* 40: 89–95. https://doi.org/10.3321/j.issn:0564-3945.2009.01.026.

Li Y, Xu J, Liu B, Sun Q, Li J, Liu J, Lang Q, Sun R, Jin H. 2021. Effects of different biogas slurries on soil microbial carbon metabolism. *Chinese Journal of Eco-*

Agriculture 29: 1921−1930. https://doi.org/10.12357/cjea.20210274

Möller K. 2015. Effects of anaerobic digestion on soil carbon and nitrogen turnover, N emissions, and soil biological activity. A review. *Agronomy for Sustainable Development* 35: 1021−1041. https://doi.org/10.1007/s13593-015-0284-3

Saruchi, Kumar V. 2020. Effective degradation of rhodamine B and Congo red dyes over biosynthesized silver nanoparticles-imbibed carboxymethyl cellulose hydrogel. *Polymer Bulletin* 77: 3349–3365. https://doi.org/10.1007/s00289-019-02920-x.

Shen S, Tu S, Kemper WD. 1997. Equilibrium and kinetic study of ammonium adsorption and fixation in sodium-treated vermiculite. *Soil Science Society of America Journal* 61: 1611–1618. https://doi.org/10.2136/sssaj1997.03615995006-100060011x.

Shi Y. 2010. The Potential Capacity for Paddy Field Ecosystem to Decontaminate Biogas Slurry and its Risks Assessment. PhD. Thesis, Zhejiang University, Hangzhou, China.

Song Y, Wang G, Li R, Chen G. 2021. Research progress of biogas slurry treatment and resource utilization. *Transactions of the CSAE* 37: 237–250. https://doi.org/10.11975/j.issn.1002-6819.2021.12.028.

Tan X, Shao D, Gu W, Liu H. 2015. Field analysis of water and nitrogen fate in lowland paddy fields under different water managements using HYDRUS-1D. *Agricultural Water Management* 150: 67–80. https://doi.org/10.1016/j.agwat.2014.12.005.

Tang Y, Luo L, Carswell A, Misselbrook T, Shen J, 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: 143786. https://doi.org/10.1016/j.scitotenv.2020.143786

Tian H. 2011. Ammonia-nitrogen adsorption characteristics onto vadose zone soils in Luanhe Delta. *Chinese Journal of Environmental Engineering* 5: 507–510.

Tigini V, Franchino M, Bona F, Varese GC. 2016. Is digestate safe? A study on its ecotoxicity and environmental risk on a pig manure. *Science of The Total*

Environment 551-552: 127–132. https://doi.org/10.1016/j.scitotenv.2016.02.004

Wan D, Zhang Y, Feng Y, Huang Y. 2004. Fixed ammonium content of soils on cultivated upland in Hunan province and its affecting factors. *Acta Pedologica Sinica* 41: 480–483. https://doi.org/10.3321/j.issn:0564-3929.2004.03.025.

Wang F, Alva AK. 2000. Ammonium adsorption and desorption in sandy soils. *Soil Science Society of America Journal* 64: 1669–1674. https://doi.org/10.2136/-sssaj2000.6451669x.

Wang L, Wang G, Wang H, Zhou G, Zhao C, Wang P, Jiang S. 2021. Effects of applying biogas slurry instead of chemical fertilizer on the growth of melon and soil microorganism. *Journal of Southern Agriculture* 52: 2498−2506. https://doi.org/10.3969/j.issn.2095-1191.2021.09.020

Wang S, Wang N, Zhang J, Fan C. 2015. Influencing factors of NH_4^+ adsorption characteristics on albic soil. *Soil and Fertilizer Sciences in China* 2: 22–28. https://doi.org/10.11838/sfsc.20150205.

Wang Z, Liang Y, Sheng J, Guan Y, Wu H, Chen L, Zheng J. 2016. Analysis of water environment risk on biogas slurry disposal in paddy field. *Transactions of the CSAE* 32: 213–220. https://doi.org/10.11975/j.issn.1002-6819.2016.05.030.

Wang Z, Wang X, Zhang Y, Guo Z, Sheng J, Zheng J. 2019. COD in biogas slurry: effects on cucumber seedling growth and soil environmental factors. *Chinese Agricultural Science Bulletin* 35: 15–22. http://www.cqvip.com/qk/91831x/-20194/7000000000000000.html (accessed on 04 June 2018)

Wang Z, Zhang L, Sun G, Zhou W, Sheng J, Ye X, Olaniran AO, Kana EBG. 2022. Adsorption characteristics of three types of soils on biogas slurry ammonium nitrogen. *Frontiers in Environmental Science* 10: 942263. https://doi.org/10.-3389/fenvs.2022.942263.

Wentzel S, Joergensen RG. 2016. Effects of biogas and raw slurries on grass growth and soil microbial indices. *Journal of Plant Nutrition and Soil Science* 179: 215−222. https://doi.org/10.1002/jpln.201400544

Xie X, Chen Y, Bu Y, Dai C. 2014. A review of allelopathic researches on phenolic acids. *Acta Ecologica Sinica* 34: 6417–6428. https://doi.org/10.5846/stxb-201302210285

Xu M, Xian Y, Wu J, Gu Y, Yang G, Zhang X, Peng H, Yu X, Xiao Y, 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: 2534–2542. https://doi.org/10.1007/s11368-019-02258-x

Xue Q, Wei Q, Gao Y, Shi H, Qu D. 1996. Kinetic characteristics of NH_4^+ adsorption-desorption for five major soils in Shanxi Province. *Acta Pedologica Sinica* 32: 129–136.

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

Yang Z, Chen W, Wang W, Li W, He X, Yang X. 2017. Effects of biogas slurry on soil microbial characteristics of broccoli. *Chinese Agricultural Science Bulletin* 29: 112–115 http://www.cqvip.com/QK/91831X/201729/673598109.html (accessed on 21 March 2017)

Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* 89: 1467–1471. https://doi.org/10.1016/j.chemos-phere.2012.06.002.

Yu D, Wen Z, Li X, Song X, Wu H, Yang P. 2018. Effects of straw return on bacterial communities in a wheat-maize rotation system in the North China Plain. *PLoS One* 13: e0198087. https://doi.org/10.1371/journal.pone.0198087

Zhang L, Sun G, Wang Z, Zong J, Zhou W, Sheng J. 2021. Analysis of rice seedling growth restriction factors under biogas slurry application. *Journal of Agro-Environment Science* 40: 2537–2543. https://doi.org/10.11654/jaes.2021-1025

Zhao W, Li Y, Zhao Q, Ning Z, Zhou C, Wang H, Lu L, Yang P, Zhang K, Wang F, Huang Z, Ouyang Z. 2013. Adsorption and desorption characteristics of ammonium in eight loams irrigated with reclaimed wastewater from intensive hogpen. *Environmental Earth Sciences* 69: 41–49. https://doi.org/10.1007-/s12665-012-1932-4.

Zhou S, Nishiyama K, Watanabe Y, Hosomi M. 2009. Nitrogen budget and ammonia volatilization in paddy fields fertilized with liquid cattle waste. *Water, Air, and Soil Pollution* 201: 135–147. https://doi.org/10.1007/s11270-008-9933-3.