Co-digestion of hybrid Pennisetum and peanut shell after adding TiO2 nanoparticles: Focusing on the synergistic effects on methane production

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Research Article

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Posted Date: May 7th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-461356/v1

Co-digestion of hybrid *Pennisetum* and peanut shell after adding TiO_2 nanoparticles: Focusing on the synergistic effects on methane production

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Abstract Anaerobic digestion is a widely accepted method to treat wastes such as peanut shell. The energy and nutrients are simultaneously recovered by this method. The objective of this study was to elucidate the effect of TiO_2 nanoparticles in co-digestion of hybrid Pennisetum and peanut shell under mesophilic conditions. The results demonstrated the met hane (CH_4) production was improved by adding the TiO_2 nanoparticles. The cumulative ga s production is best (up to 11,133.3 mL) by adding 0.15% nano-TiO_2 particles. The micro bial community analysis showed that Methanobacterium and Methanosarcina were enriched in the presence of TiO_2 nanoparticles indicating that TiO_2 can improve CH_4 production by stimulating the growth of methanogens.

Key words: anaerobic fermentation; methane production; TiO_2 nanoparticles; Hybrid *Pennisetum*; peanut shell

1. Introduction

The total annual output of peanuts in China is 5 million tons. Peanut shells (PS) are food waste, and food waste constitutes 30–50% of municipal solid waste [1-2]. Approximately 60 million tons of food waste was produced last year in China alone. Food waste production is expected to keep increasing while maintaining social/economic growth as well as population growth.

Hybrid *Pennisetum* (HP) is herbaceous plant with great energetic potential. It has a high biological yield, strong regeneration ability, and multiple rounds of harvest [3-4]. Many researchers have focused on methane production from anaerobic fermentation of hybrid Pennisetum. However, Pennisetum is not fully utilized when used as a carbon source. Therefore, significant effort is needed to handle ever-increasing peanut shell waste and use it to produce biogas via *Pennisetum*.

Aerobic digestion has been developed and is well recognized as a promising tool for waste stabilization and energy recovery in the form of biogas. It has two processes: wet anaerobic digestion and dry anaerobic digestion. The total solid of wet anaerobic digestion system is less than 15%, and the total solid of dry anaerobic digestion system is higher than 15% [5-6]. Dry anaerobic digestion (DAD) is increasingly popular. This requires less water, and it does not cause more pollution than a wet digestion system [7-9]. In addition, co-digestion can greatly improve specific methane yields and methane production rates versus mono-digestion because of the superior nutrient availability and synergistic microbiomes.

Nanoparticles offer unique physiochemical properties and widespread applications [10]. Their effects on the environment have been investigated, but most studies focused on soil and wastewater toxicity [11-12]. The effect of nanomaterials on wastewater treatment has been reported [13-15]. The adsorption of activated sludge was reported to be the main mechanism of nanoparticles. Nevertheless, the effects of metal oxide nanoparticles (such as TiO_2 nanoparticles) on anaerobic digestion for HP and PS are rarely investigated. TiO_2 nanoparticles have no significant toxicity on the viability of bacterial cells and show no inhibitory effects on waste-activated sludge digestion.

In this study, dry anaerobic experiments were conducted under mesophilic conditions with different mixing ratios of HP and PS. The purpose was to investigate methane production with different ratios of HP and PS, investigate the effects of five dosages of the TiO_2 nanoparticles on methane yield, and assess the influences of TiO_2 nanoparticles on flora.

2 Materials and Methods

2.1 Feedstock and inoculum

The surface part of hybrid Pennisetum used here was from the experimental farm of Yunnan Agricultural University, Kunming, Yunnan Province. The samples were cut into 2–3 cm. The dehydrated sludge was taken from the fifth water purification plant in Kunming, Yunnan Province, and appeared brown. The total solids (TS) content was 15.46%, and the volatile solid (VS) content was 41.54%.

2.2 Nanoparticles synthesis

Nano-TiO_2 powder was synthesized according to a reported route [16]. Here, 0.1600 g (0.84 mmol) of dopamine (3,4-dihydroxy-β-phenylethylamine) and 30 mL of benzyl alcohol were added to an Erlenmeyer flask and stirred vigorously for 20 min. We then added 1.5 mL of $TiCl_4$ dropwise. This was stirred vigorously at room temperature for 2 h. The temperature was then increased to 80°C, and the mixture was transferred to a polytetrafluoroethylene reactor at 80°C for 3 days. After cooling, the resulting red-brown mixture was centrifuged, the supernatant was decanted, and the precipitate was washed three times with chloroform and dried at 60°C to obtain a large amount of dark red nano-TiO_2 powder.

2.3 DNA extraction and PCR amplification

DNA extraction of different digestion period samples was detected by a MIO-BIO Power Soil DNA Isolation Kit. The remaining steps for DNA extraction were performed via the DNA isolation kit protocol. Subsequently, the V4-V5 variable region of the bacterial 16S rRNA gene was amplified using primers 515F and 926R through polymerase chain reactions (PCRs). PCR was performed in a 10 μL volume containing 1× PCR buffer, 1 μL dNTPs, 1 μL primer, 1 unit taq DNA polymerase, and 5–50 ng template DNA under the two cycling conditions: Bacteria had pre-denaturation at 94°C for 2 min, 22 cycles of denaturation at 94°C for 30 s, annealing at 55°C for 30 s or 50°C for 30 s, extension at 72°C for 30 s, and a final extension at 72°C for 5 min. Archaea had pre-denaturation at 94°C for 2 min, 30 cycles of denaturation at 94°C for 30 s, annealing at 50°C for 30 s, extension at 72°C for 30 s, and a final extension at 72°C for 5 min. Finally, the PCR products were tested through high-throughput sequencing using the Illumina Miseq 2x300bp platform.

2.4 Anaerobic digestion tests

2.4.1 Experimental set-up

The digestion device consists of a 1 L reaction bottle, gas bottle, water bottle, and constant-

temperature water bath. According to the experimental design, different ratios of substrates and TiO_2 nanoparticles were added to the reactors. All rectors were incubated at 37(±1°C).

2.4.2 Feedstock

The carbon to nitrogen ratio (C/N) plays an important role in dry AD. If the C/N is higher, then the gas yield may be lower. The methanogenic bacteria will be toxic if the C/N is lower. According to Weiland and Richa, a C/N ratio in the range of 20%–30% is the best. The C/N ratio of hybrid Pennisetum is 31.15 (C 47.35% and N 1.52%). The C/N of peanut shell was also measured (Table 1). The C/N ratio is 25. We choose the hybrid Pennisetum and peanut shell as feedstocks.

Table 1. Analysis of the content of HP and PS elements.

Sample	The content of elements			
	C	H	N	元素 C/N
PS	60.60%	5.90%	2.40%	25.25
HP	47.35%	5.89%	1.52%	31.15

2.4.3 Experimental design

The digestion process contains two steps. First, to determine the best ratio, the HP:PS mixing ratios were selected as 0:4, 1:3, 2:2, 3:1, and 4:0. Each sample group was set up in triplicates. Second, different quality scores of TiO_2 nanoparticles were added to the reactors under the best ratio of HP:PS.

2.5 Analytical methods and characterization

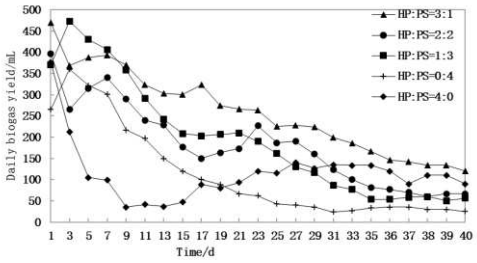
The volatile solids (VS) and the total solids (TS) were measured by standard methods [17-18]. Total carbon (TC) and total nitrogen (TN) were measured with an elemental analysis instrument (VARIOEL III, Germany). The 16s rRNA gene amplification and sequencing used NGS Illumina MiSeq 2 x 300 bp.

3 Results and Discussion

3.1 Cumulative Methane production and daily methane yield

Fig. 1 shows 40-day methane yields for different ratios of mixed feedstock and cumulative methane production. The pH values in reactors ranged from 6.5 to 7.5 because they were suitable for

methanogenesis. The changing trend of daily methane yield and cumulative methane production are similar. However, the peak values of daily methane yield were different. The sample at 3:1 shows the highest daily methane yield on the 17th day and the highest value at 323 mL. The highest cumulative production of the sample of 3:1 is 10,405 mL. The results suggested that the best ratio of HP and PS is 3:1.



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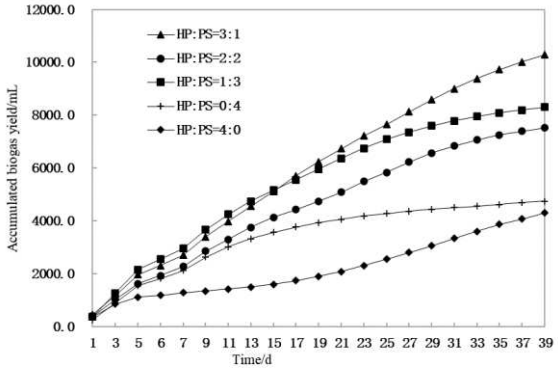


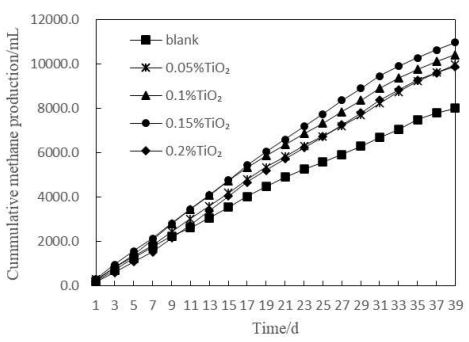
(b)

Fig. 1(a) Daily methane yield and (b) cumulative methane production.

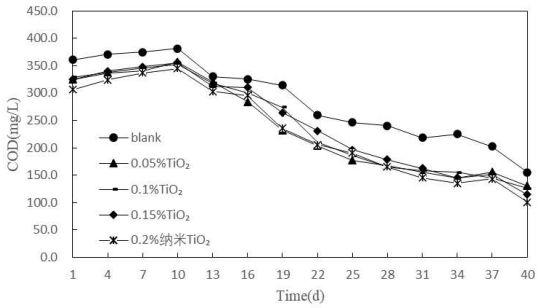
3.2 Impact of nano-TiO_2 on methane production

The effects of TiO_2 nanoparticles on anaerobic digestion are shown in Fig. 2a. The pH values in the reactors also ranged from 6.5 to 7.5. Five sets of experiments with different amounts of TiO_2 starting from 0 to 2% were performed. The results showed that the addition of TiO_2 had an

encouraging impact on methane production. Under TiO_2 nanoparticles addition, the cumulative methane production increased significantly. When 0.15% TiO_2 was added, the cumulative methane production increased by 23.7%. However, the methane production decreased when the concentration of TiO_2 was 0.20%. This indicated that the high concentration of TiO_2 NPs inhibits anaerobic digestion. The COD curves of different samples on anaerobic digestion are shown in Fig. 2b. The trend of COD decreased after 10 days. The nitrogen and carbon content is exhausted along with the aging of the microbial cells. Moreover, the COD removal efficiency was gradually increased, and the order of COD removal rates was blank (57%) < 0.05% TiO_2 (60%) < 0.1% TiO_2 (62%) < 0.15% TiO_2 (65%) < 0.2% TiO_2 (67%).



(a)



(b)

Fig. 2 The curves of cumulative methane production (a) and COD (b).

3.3 Community diversity of archaea

Archaeal community diversity of three samples with different fermentation periods is shown in Table 2. ACE and Chao1 indexes were used to compare the species richness, and the Shannon index was used to compare community diversity in different samples. The un-fermented (NF) samples had highest species richness with ACE and Chao 1 values of 57 and 58 followed by pre-

fermented (FQ) samples (ACE of 57 and Chao1 of 55) and middle-fermented (FM) samples with the lowest ACE (51) and Chao1 (50). The Shannon index also decreased in fermentation progresses.

Table 2. Comparison of species richness and community diversity estimators of the Archaeal communities in different samples.

Sample	Number of sequences	OTUs	ACE	Chao 1	Shannon	Coverage
NF	10302	56	57	58	2.69	99.98%
FQ	8284	52	57	55	2.52	99.93%
FM	18361	50	51	50	2.32	99.99%

3.4 Archaeal flora distribution of different samples

As many as 14 archaeal flora were identified in the three different fermentation periods (Fig. 3). In the un-fermented period, the dominant archaea are *Methanobacterium* (35.20%), *Methanosaeta* (19.37%), *Methanosporillum* (18.00%), and *Methanobrevibacter* (7.61%). In pre-fermented period, the dominant archaea are *Methanobacterium* (52.90%), *Methanosaeta* (14.18%), *Methanosporillum* (7.69%), *Methanobrevibacter* (9.11%), and *Metgabisarcina* (7.40%). In the middle-fermented period, the dominant archaea are *Methanobacterium* (40.40%), *Methanosaeta* (20.47%), *Methanosporillum* (23.06%), and *Metgabisarcina* (5.23%).

Therefore, the categories of major archaea genera were similar, but their relative abundances were different. The archaea of *Methanobacterium* and *Metgabisarcina* were enriched with the addition of TiO_2 nanoparticles. These results indicate that TiO_2 played an important and positive role in CH_4 production.

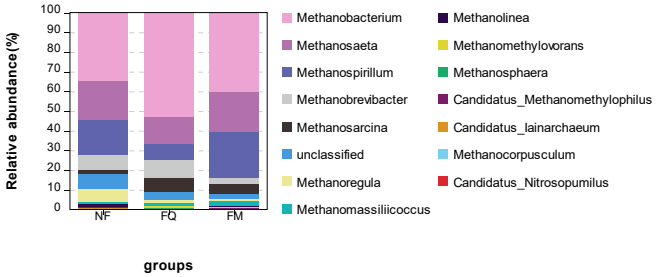


Fig. 3 Distribution of various stains at the genus level during anaerobic digestion.

4 Conclusion

This study indicated that the addition of TiO_2 nanoparticles promoted methane production in the system of anaerobic co-digestion of hybrid Pennisetum and peanut shell. The archaea of *Methanobacterium* and *Metgabisarcina* can be enriched upon addition of TiO_2 nanoparticles. This

study expands our knowledge of the role of TiO_2 nanoparticles in mixed dry anaerobic fermentation. In our future work, the effect of nanoparticles on fermentation will be further investigated, and biological flora will be studied in the fermentation process.

Acknowledgments

This work was supported by Engineering and Research Center for Industrial Biogas Technology of Yunnan Province University. The archaeal diversity analysis was performed using the Omicshare tools—a free online platform for data analysis (http://www.omicshare.com/tools.) We thank LetPub (www.letpub.com) for its linguistic assistance during the preparation of this manuscript.

Funding Information

The work received financial support from the Agricultural Joint Youth Project of Yunna Provincial Department of Science and Technology (2018FG001-102).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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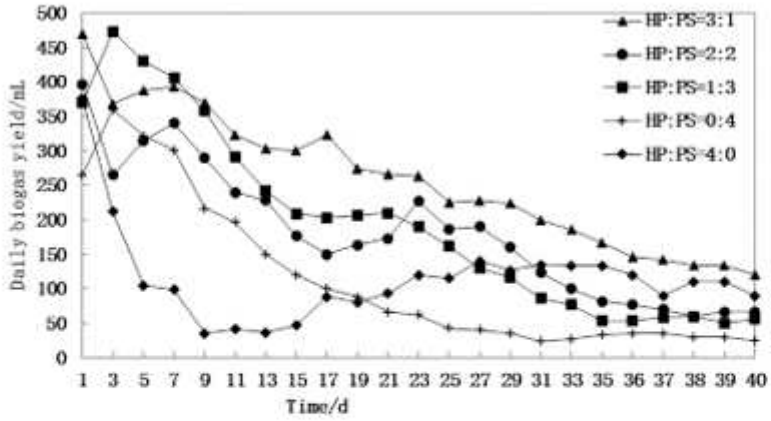
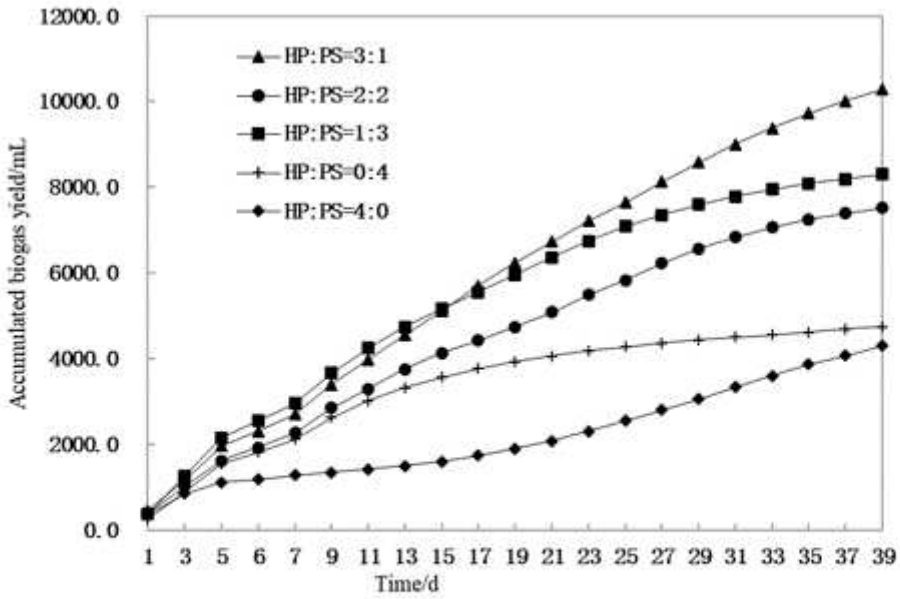
Figures



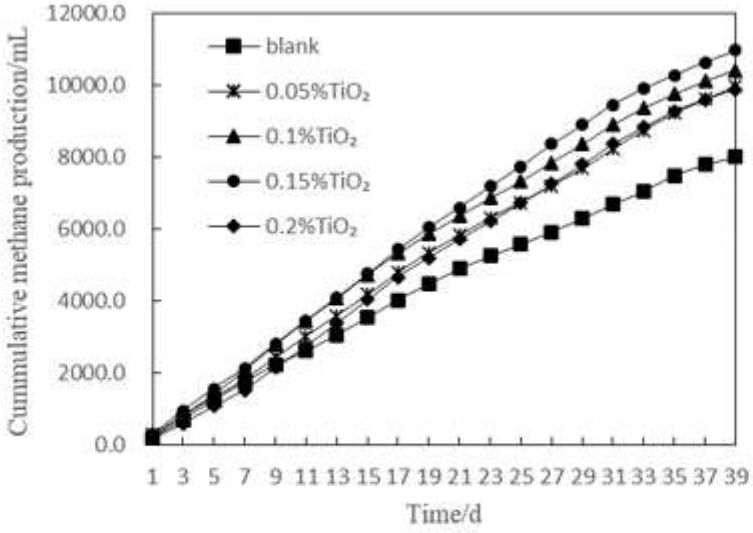
(a)



(b)

Figure 1

(a) Daily methane yield and (b) cumulative methane production.



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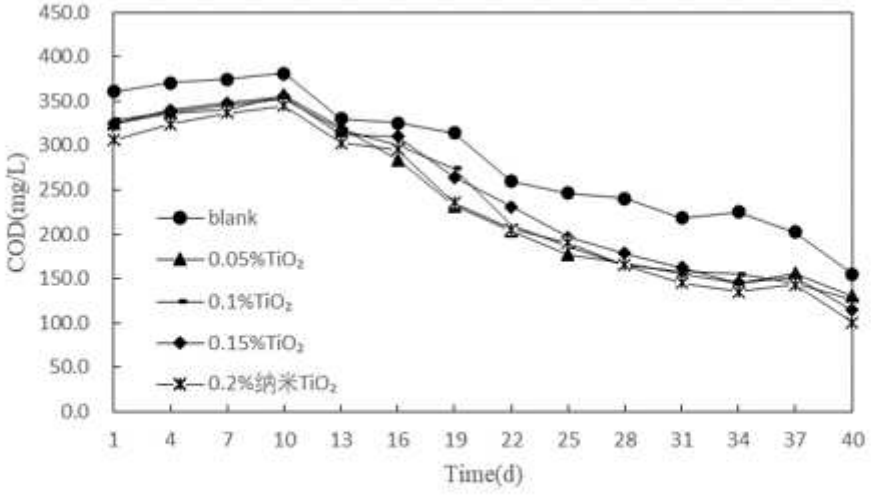

(b)

Figure 2

The curves of cumulative methane production (a) and COD (b).

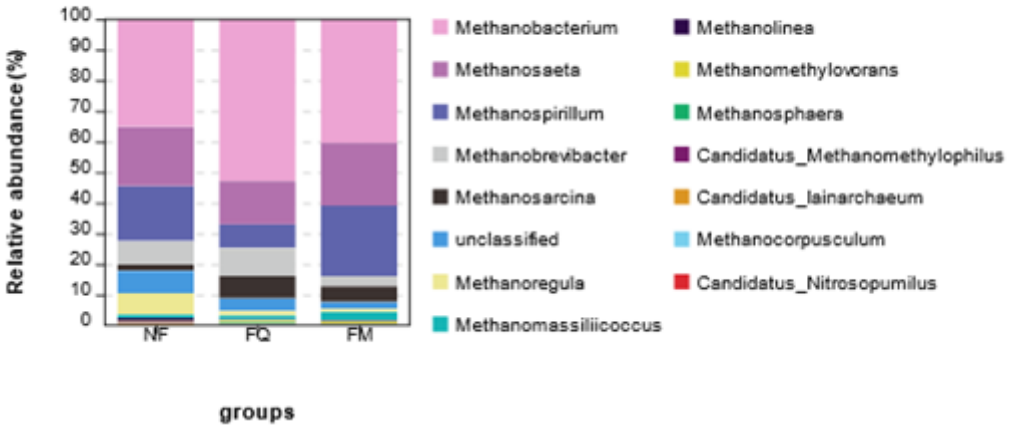

Figure 3

Distribution of various stains at the genus level during anaerobic digestion.