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基于中小型沼气工程的农业废弃物厌氧产沼气强化方法的研究

STUDIES ON ENHANCING BIOGAS PRODUCTION FROM ANAEROBIC DIGESTION OF AGRICULTURAL WASTES FOR APPLICATION IN SMALL AND MEDIUM-SIZED BIOGAS PROJECT

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摘要

随着能源消耗量和因人类活动产生的废弃物的增加，厌氧发酵（AD）作为一种将废弃物转化为生物能源的技术，在全球范围内受到越来越多的关注。中国农村地区的中小型沼气工程在改善农村生产和生活条件以及节能减排等方面发挥着重要作用。另一方面，中国是世界上农业大国之一，拥有丰富的生物质资源如农作物秸秆和动物粪便等。这些废弃物若得不到及时的无害化处理，将会导致许多环境问题如气味，土壤和水污染以及空气污染等。因此，利用这些废弃物产生可再生能源具有许多经济、环境和气候优势，且助于减轻与粪便存储有关的气味并清除病原体。但是，发

酵池温度过低会导致发酵效率及沼气产量降低，需要采用加热措施来提高寒冷地区的发酵效率。除此以外，农业作物废弃物（ACW）中的有机组分纤维素（CEL）、半纤维素（HCEL）和难消化的木质素化合物强烈地结合在一起，形成了复杂的结构，这也是影响厌氧发酵的利用效率低的主要原因。有机组分的这种结构造成了抵抗微生物作用的化学和物理抑制性，因而抑制厌氧发酵中有机物的水解。此外，农业废弃物有机负荷高、微生物多样性不足、氮含量低（C/N 高）以及成分构成都不利于厌氧发酵。因此，本研究的主要目标是：1）以软体沼气池为对象，在小试验规模上研究利用太阳能提高发酵温度的设施形式，以达到寒冷气候下提高沼气产量的目的；2）以农作物秸秆为原料，研究预处理方式对分解木质纤维素复杂的晶体结构，进而提高厌氧消化沼气产率的作用机理；3）在实验室规模上研究厌氧共消化（ACoD）对农业废弃物厌氧产沼气的影响，以解决单物料厌氧发酵沼气产量低的问题。

为了实现这些目标，本研究分别在小试和实验室规模上进行了相关试验研究，以提高农业废弃物产沼气的能力。主要试验结果如下：

1. 作为解决方案，本研究提出了一种与北墙集成的日光温室采暖技术，用以加热半埋式低成本软体发酵池。该实验包括两个类似的半埋式发酵池，第一个（DA）由集成有北墙的日光温室加热，而第二个（DB）仅由直接的太阳辐射（无温室）加热，两个消化池都以牛粪为原料。通过连续运行试验研究分析两个沼气池的加温效率以及对沼气产量的影响。结果表明，DA 和 DB 的平均沼液温度分别为 24.9°C 和 23. 45°C。此外，DA 和 DB 的沼气平均产率分别为 173 L/kg VS 和 155.3 L/kg VS，甲烷含量无明显变化（≈62.2%-62.76%）。研究表明，采用日光温室，可以提高软体沼气池的沼气产率。

2. 本研究旨在研究集成太阳能加热技术在低成本软体发酵池中提高沼液温度的潜力及其对沼气产量的影响。使用了两个类似的沼气池，第一个（D1）由带有太阳能热水系统和毛细管热交换器的日光温室加热，而第二个（D2）仅由日光温室加热，两个沼气池都在地面上并以牛粪为原料。结果表明， D1 和 D2 的平均沼液温度分别比平均环境温度高 9.5℃和 4.9℃。此外，D1 和 D2 的沼气平均产率分别为 247 L/kg VS 和 181 L/kg VS，甲烷含量无明显变化（≈62.7%）。研究表明，一年中的大部分时间，使用集成太阳能可以有效地为沼气生产过程提供最佳温度。

3. 农村地区每年产生大量农作物秸秆废弃物等木质纤维素，因此其厌氧发酵受到广泛关注。然而，这些生物质原料的厌氧消化通常需通过预处理来增强消化率。本研究

使用稀酸处理(浓度为 2%H2SO4 在 130℃下保持 20min)、稀酸与蒸汽爆破(SE)(160, 190 和 210℃下保持 3min)联合处理、蒸汽爆破(180℃下保持 5min)与超微粉碎(SFG)联合处理等三种预处理方法, 探讨了油菜秸秆通过厌氧消化实现增值以及提高生物甲烷产率的可能性;使用 SEM、FTIR、XRD 以及组分分析等方法来评估预处理方法的效果。结果表明, 联合预处理可效破坏木质纤维素的结构, 从而有效提升厌氧消化的甲烷产率。SE (180 ˚C 下保持 5 min)联合 SFG 处理以及 H2SO4 联合 SE (190 ˚C 下保持 3 min)处理可获得最高的甲烷产量, 其累计甲烷产量(CMY)分别为 305.7 mL/g VS 和 263.3 mL/g VS, 比对照分别提升 77.84% 和 53.17%。研究表明, 在最适酸浓度条件下, SEG180 和 DASE190 这两种预处理可显著提升油菜秸秆厌氧消化的 CMY。

4. 厌氧联合发酵由于可以显著平衡发酵底物养分、提高金属等微量元素的含量并增加其缓冲性能, 被认为是一种非常有效的发酵技术手段, 可以克服传统厌氧发酵技术产气量偏低的问题。本研究中, 为了提高气体产量, 以油菜秸秆为原料, 采用了蒸汽爆破的方式预处理后, 与牛粪以不同的混合比例配比(由秸秆:牛粪从 100:0 至 0:100)进行联合厌氧发酵。试验在相同控制条件下的密闭系统中进行, 研究分析了预处理对秸秆纤维结构及其联合厌氧发酵效果的影响。结果表明:预处理能够分解秸秆的纤维结构, 显著提高厌氧发酵的甲烷总量。经过联合厌氧发酵之后甲烷的产量相比对照组(纯牛粪为原料), 显著提高了 11.4%~59%。发酵产气量牛粪:油菜秸秆的最佳比例组为 60:40, 产气达 337.8 mL/g VS。相比对照发酵组, 最佳比例组比单独牛粪发酵产气量提高了 59%, 比单独秸秆发酵提高了 16.8%。本研究表明了最佳发酵参数条件下, 采用 180° C 蒸汽爆破能够显著提高牛粪和油菜秸秆联合厌氧发酵的产气量。

關鍵字:沼气生产;管式沼气池;太阳能采暖系统;毛细管换热器;农业废弃物;预处理技术;厌氧共消化

Abstract

With the rise in energy consumption and the production of wastes due to human activities, anaerobic digestion (AD), a technology that converts waste into bio-energy, is gaining growing attention worldwide. Small and medium-sized biogas projects in rural areas of China play a significant role to improve the rural production and living conditions, leading to energy conservation and reduction of emissions. On the other hand, China is one of the world's agricultural country, rich in biomass resources, such as crop straw and animal waste. If these wastes are not treated in time, they will cause many environmental problems, such as odor, soil and water pollution, air pollution, and so on. Therefore, the utilization of these wastes for renewable energy generation bring numerous economic, environmental and climate advantages. However, the low-temperature of digesters results in relatively low digestion efficiency and reduction of biogas output, so it is necessary to

adopt heating systems to improve the digestion process efficiency in cold areas. In addition, the major problem for the low exploitation effectiveness of agricultural crop waste (ACW) for AD is that cellulose (CEL), hemicellulose (HCEL), and indigestible lignin compounds integrate together strongly forming a complex structure. This structure of organic components results in chemical and physical inhibition against microbial action, thus inhibiting the hydrolysis of organic matters in AD. Besides, high organic load, low microbial diversity, low nitrogen content (high C/N) and composition of ACWs are not conducive to AD. Therefore, the main objectives of this study are as follows: 1) taking the soft biogas digester as the object, the facility form of using solar energy to increase fermentation temperature is studied on a small scale, so as to achieve the purpose of increasing biogas production in a cold climate; 2) using crop straw as raw material, the mechanism of pretreatment to decompose the complex crystal structure of lignocellulose and improve the biogas yield of AD was studied; 3) The effect of anaerobic co-digestion (ACoD) on biogas production from agricultural waste was studied in laboratory scale to solve the problem of low biogas generation from single material AD.

In order to achieve these goals, this study has carried out relevant experimental research on the scale of small-scale and laboratory tests, respectively, in order to improve the ability of agricultural waste products to produce biogas. The main experimental results are as follows:

1. The present study proposes a solar-greenhouse heating technique integrated with a north wall to heat a semi-buried low-cost soft tubular digester bag, as a solution. This experiment includes two similar semi-buried digesters, the first one (DA) was heated by the solar-greenhouse integrated with a north wall, while the second (DB) was heated by only direct solar radiation (without a greenhouse), which used as a control, and both digesters were fed with cattle manure. The heating efficiency of two biogas digesters and its effect on biogas production was studied by continuous operation tests. The results showed that the average slurry temperature was 24.9 ˚C and 23.45 ˚C for DA and DB, respectively. Furthermore, the mean specific biogas production of DA and DB were 173 and 155.3 L/kg VS, respectively, with no significant variations in the methane content (≈62.2- 62.76%). The results shown that the use of solar-greenhouse can improve the biogas output of soft biogas digester.

2. This study aimed to investigate the potential of integrated solar heating techniques to raise the slurry temperature within a low-cost soft tubular digester and its impact on the

biogas yield. Two similar digesters were used, the first one (D1) was heated by the solar greenhouse integrated with a solar water heating system and a capillary heat exchanger, while the second (D2) was heated by only solar greenhouse, and both digesters were above ground and were fed with cattle manure. The results showed average slurry temperature of 9.5 and 4.9 ˚C above the mean ambient temperature for D1 and D2, respectively. Furthermore, the mean specific biogas production of D1 and D2 were 247 and 181 L/kg VS, respectively, with no significant variations in the methane content (≈62.7%). The study indicated that using of integrated solar energy is efficient to achieve the optimum temperature for the process of biogas production roughly the most of the year.

3. Anaerobic digestion of lignocellulosic biomass like agricultural crop residues has gained attention due to their excess availability in rural areas. However, anaerobic digestion of such biomass feedstock requires a pretreatment to enhance their digestibility. The present study examined the possibility of valorizing rape straw through anaerobic digestion and the possibility of improving the biomethane yield by sole dilute acid (2% H_2SO_4 at 130 ˚C for 20 min), combined dilute acid with steam explosion (SE) (at 160, 190 and 210 ˚C for 3 min), and steam explosion (at 180 ˚C for 5 min) combined with superfine grinding (SFG) pretreatments. To evaluate the efficiency of the pretreatment method, several analytical methods such as SEM, FTIR, XRD and fiber composition were used. The results showed that combined pretreatment could dissolve the lignocellulosic structure, which positively stimulated anaerobic methane yield. The highest cumulative CH_4 yield (CMY) of 305.7 and 263.3 mL/g VS was achieved from SE at 180 ˚C for 5 min with SFG and H_2SO_4 with SE at 190 ˚C for 3 min, which were 77.84% and 53.17% more than untreated, respectively. This study revealed that, under optimal parameters of AD, pretreatment with SEG180 and DASE190 could significantly boost the CMY from anaerobic digestion of rape straw.

4. Anaerobic co-digestion is considered to be a very effective digestion technology because it can significantly balance the nutrient of the fermentation substrate, increase the content of trace elements such as metals and increase its buffering performance, and it can overcome the problem of low gas production of traditional anaerobic digestion technology. In this study, in order to improve the biogas output, rape straw was used as the raw material, and a steam explosion combined with superfine grinding was used to pre-treatment, then anaerobic co-digestion was carried out with cattle manure (CM) at

different mixture ratios (from straw: cattle 100:0 to 0:100). The experiment was carried out in a closed system under the same control conditions. The effects of combined pretreatment on the fiber structure of straw and the effect of combined anaerobic co-digestion were studied and analyzed. The results showed that combined pretreatment could dissolve the fiber structure of straw, which significantly increase the total amount of methane in anaerobic digestion. The cumulative CH_4 yield (CMY) for co-digestion was improved by 11.4-59% higher than the control (CM). The highest CMY of 337.8 mL/g VS was achieved from CM:PRS40 (CM:PRS, 60: 40), and this yield was 59% and 16.8% higher than the CM and pretreated rape straw (PRS) alone, respectively. This study revealed that, under optimal parameters of AD, pretreatment with SEG180 could significantly boost the CMY from co-digestion of cattle manure and rape straw.

Keywords: Biogas production; Tubular digesters; Solar heating system; Capillary heat exchanger; Agricultural wastes; Pretreatment technology; Anaerobic co-digestion