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Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes

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HIGHLIGHTS

- We simulate the coupling of pyrolysis and anaerobic digestion process.
- Pyrolysis anaerobic digestion process integration shows combined efficiency of 67%.
- The process integration produces 1.2-fold more biomethane than stand-alone process.
- The cost of producing biomethane from waste is less than heat and power production.

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ABSTRACT

The anaerobic digestion of source-separated organic waste is a mature and increasingly used process for biomethane production. However, the efficient use of different fractions of waste is a big concern in anaerobic digestion plants. This study proposes the use of a new process configuration that couples the anaerobic digestion of biodegradable waste with the pyrolysis of lignocellulosic or green waste. The biochar obtained from pyrolysis was added to a digester as an adsorbent to increase the biomethane content and to support the development of a stable microbial community. In addition, the bio-oil and syngas produced by the pyrolysis process were reformed into syngas and then converted to biomethane via methanation. Modelling and simulations were performed for the proposed novel process. The results showed an approximately 1.2-fold increase in the biomethane volume produced. An overall efficiency of 67% was achieved, whereas the stand-alone anaerobic digestion system had an efficiency of only 52%. The results also indicated a high annual revenue for the integrated process compared to that for an alternative treatment (incineration) of green waste.

1. Introduction

Biorefineries are gaining attention among researchers around the world owing to the possibility of simultaneously valorising diverse feedstocks and producing multiple products [1]. According to the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), it is estimated that the total share of biofuels in the transportation sector will increase to 10–20% by 2030 [2]. Furthermore, large amounts of municipal solid waste are still generated worldwide despite the concerns of many countries and efforts to limit the production of waste. In 2013, the global generation of municipal solid waste was estimated by the World Bank to be approximately 1.3 billion tonnes, and this is expected to increase to 2.2 billion tonnes per annum by 2025 [3]. Various technologies are under development – e.g., anaerobic digestion, gasification, combustion, pyrolysis, etc. – to enable the valorisation of the waste for useful and renewable products.

Anaerobic digestion is a technology that is widely used worldwide to produce biogas from the biodegradable municipal solid waste (MSW) collected primarily from households and municipal districts [4]. MSW is composed of 30–70% organic matter, consisting of food waste from kitchens, green waste from gardens and plants, etc. [5]. Kitchen or food waste is highly biodegradable and readily used as feedstock in anaerobic digestion plants. However, approximately 30% of MSW is lignocellulosic green waste, which is not suitable for the anaerobic digestion process [5]. Hence, MSW is source-separated into biodegradable and non-biodegradable fractions to utilise the biodegradable fraction via anaerobic digestion. The remaining green waste must be utilised via other processes, which include incineration for heat and power production, thermochemical conversion via gasification or

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Nomenclature

Abbreviations

AIC	annualised investment cost
CEPCI	chemical engineering plant cost index
CRF	capital recovery factor
FCI	fixed capital investment
LCOE	levelised cost of energy
LHV	low heating value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MSW	municipal solid waste
NAP	net annual profit
NPV	net present value
O&M	operating and maintenance cost
PSA	pressure swing absorption
PBP	payback period
ROR	rate of return
TCI	total capital investment
WCI	working capital investment

Symbols

m	mass flow rate (kg/s)
C	cost (Euro)
A	capacity (t/y)
n	scaling factor (–)
P	production (t/y)
I	consumption (t/y)
Δh	lower heating value (MJ/kg)
Q_R	heat required (MWh)
Q_G	heat generated (MWh)
E_R	power required (MWh)
t	tonne
y	year
i	interest rate (%)
N	project life (years)
k	kinetic parameter (1/s)
T	temperature (K)
E	activation energy (J/mol)
R	gas constant (J/mol/K)

Subscript

o	base scale
daf	dry ash-free

pyrolysis, or composting to reduce the amount of waste without further energetic utilisation.

Pyrolysis is an endothermic thermochemical process that converts organic material into useful energy products [6]. The pyrolysis of biomass generates three main products: bio-oil, biochar, and syngas. All the pyrolysis products are able to produce heat and power both individually and simultaneously [7]. The bio-oil produced from pyrolysis can be treated as crude oil and converted into liquid fuels as an alternative to fossil fuels [8]. Martin et al. [9] studied the possibility of converting bio-oil and syngas to biomethane and found that the process is technically more feasible than was the alternative of upgrading bio-oil to transport fuels and other processes such as gasification and combustion.

Furthermore, the biochar obtained from pyrolysis can be used in multiple ways, such as for carbon sequestration, as a soil conditioner and as an adsorbent precursor [10]. The addition of biochar to an anaerobic digester can increase the biomethane yield by 5–31%, as reported in various studies [11–15]. According to the reviewed literature, the addition of biochar shortens the lag phase, minimises ammonia-induced inhibition by acting as an adsorbent, and increases alkaline behaviour, and thus biochar can be used to increase the biomethane content in biogas by enabling the in situ upgrading of a biogas [16]. Tobias et al. [17] went a step further by putting the aqueous liquor obtained from digested pyrolysis back into an anaerobic digester, and found that the aqueous liquor obtained from pyrolysis is biodegradable and can be digested to produce biogas. This example of the versatile nature and use of pyrolysis products reveals a high potential for feasible and beneficial integration of pyrolysis with anaerobic digestion.

Some researchers have studied the integration of the pyrolysis and anaerobic digestion processes [17–19]. Most of them considered the digestate as the potential feedstock for the pyrolysis process and found the integration of the processes to be technically feasible [18–20]. Serena et al. [21] studied the life cycle assessment of the pyrolysis process coupled with anaerobic digestion and concluded that a significant reduction of greenhouse gasses could be achieved through process integration. In their review on linking pyrolysis with anaerobic digestion, Fabbri et al. [22] stated that the upgrading of pyrolysis products via anaerobic digestion could increase energy recovery. Furthermore, a non-biodegradable fraction of MSW can be used to increase the biomethane yield. However, it is noted that the previous publications mainly focused on experiment-based studies. Additionally, the biochar added to the digestion process was prepared via the pyrolysis of various feedstocks, such as fruit wood [12], paper sludge [14], and digestate [17–19]. Moreover, the utilisation pathway of other pyrolysis products, such as bio-oil and syngas, was not addressed thoroughly in the abovementioned studies, and little attention was given to the heat demand of the whole process of integrated pyrolysis and anaerobic digestion.

In our previous work [23], we performed modelling and simulation of an integrated anaerobic digestion and pyrolysis process and showed that the net positive energy balance and overall efficiency of the coupled process was larger than that of the stand-alone approach. We also found that there is a need to evaluate alternative options to utilise the pyrolysis products in a more efficient way. We selected the more conventional route to enhance biomethane production via catalytic methanation as a promising first step to valorise green waste biomass unsuitable for anaerobic digestion via pyrolysis since the infrastructure for the utilisation of the biomethane is available. In this study, a novel approach has been selected to increase the final amount of biomethane via the integration of these processes through process modelling and simulation. The bio-oil produced by the pyrolysis process can be converted into syngas via a steam cracking and reforming process [24]. The modelling and simulation study for the production of biomethane via pyrolysis has previously been studied only as a stand-alone process [9] and never as part of an integration with anaerobic digestion. To the best of the authors' knowledge, this is the first study to model the integration of pyrolysis and anaerobic digestion to estimate the possible amount of biomethane that can be achieved in the final mix.

2. Methods and modelling

The aim of this work is to present the overall system analysis of a biorefinery that forms biomethane as the main product via the