

# Synergy in Syngas Yield From Co-Pyrolysis of Cow and Chicken Manures

**Kiran Raj Goud Burra**<sup>1</sup>

Department of Mechanical Engineering,  
University of Maryland,  
College Park, MD 20742  
e-mail: kiranraj@umd.edu

**Osama M. Selim**

Department of Mechanical Engineering,  
University of Wisconsin-Milwaukee,  
115 East Reindl Way,  
Glendale, WI 53212  
e-mail: oelsayed@uwm.edu

**Ryoichi S. Amano**

Department of Mechanical Engineering,  
University of Wisconsin-Milwaukee,  
115 East Reindl Way,  
Glendale, WI 53212  
e-mail: amano@uwm.edu

**Ashwani K. Gupta**

Department of Mechanical Engineering,  
University of Maryland,  
College Park, MD 20742  
e-mail: ak Gupta@umd.edu

*Manure waste from dairy, livestock, and poultry industries can pose significant challenges in their disposal due to their odor, nitrogen, phosphorous, and heavy metals contents, and pathogens. Existing disposal techniques like anaerobic digestion, although can provide biogas with energy output, is a slow process with significant carbon loss to CO<sub>2</sub> and can also result in leaching. High-temperature pyrolysis can convert these wastes into syngas along with biochar which can be used for various applications. Thermochemical conversion needs to be feed-flexible, and operating it with manures from various animal sources such as poultry and dairy sectors can provide sustained operation, intensified process, and improved conversion throughput. So, we examined high-temperature co-pyrolysis of chicken and cow manures to understand the influence of their mixture fractions on the syngas components and char yield. Lab-scale semi-batch co-pyrolysis was carried out for cow and chicken manures at 900 °C with mixture fractions varying from 0 to 100%. Syngas analysis from these tests revealed the presence of synergistic enhancement of its components and in terms of syngas energy yield and carbon conversion, a 2:3 ratio of cow to chicken manure resulted in the most enhancement compared to the expected aggregate of pyrolyzing cow and chicken manures separately. This paper provides a detailed analysis of these syngas components from co-pyrolysis in comparison with separate pyrolysis to explore the advantages of blended feedstock toward an efficient, clean, and feed-flexible pathway for manure waste disposal and utilization. [DOI: 10.1115/1.4056563]*

*Keywords: chicken manure, cow manure, co-pyrolysis, syngas, synergy, feed-flexible, alternative energy sources, energy from biomass, hydrogen energy, renewable energy*

## Introduction

With rising population and food demands, significant manure wastes are produced from livestock, dairy, and poultry industries every year. These wastes contain significantly excessive amounts of nitrogen (N), phosphorous (P), and potassium (K)—key fertilizer ingredients, along with lignocellulosic and lipid content. According to the US Agriculture Census of 2007, per sq. km of US farmland, up to 1.6 tons of N and 0.5 tons of P were produced in the form of manure on an average [1–3]. This nutrient production in the form of manure was even higher in some states that increased to 4.4–9.7 tons of N and 1.2–2.8 tons of P, such as in Maryland, North Carolina, and Delaware regions. Due to their nutrient content, a sizable portion (up to 83%) of this manure is utilized via land application as a fertilizer [4]. But this application is a cause of significant air and water pollution, especially around these geographical areas. Currently, manure management is the source of approximately 12% of total greenhouse gas (GHG) emissions from agricultural sector, and 9% of the total US methane emissions in 2020 [5]. As a part of air pollution and GHG emissions, in addition to the CH<sub>4</sub> produced from these wastes, NO<sub>x</sub> (N<sub>2</sub>O) from manure management is around 5% of the total US NO<sub>x</sub> emissions and overutilization of farmland with manure leads to increased availability of N in the soil causing NO<sub>x</sub> emissions, which indirectly accounts for the rest of significantly higher portions of NO<sub>x</sub> emissions as a part of agricultural soil management [5]. In addition to these high GHG

emissions, excessive utilization of manure as fertilizer led to significant contamination of surface and groundwater with the nutrients from the water runoffs from these farms. The manure management at concentrated animal feeding operations (CAFO) also leads to these runoffs. This leads to eutrophication, where the high nutrient content in this water leads to excessive algal growth, called algal bloom which produces cyanotoxins in the water that is harmful to the fish, mammals, and birds. These toxins pose health hazards to humans as they enter drinking and recreational water resources. In addition, these blooms also lead to hypoxia in the affected water which kills the fish and other species surviving over them, thus leading to significant ecological disruption [6]. Along with the water contamination by nutrients from the manure, pathogen transfer, and heavy-metal contamination are also impacted by such manure application [7]. Thus, the development of a significantly better manure management and disposal route is imminently needed. While anaerobic digestion has been proposed and utilized as a pathway for manure disposal to produce biogas and organic fertilizer, this process is slow and carbon inefficient. A significant portion of carbon is lost in the form of CO<sub>2</sub>, and the biogas obtained contains NH<sub>3</sub> and H<sub>2</sub>S [8]. Thus, thermochemical routes for manure disposal are of significant interest as they can provide the benefits of fast and high throughput conversion of manure, avoiding pathogens, and stabilizing the heavy metals such that the products can be utilized downstream [9].

Thermochemical routes for waste management include processes such as combustion/incineration, pyrolysis, and gasification. High moisture and ash content in manure wastes and thus low calorific value makes combustion an inefficient route for their disposal. Due to high N and P and heavy-metal content in manure wastes, direct combustion of these wastes also leads to significant pollutant emissions, which makes it unfeasible [10]. Pyrolysis involves

<sup>1</sup>Corresponding author.

Contributed by the Advanced Energy Systems Division of ASME for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received November 17, 2022; final manuscript received December 13, 2022; published online January 24, 2023. Assoc. Editor: Hameed Metghalchi.

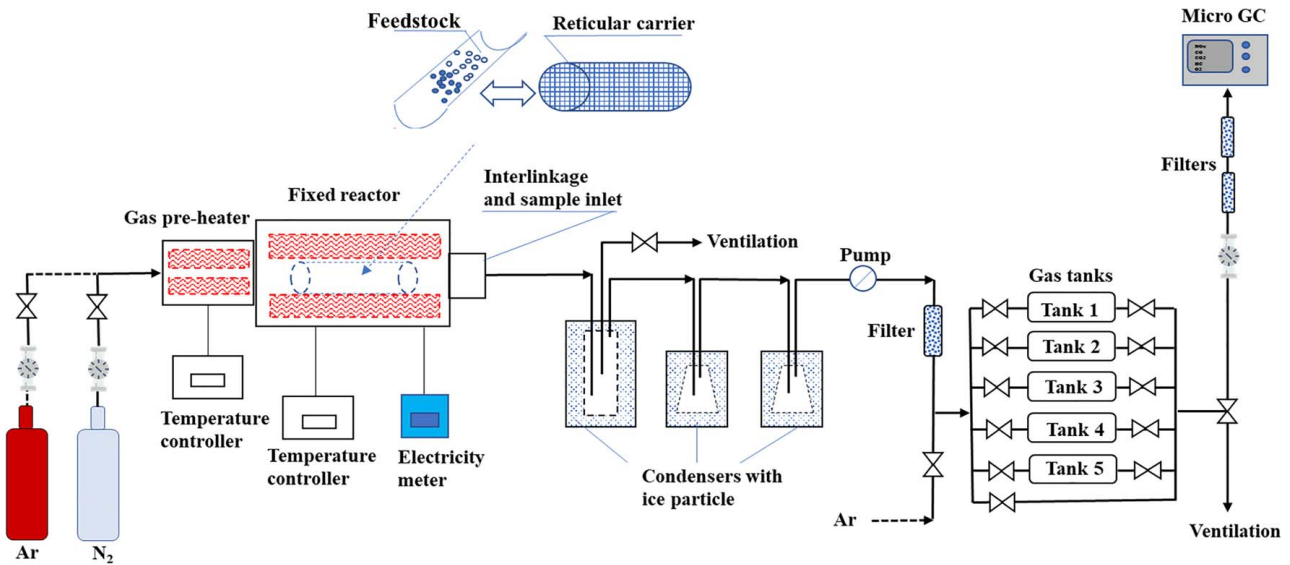


Fig. 1 A schematic of the lab-scale reactor used for co-pyrolysis

moderate- to high-temperature decomposition of manure wastes in the absence of air and in the presence of gasifying agents (such as  $H_2O$ ,  $CO_2$ , and air) in the case of gasification to convert into syngas, bio-oil, and biochar products. The relative yields of these products are dependent upon the operating conditions such as temperature, residence times, feedstock composition, and gasifying agent. From these processes, syngas produced (containing  $H_2$ ,  $CO$ ,  $CO_2$ , and hydrocarbons) can be used for energy and chemicals while bio-oil can be converted into liquid fuels. More importantly, the biochar obtained contains stabilized heavy metals, with nutrients and free of pathogens and thus can be utilized as a soil amendment or converted into other valuable carbon materials such as catalyst, adsorbent, and electrode for energy storage applications [7,11].

Among these products, bio-oil production from manure is difficult to process for fuel needs due to its stability and viscosity issues from high O content along with the low heating value. Instead, bio-oil from manure was found to be a valuable alternative to petroleum asphalt and thus not only provides value and sustainable manure management but also lowers the need for petroleum asphalt [12]. In the case of biochar produced via thermochemical routes, slow pyrolysis and hydrothermal carbonization are the preferred routes to maximize its yield. Biochar produced from manure and other biowastes is enhanced in carbon content, calorific value, and porosity compared to the precursor [11,13,14]. In addition, literature on biochar reveals that the heavy-metal content in feedstocks is stabilized in the biochar which prevents leaching and renders it safe to use [7,9,10]. In addition, biochar from slow pyrolysis was also found to improve nitrogen retention and carbon sequestration and avoid  $NO_x$  emissions and nitrate leaching when used for soil amendment [15]. Due to high surface area and presence of alkali metals, manure biochar was also investigated for catalytic applications in various processes including transesterification of waste cooking oils into biodiesel, gasification, and adsorption applications in wastewater cleaning [7,11,14,16–20]. Syngas is produced from all the thermochemical routes, albeit varying in composition and yield. Typical components of interest in syngas produced from biomass and manure are  $H_2$ ,  $CO$ ,  $CO_2$ ,  $CH_4$ ,  $C_2$ , and  $C_3$  gases while the total gas yield increases with an increase in temperature and residence time. Syngas produced from coal and biomass gasification was demonstrated to be utilized for various applications including combustion for power, Fisher-Tropsch for liquid fuels, and syngas fermentation for alcohol production [21].

With these diverse valuable products of interest, thermochemical routes, pyrolysis especially, seem the more viable choice for manure disposal. Moreover, due to the uniformity and ease of use, focusing

on maximizing syngas via pyrolysis can help in obtaining clean and usable syngas as fuel along with stable and sustainable biochar. So, investigations into improving syngas yield and quality from pyrolysis of manure waste are of critical need. Significant literature exists on the pyrolysis and gasification of different types of manure wastes from livestock (pig, sheep, and cow), dairy, and chicken with the goal of improving the viability [7,13,22–29]. Various in situ catalysts such as  $CaO$ ,  $CaCO_3$ , activated carbon, and char were examined as catalysts, and they were found to improve bio-oil or syngas yield depending on the operating conditions, especially volatiles' residence times, as longer times lead to better catalytic cracking and thus improved syngas yield [7,11,30].

In addition to catalytic pyrolysis, co-pyrolysis was also proposed and explored as a possible route to improve the viability and sustainable operation of manure pyrolysis. Various co-feeds such as cellulose, plastics, wood shavings, agricultural wastes (rice husk, straw, and hay) were investigated with cow manure, chicken manure, and swine manure with multiple goals such as improving the overall feedstock volatile content, lower ash content, H/C, and sustained feedstock availability [13,31–33]. With the addition of these co-feeds, the quality of the bio-oil and syngas products improved along with their yield and heating value, especially when used with higher value feedstocks, such as plastics and wood [7,13,32,34]. While these studies did not reveal or focus on the synergistic enhancement of products beyond the weighted aggregates, similar co-pyrolysis and co-gasification studies of various kinds of biomass and plastics revealed that in a significant number of cases, synergistic interaction between the feeds lead to improved syngas yield and quality [34,35]. Our investigations on co-pyrolysis and co-gasification of lignocellulosic biomass/biowastes such as pinewood and paper wastes, with plastic wastes such as polypropylene, polycarbonate, polyethylene, and PET revealed improved  $H_2$  yield, and carbon conversion compared to weighted sum of separate conversion of the respective feedstocks [35,36]. Further investigations into the sources of these synergies revealed that catalytic cracking effects of the char, and H and O transfer between the feedstock were some of the main reasons for such interaction [37–39].

The previous studies lack co-pyrolysis investigations of different manure wastes. Additionally, the development of a feed-flexible pyrolyzer optimized for manure wastes from various animal agricultural sources is desirable as such a reactor can be designed to focus on the commonalities among these manure wastes such as ash, moisture, and energy content. In such a reactor, feed-flexibility among these different manures can help to maintain a sustained product stream from the varying availabilities of manure wastes

**Table 1 Proximate and ultimate analysis of chicken manure and cow manure [41]**

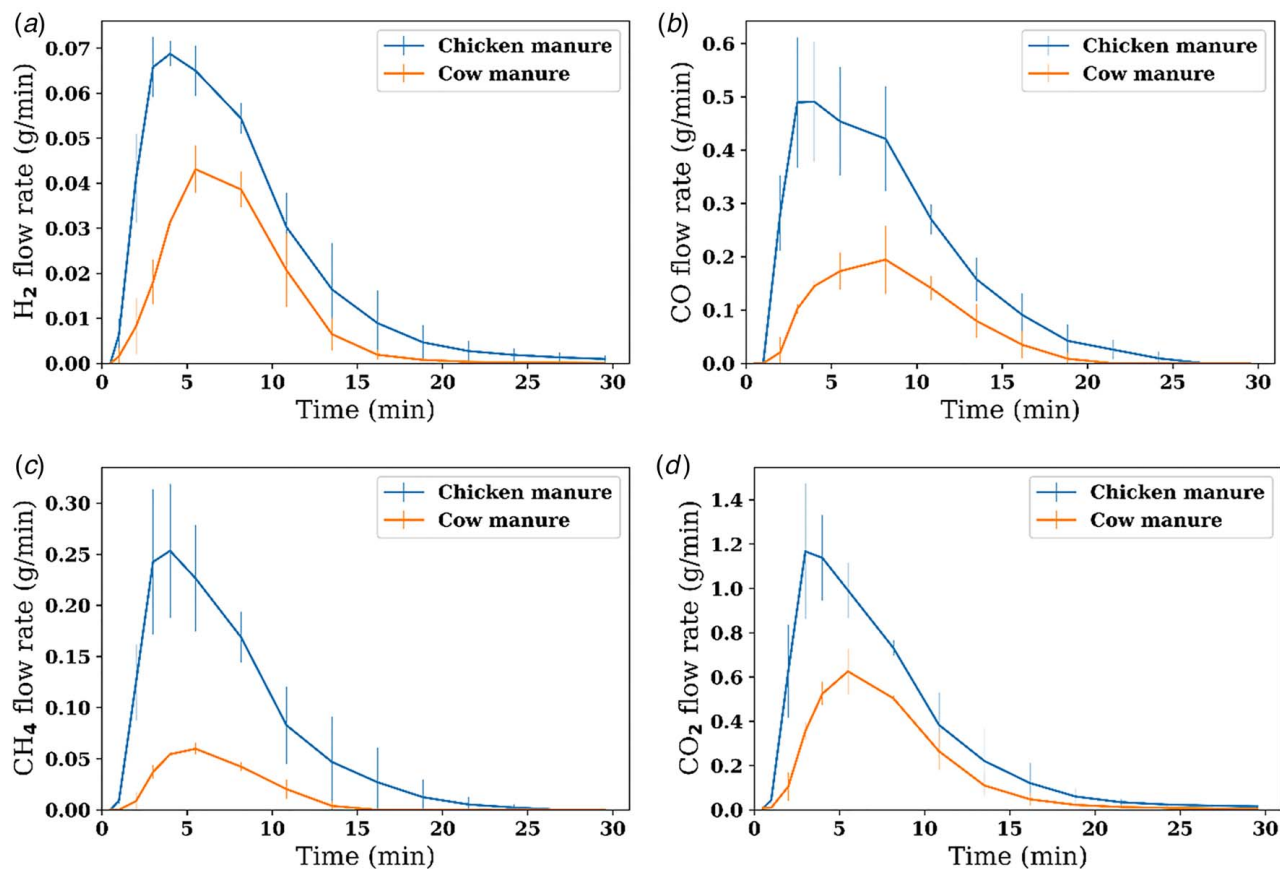
	Chicken manure	Cow manure
Proximate analysis (dry wt%)		
Volatile content	65.56	62.00
Ash content at 550 °C	21.65	23.00
Fixed carbon	12.80	15.00
Ultimate analysis (dry wt%)		
Carbon	35.59	35.20
Hydrogen	4.57	3.10
Nitrogen	4.98	2.20
Sulfur	1.45	0.70
Oxygen	35.52	33.30
HHV (in MJ/kg)	13.15	16.00

and their composition with the robust design of operating conditions. But for the development of feed-flexible manure pyrolyzer, investigation into co-pyrolysis of manures from different animal and application sources is necessary as they can significantly vary in composition and form. With that focus, in this paper, we investigated the co-pyrolysis of mixtures of cow manure and chicken manure with different mixture fractions and compared the results from the separate pyrolysis of these manures from the perspective of syngas components and their evolution. We conducted these tests to examine the potential for synergistic interaction between these feedstocks and enhancement of syngas yield. These results are not only important to understand the feedstock interactions from various sources, but also demonstrate the viability and feed-flexibility of pyrolysis to handle manures from various streams.

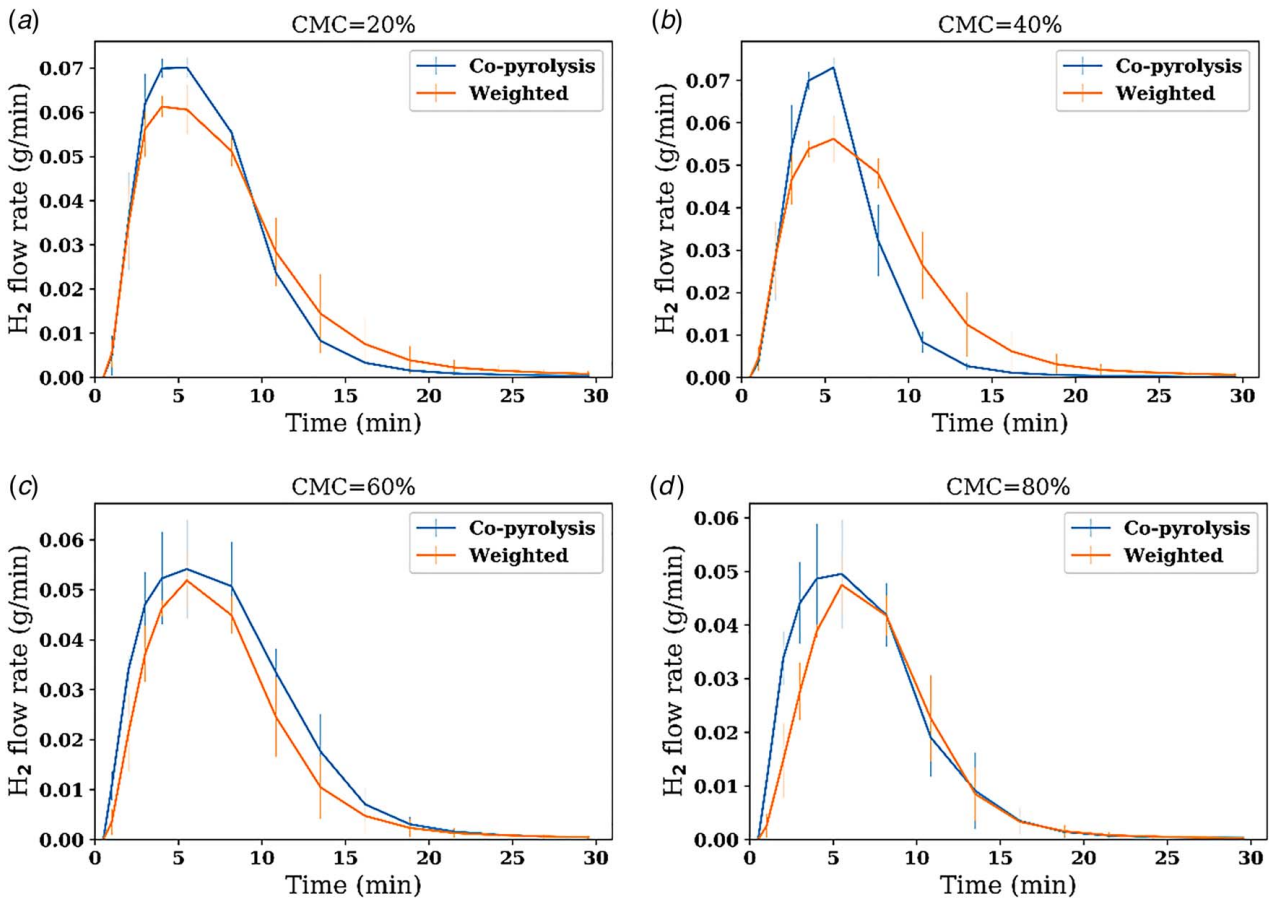
## Experimental

Lab-scale semi-batch reactor facility was utilized to conduct the investigations into co-pyrolysis of different mixtures fractions of cow manure and chicken manure (Fig. 1). The reactor facility was equipped with online syngas analysis via micro-GC (gas chromatography) calibrated to analyze  $H_2$ , CO,  $CO_2$ ,  $CH_4$ ,  $C_2H_6$ ,  $C_2H_4$ ,  $C_2H_2$ ,  $C_3H_8$ ,  $O_2$ , and  $N_2$ . Co-pyrolysis was performed at 900 °C for better cracking of volatiles into syngas and to obtain the most stable biochar while keeping the temperature low enough to avoid significant losses. For each pyrolysis test, the reactor system was initially heated to 900 °C. Once it reached the set temperature, the sample mixture (loaded in a sample holder) was loaded into the reactor via quick disconnect coupling followed by drying and filtering the evolved gases and analyzing them using sampling bottles and online GC analysis to obtain the evolutionary behavior of syngas components with time. For each test, 2.1 scfm of  $N_2$  was flown through the reactor to function as a carrier gas. This  $N_2$  flow also acted as a tracer gas to provide the changing flowrates of syngas components with time which was integrated over time to obtain their respective yields. Further details about the reactor facility and the syngas analysis can be found in our previous articles [36,40]. Different mixture fractions of cow manure and chicken manure were prepared for co-pyrolysis while for each test, the total mass of mixture utilized was 35 g.

Cow manure and chicken manure feedstocks utilized in the work were obtained from a farm in Wisconsin and their typical composition in terms of proximate and ultimate analysis along with high heating value (HHV) are given in Table 1. For co-pyrolysis tests, different mixtures of these manures were prepared with cow manure content (CMC) of 0, 20, 40, 60, 80, and 100 wt% in the mixture while keeping the overall test mass of 35 g for each case. Each pyrolysis and co-pyrolysis case was evaluated three times,



**Fig. 2 Comparing temporal evolution of (a)  $H_2$ , (b) CO, (c)  $CH_4$ , and (d)  $CO_2$  flowrates from individual pyrolysis of chicken manure and cow manure**



**Fig. 3 Evolution of H<sub>2</sub> flowrate with time from co-pyrolysis of chicken manure and cow manure with cow manure content (CMC) of (a) 20%, (b) 40%, (c) 60% and (d) 80% compared to weighted sum of separate pyrolysis**

and the average and standard deviations of the results are reported in this paper.

## Results and Discussion

### (a) Separate pyrolysis of chicken manure and cow manure

To understand the syngas behavior from co-pyrolysis of chicken and cow manures, we first start by comparing the evolution of syngas components from separately pyrolyzing these feedstocks to reveal their individual syngas production capabilities. Figure 2 shows the comparison of the evolution of major syngas components from chicken manure and cow manure in terms of the varying flowrates with the reaction time. The most apparent feature from the figure is the significantly low yields of syngas components from cow manure compared to chicken manure. These stable components of syngas form from the breakdown of the volatiles via cracking and reforming reactions in addition to the decarboxylation reaction for CO<sub>2</sub>. With similar extents of volatiles evolution from these manures, this low syngas evolution from cow manure suggests that the volatiles from cow manure are significantly more thermally stable compared to chicken manure. Typical high-temperature stability among volatiles suggests that this could be from higher aromaticity in cow manure volatiles. Thermogravimetric analysis (TGA) of this cow manure revealed multiple peaks of extractives and proteins which could result in increased rearrangement reactions that increase aromaticity and stability during pyrolysis. However, mass loss from chicken manure pyrolysis showed one major low-temperature peak associated with

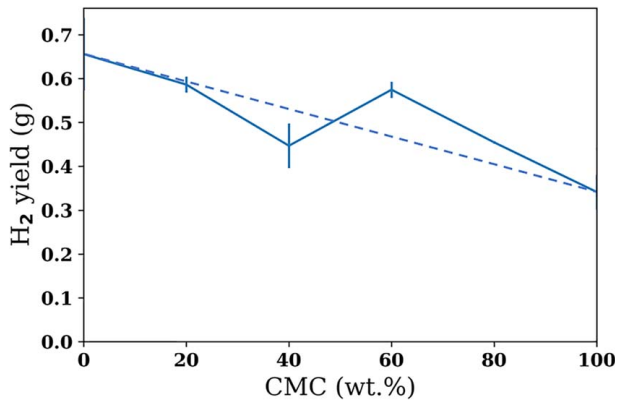
lignocellulosic content followed by lower content of high-temperature peaks [33].

Figure 2 also reveals the time taken for the complete pyrolysis of these manures. While syngas components from chicken manure notably evolved until 25 min, their evolution vanished in 20 min from cow manure, especially CH<sub>4</sub> which finished evolving in 15 min. This was also similar to the TGA data which revealed fast low-temperature decomposition of chicken manure followed by slow reactions while cow manure yielded several sharp peaks, including some significant high-temperature peaks. These results conclude that, in the perspective of syngas formation, chicken manure is faster and more favorable compared to cow manure. Now that we have established the differences between syngas behavior from these feedstocks, we can investigate the impact of co-pyrolyzing their mixtures on the syngas evolution.

### (b) Co-pyrolysis of chicken manure (CHM) and cow manure (CM)

$$Y_{weighted} = CMC \times Y_{CM \text{ pyrolysis}} + (1 - CMC) \times Y_{CHM \text{ pyrolysis}} \quad (1)$$

To effectively compare the syngas evolution from co-pyrolysis to the individual pyrolysis of chicken and cow manures, we utilized the weighted aggregate of the respective data from separate pyrolysis as the baseline, referred to as "Weighted." This can be explained in Eq. (1) where  $Y_{weighted}$  refers to the weighted result of interest,  $Y_{CM \text{ pyrolysis}}$  refers to the results from cow manure pyrolysis and  $Y_{CHM \text{ pyrolysis}}$  refers to the results from chicken manure pyrolysis



**Fig. 4** Variation of cumulative H<sub>2</sub> yield from co-pyrolysis of chicken manure in various fractions of CMC

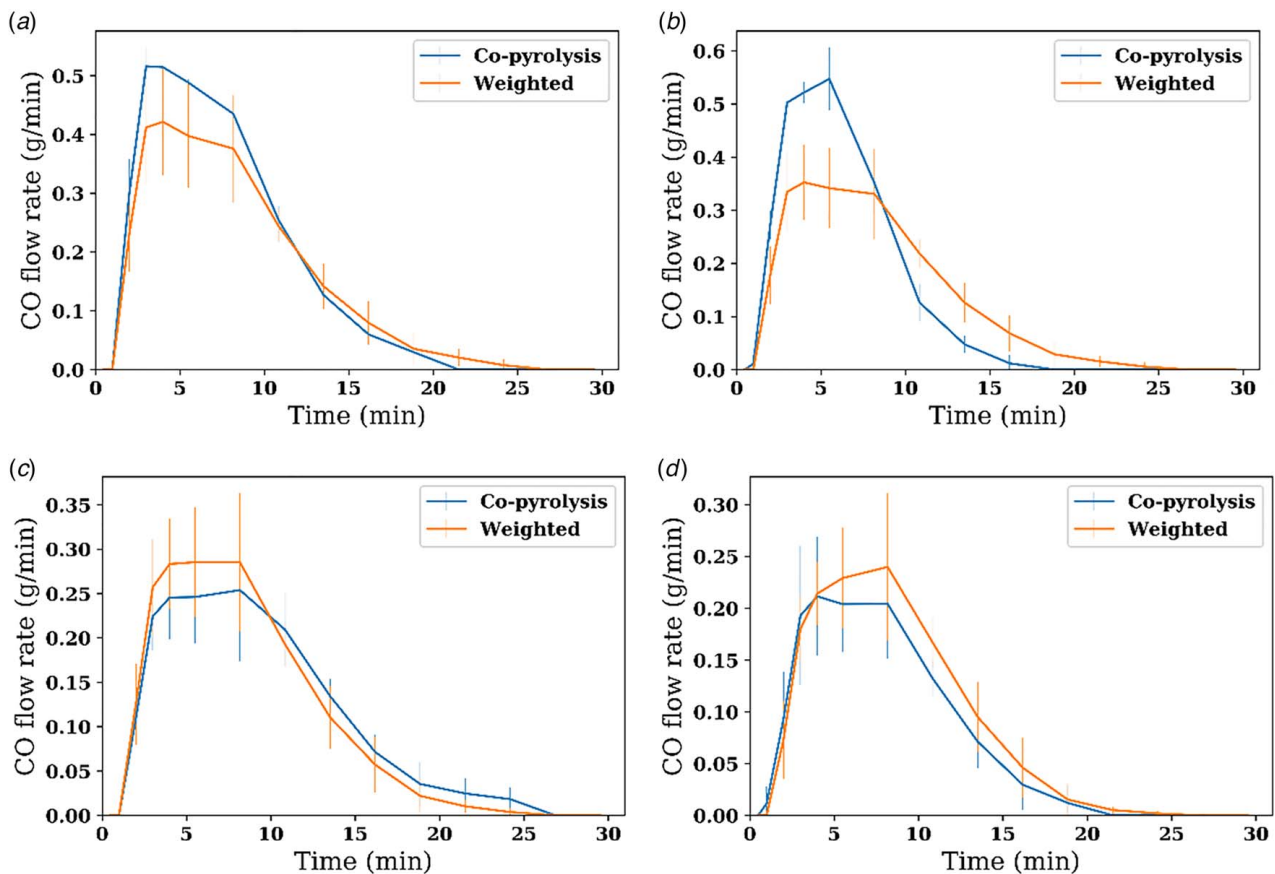
and CMC refers to the cow manure content in the co-pyrolysis mixture to which it is compared.

Based on such a calculated baseline, we can effectively observe the synergistic influence of co-pyrolysis which would be absent in the separate pyrolysis. Figure 3 reveals the synergistic influence of co-pyrolysis on H<sub>2</sub> evolution from different mass fractions of the feedstocks. It reveals that at lower CMC values, co-pyrolysis resulted in faster evolution of H<sub>2</sub>, especially at CMC = 40%. But for higher CMC, the H<sub>2</sub> evolution rates were similar to the weighted case. Faster reaction rates were characteristics of chicken manure, and manure mixtures with higher amounts of chicken manure tended to synergistically enhance the rate of cow manure pyrolysis too when co-pyrolyzed. According to our

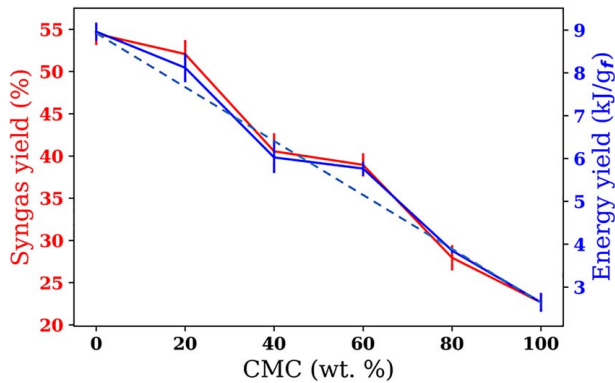
deconvolution studies on co-pyrolysis, while multiple pathways are feasible for synergistic interaction, improved rate can be associated with catalytic influence. The ash content from both these feedstocks is reported to be catalytic to pyrolysis reactions, especially volatile cracking reactions. But at high chicken manure fractions, the faster decomposition and its char formation can lead to improved breakdown of cow manure at an earlier stage.

The H<sub>2</sub> evolution results in juxtaposition with the variation of cumulative H<sub>2</sub> yield with mixture fraction reveals that while co-pyrolysis led to earlier evolution, no significant synergy was observed in the total yield (lack of diversion from the dashed line in Fig. 4), confirming the improved kinetics. The total H<sub>2</sub> yield was slightly reduced at 40% CMC and slightly increased at 60% and 80% CMC. Additionally, while increasing cow manure fractions is expected to lower the H<sub>2</sub> yield, at high CMC, the yields were still relatively closer to chicken manure cases, suggesting the definite presence of synergy. This non-linear synergy behavior could also arise from the variable composition of these feedstocks. Further deconvoluted studies are needed to further understand the potential interaction pathways among different manures.

Figure 5 reveals similar comparisons of CO evolution from co-pyrolysis with the weighted aggregates of separate pyrolysis. Similar to H<sub>2</sub> evolution, improved kinetics of CO formation were observed for CMC of 20 and 40% while higher CMC revealed a very slight decrease in CO, but still within the uncertainty limits. These results also confirm the synergistic kinetics in co-pyrolysis and variation in the overall yield of H<sub>2</sub> and CO could also arise from the uncertainty in the overall moisture content of the feedstocks, which could lead to different extents of secondary reforming. The evolution and yields of other components such as CO<sub>2</sub> and CH<sub>4</sub> were qualitatively similar to those of H<sub>2</sub> and CO in that



**Fig. 5** Evolution of CO flowrate with time from co-pyrolysis of chicken manure and cow manure with CMC of (a) 20%, (b) 40%, (c) 60%, and (d) 80% compared to weighted sum of separate pyrolysis



**Fig. 6 Syngas and energy yield from co-pyrolysis of chicken manure in different mass fractions of CMC**

the lower CMC yielded kinetic improvements and higher CMC showed no significant synergy (not shown here)

$$\text{Energy yield} = \frac{\sum_{\text{syngas species}} m_i \times \text{LHV}_i}{m_{\text{feedstock}}} \quad (2)$$

We also report on the synergy in the overall product yields from co-pyrolysis of chicken and cow manures. Energy yield was calculated using Eq. (2) where  $m_i$  refers to cumulative mass yields of syngas species,  $\text{LHV}_i$  to their respective lower heating value, and  $m_{\text{feedstock}}$  to the initial feedstock mass. Figure 6 shows the syngas yield (wt% of the initial feedstock mass) and energy (kJ per gram of feedstock) yielded in the form of syngas via co-pyrolysis for different cow manure content (CMC) in the sample examined. Due to the lower tendency of syngas formation from cow manure, this figure reveals the decrease in syngas yield and its associated calorific output. In the case of cow manure, only 25% feedstock mass was converted into syngas. The energy output from cow manure was almost three times lower than chicken manure (Fig. 6). While separate pyrolysis of cow manure led to conversion values in the range of 25%, co-pyrolysis results reveal the feasibility of manure conversion as CMC of 40 and 60% revealed the syngas yield around a healthy 40% and energy yield of 6 kJ/g of feedstock which can effectively improve the viability of these low tendency feedstocks for pyrolysis processes. In addition, the char yield measured from all these cases was similar at 25–28% of the initial feedstock mass. These yield results reveal the viability of co-pyrolysis as it provides a valuable energy output, especially from feedstocks with low syngas evolution tendency, and provides a uniform biochar by-product with carbon, nitrogen, and ash sequestration for usage beyond the conventionally direct application of organic fertilizer into potentially wide applications in catalysis, adsorption, and energy storage with improved process value. Since our focus here is on a consolidated process that can manage several types of manures varying in their source and composition, these co-pyrolysis results show that average mixtures of chicken and cow manure provided not only synergistically improved kinetics in syngas evolution but also a feasible level of syngas conversion which can improve the manure pyrolysis reactor throughout.

## Conclusions

With the growing concerns of GHG emissions and rising nutrient levels in water bodies (leading to ecological damage and health concerns) from the lack of efficient and viable pathway for manure management and disposal in different sectors of animal wastes, we investigated the potential for co-pyrolysis of chicken manure and cow manure as a route toward developing consolidated manure pyrolyzer designed specifically for manure management

needs. Lab-scale semi-batch reactor was utilized to conduct co-pyrolysis of chicken manure in different mass fractions of cow manure at 900 °C followed by the evolved syngas analysis. These results revealed that relative to chicken manure, cow manure has a lower tendency for syngas formation, and thus, the development of pyrolysis for itself could pose severe viability issues. But co-pyrolyzing cow manure with chicken manure revealed a viable 40% syngas formation with char yield of around 25–28% of the initial feedstock mass, for CMC of 40–60%. Moreover, comparing the co-pyrolysis of these manures with results from their separate pyrolysis also revealed synergistic enhancement in the kinetics of  $\text{H}_2$ , CO, and other syngas components' evolution, possibly from the catalytic influence of char from the early decomposition of chicken manure. While the synergistic impact on the total cumulative yields was minimal, the improvement in kinetics, the lack of inhibitive behavior, and viable syngas and char product yields from co-pyrolysis of chicken manure and cow manure were obtained to demonstrate the viability of developing dedicated manure pyrolysis reactor with feed-flexibility for manure from diverse sources and applications in animal husbandry.

## Acknowledgment

This research was supported by the Office of Naval Research (ONR), and their support is gratefully acknowledged. The authors also acknowledge Emily Wise at UMD for her help in experiments.

## Conflict of Interest

There are no conflicts of interest.

## Data Availability Statement

The data sets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

## References

- [1] Environmental Protection Agency, USA, 2007, <https://www.epa.gov/nutrient-policy-data/estimated-animal-agriculture-nitrogen-and-phosphorus-manure>
- [2] U.S. Department of Agriculture, 2007, [https://agcensus.library.cornell.edu/wp-content/uploads/2007-United\\_States-State-usv1.pdf](https://agcensus.library.cornell.edu/wp-content/uploads/2007-United_States-State-usv1.pdf).
- [3] Ruddy, B. C., Lorenz, D. L., and Mueller, D. K., 2006, "County-Level Estimates of Nutrient Inputs to the Land Surface of the Conterminous United States, 1982–2001: U.S. Geological Survey Scientific Investigations Report 2006-5012," *Scientific Investigations Report 2006-5012*, USGS, USA.
- [4] Wu, H., Hanna, M. A., and Jones, D. D., 2013, "Life Cycle Assessment of Greenhouse Gas Emissions of Feedlot Manure Management Practices: Land Application Versus Gasification," *Biomass Bioenergy*, **54**, pp. 260–266.
- [5] EPA, 2022, "Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990 to 2020. U.S. Environmental Protection Agency, EPA 430-R-22-003," <https://www.epa.gov/ghgemissions/draft-inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020>.
- [6] Committee on Environment and Natural Resources, 2010, *Scientific Assessment of Hypoxia in U.S. Coastal Waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology*, Washington, DC.
- [7] Su, G., Ong, H. C., Mohd Zulkifli, N. W., Ibrahim, S., Chen, W. H., Chong, C. T., and Ok, Y. S., 2022, "Valorization of Animal Manure via Pyrolysis for Bioenergy: A Review," *J. Clean. Prod.*, **343**, p. 130965.
- [8] Wijesinghe, D. T. N., Suter, H. C., Scales, P. J., and Chen, D., 2021, "Lignite Addition During Anaerobic Digestion of Ammonium Rich Swine Manure Enhances Biogas Production," *J. Environ. Chem. Eng.*, **9**(1), p. 104669.
- [9] Li, S., Zou, D., Li, L., Wu, L., Liu, F., Zeng, X., Wang, H., Zhu, Y., and Xiao, Z., 2020, "Evolution of Heavy Metals During Thermal Treatment of Manure: A Critical Review and Outlooks," *Chemosphere*, **247**, p. 125962.
- [10] Nzihou, A., and Stanmore, B., 2013, "The Fate of Heavy Metals During Combustion and Gasification of Contaminated Biomass-A Brief Review," *J. Hazard. Mater.*, **256–257**, pp. 56–66.
- [11] Lee, D. J., Jung, S., Jang, Y. N., Jo, G., Park, S. H., Jeon, Y. J., Park, Y. K., and Kwon, E. E., 2020, "Offering a New Option to Valorize Hen Manure by CO<sub>2</sub>-Assisted Catalytic Pyrolysis Over Biochar and Metal Catalysts," *J. CO<sub>2</sub> Util.*, **42**, p. 101344.

- [12] Wang, H., Jing, Y., Zhang, J., Cao, Y., and Lyu, L., 2021, "Preparation and Performance Evaluation of Swine Manure Bio-Oil Modified Rubber Asphalt Binder," *Constr. Build. Mater.*, **294**, p. 123584.
- [13] Ro, K. S., Cantrell, K. B., and Hunt, P. G., 2010, "High-Temperature Pyrolysis of Blended Animal Manures for Producing Renewable Energy and Value-Added Biochar," *Ind. Eng. Chem. Res.*, **49**(20), pp. 10125–10131.
- [14] Sharma, R., Jasrotia, K., Singh, N., Ghosh, P., Srivastava, S., Sharma, N. R., Singh, J., Kanwar, R., and Kumar, A., 2020, "A Comprehensive Review on Hydrothermal Carbonization of Biomass and Its Applications," *Chem., Africa*, **3**(1), pp. 1–19.
- [15] Sanford, J., Aguirre-Villegas, H., Larson, R. A., Sharara, M., Liu, Z., and Schott, L., 2022, "Biochar Production Through Slow Pyrolysis of Animal Manure," *Manure Processing for Farm Sustainability*. University of Wisconsin–Madison Division of Extension.
- [16] Yao, D., Hu, Q., Wang, D., Yang, H., Wu, C., Wang, X., and Chen, H., 2016, "Hydrogen Production From Biomass Gasification Using Biochar as a Catalyst/Support," *Bioresour. Technol.*, **216**, pp. 159–164.
- [17] Kambo, H. S., and Dutta, A., 2015, "A Comparative Review of Biochar and Hydrochar in Terms of Production, Physico-Chemical Properties and Applications," *Renew. Sustain. Energy Rev.*, **45**, pp. 359–378.
- [18] Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Wade, P., and Bolan, N., 2021, "Assessment of the Fertilizer Potential of Biochars Produced From Slow Pyrolysis of Biosolid and Animal Manures," *J. Anal. Appl. Pyrolysis*, **155**, p. 105043.
- [19] Li, Z., Deng, H., Yang, L., Zhang, G., Li, Y., and Ren, Y., 2018, "Influence of Potassium Hydroxide Activation on Characteristics and Environmental Risk of Heavy Metals in Chars Derived From Municipal Sewage Sludge," *Bioresour. Technol.*, **256**, pp. 216–223.
- [20] Zhang, H., Zhang, F., and Huang, Q., 2017, "Highly Effective Removal of Malachite Green From Aqueous Solution by Hydrochar Derived From Phycocyanin-Extracted Algal Bloom Residues Through Hydrothermal Carbonization," *RSC Adv.*, **7**(10), pp. 5790–5799.
- [21] Burra, K. G., and Gupta, A. K., 2018, "Thermochemical Reforming of Wastes to Renewable Fuels," *Energy for Propulsion: A Sustainable Technologies Approach*, A. K. Runchal, A. K. Gupta, A. Kushari, A. De, and S. K. Aggarwal, eds., Springer Singapore, Singapore, pp. 395–428.
- [22] Font-Palma, C., 2012, "Characterisation, Kinetics and Modelling of Gasification of Poultry Manure and Litter: An Overview," *Energy Convers. Manag.*, **53**(1), pp. 92–98.
- [23] Cantrell, K. B., Hunt, P. G., Uchimiya, M., Novak, J. M., and Ro, K. S., 2012, "Impact of Pyrolysis Temperature and Manure Source on Physicochemical Characteristics of Biochar," *Bioresour. Technol.*, **107**, pp. 419–428.
- [24] Mante, O. D., and Agblevor, F. A., 2010, "Influence of Pine Wood Shavings on the Pyrolysis of Poultry Litter," *Waste Manag.*, **30**(12), pp. 2537–2547.
- [25] Kim, S.-S., and Agblevor, F. A., 2007, "Pyrolysis Characteristics and Kinetics of Chicken Litter," *Waste Manag.*, **27**(1), pp. 135–140.
- [26] Burra, K. G., Hussein, M. S., Amano, R. S., and Gupta, A. K., 2016, "Syngas Evolutionary Behavior During Chicken Manure Pyrolysis and Air Gasification," *Appl. Energy*, **181**, pp. 408–415.
- [27] Burra, K. R. G., and Gupta, A. K., 2019, "Modeling of Biomass Pyrolysis Kinetics Using Sequential Multi-step Reaction Model," *Fuel*, **237**, pp. 1057–1067.
- [28] Zhang, S. Y., Hong, R. Y., Cao, J. P., and Takarada, T., 2009, "Influence of Manure Types and Pyrolysis Conditions on the Oxidation Behavior of Manure Char," *Bioresour. Technol.*, **100**(18), pp. 4278–4283.
- [29] Sasikumar, C., Sundaresan, R., Nagaraja, M., and Rajaganapathy, C., 2021, "A Review on Energy Generation From Manure Biomass," *Mater. Today Proc.*, **45**, pp. 2408–2412.
- [30] Xiao, X., Le, D. D., Li, L., Meng, X., Cao, J., Morishita, K., and Takarada, T., 2010, "Catalytic Steam Gasification of Biomass in Fluidized Bed at Low Temperature: Conversion From Livestock Manure Compost to Hydrogen-Rich Syngas," *Biomass Bioenergy*, **34**(10), pp. 1505–1512.
- [31] Espindola, J., Selim, O. M., and Amano, R. S., 2021, "Co-Pyrolysis of Rice Husk and Chicken Manure," *ASME J. Energy Resour. Technol.*, **143**(2), p. 022101.
- [32] Ro, K. S., Hunt, P. G., Jackson, M. A., Compton, D. L., Yates, S. R., Cantrell, K., and Chang, S., 2014, "Co-Pyrolysis of Swine Manure With Agricultural Plastic Waste: Laboratory-Scale Study," *Waste Manag.*, **34**(8), pp. 1520–1528.
- [33] Selim, O. M., and Amano, R. S., 2021, "Co-Pyrolysis of Chicken and Cow Manure," *ASME J. Energy Resour. Technol.*, **143**(1), p. 011301.
- [34] Wang, Z., Burra, K. G., Lei, T., and Gupta, A. K., 2021, "Co-Pyrolysis of Waste Plastic and Solid Biomass for Synergistic Production of Biofuels and Chemicals-A Review," *Prog. Energy Combust. Sci.*, **84**, p. 100899.
- [35] Burra, K. R. G., and Gupta, A. K., 2020, "Nonlinear Synergistic Effects in Thermochemical Co-Processing of Wastes for Sustainable Energy," *Innovations in Sustainable Energy and Cleaner Environment*, A. K. Gupta, A. De, S. K. Aggarwal, A. Kushari, and A. Runchal, eds., Springer Nature Singapore, Singapore.
- [36] Déparrois, N., Singh, P., Burra, K. G., and Gupta, A. K., 2019, "Syngas Production From Co-Pyrolysis and Co-Gasification of Polystyrene and Paper With CO<sub>2</sub>," *Appl. Energy*, **246**, pp. 1–10.
- [37] Burra, K. R. G., Liu, X., Wang, Z., Li, J., Che, D., and Gupta, A. K., 2021, "Quantifying the Sources of Synergistic Effects in Co-Pyrolysis of Pinewood and Polystyrene," *Appl. Energy*, **302**, p. 117562.
- [38] Liu, X., Burra, K. G., Wang, Z., Li, J., Che, D., and Gupta, A. K., 2020, "On Deconvolution for Understanding Synergistic Effects in Co-Pyrolysis of Pinewood and Polypropylene," *Appl. Energy*, **279**, p. 115811.
- [39] Li, J., Burra, K. G., Wang, Z., Liu, X., and Gupta, A. K., 2021, "Effect of Alkali and Alkaline Metals on Gas Formation Behavior and Kinetics During Pyrolysis of Pine Wood," *Fuel*, **290**, p. 120081.
- [40] Singh, P., Déparrois, N., Burra, K. G., Bhattacharya, S., and Gupta, A. K., 2019, "Energy Recovery From Cross-Linked Polyethylene Wastes Using Pyrolysis and CO<sub>2</sub> Assisted Gasi Fi Cation," *Appl. Energy*, **254**, p. 113722.
- [41] 2018, "Phyllis2, Database for Biomass and Waste," Energy Research Center, Netherlands, <https://www.ecn.nl/phyllis2/Biomass/View/3501>, Accessed May 28, 2018.