



ELSEVIER

Contents lists available at ScienceDirect

Cleaner and Circular Bioeconomy

journal homepage: www.elsevier.com/locate/clcb

A review on treatment processes of chicken manure

M. Devendran Manogaran^a, Rashid Shamsuddin^{a,*}, Mohd Hizami Mohd Yusoff^a, Mark Lay^b, Ahmer Ali Siyal^a^a HICoE-Centre for Biofuel and Biochemical Research, Institute for Self-Sustainable Building, Chemical Engineering Department, Universiti Teknologi PETRONAS, Seri Iskandar, Perak 32610, Malaysia^b School of Engineering, Faculty of Science and Engineering, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand

ARTICLE INFO

Keywords:

Chicken manure
Circular economy
Composting
Pyrolysis
Gasification
Anaerobic digestion

ABSTRACT

The poultry industry is a fast-growing industry fuelled by overwhelming customer demand. Of the different poultry meat options, chicken is arguably the most popular as it is the second most staple food item in Malaysia after rice. Consequently, due to the overwhelming demand for chicken meat, chicken manure is produced in abundance. In fact, a chicken produces 80 g to 100 g of manure daily, corresponding to 3–4% of its body weight. Utilizing the raw manure as an organic fertilizer without any prior treatment results in adverse environmental consequences as this common practice acts as a vector for propagation of pathogens, attracting flies and pests as well as contributing to odour problems. Treatment methods using pesticides, effective microorganisms and daily collection and disposal have been adopted by the farmers but these techniques are relatively costly and associated with potential environmental threats. Other techniques such as composting, pyrolysis, gasification, anaerobic digestion, hydrothermal liquefaction and torrefaction are drawing interest due to their ability to convert waste to value-added products. Approximately, 77,209 tonnes of chicken manure produced per day in Malaysia in 2014 can potentially generate up to 3.86 million m³ of methane from anaerobic digestion, equivalent to potential generation of 139.5 TJ of heat or 38.7 GWh of electricity theoretically. This paper reviews the technical and practical aspects of the techniques mentioned above in terms of operation, performance and limitations. This paper also examines the preferential treatment techniques in relation to the product outputs with good market potential while being environmentally sustainable.

1. Introduction

The global population has increased significantly to 7 billion in 2020 and is foreseen to grow to approximately 10 billion by 2050. Consequently, the worldwide food demand has been on the rise and by 2050, it is predicted that the food requirement per capita will double (Manogaran et al., 2020). The past few years have observed a dietary haul in developing nations, being on par with developed nations due to enhanced income, growing populations and rapid development which has caused an overwhelming demand for animal protein compared to grains and other pantry staples (Godfray et al., 2018). Malaysia is one of the highest poultry consumers globally and the poultry industry is observed as a vital reservoir for protein meat supply to Malaysians (Nematbakhsh et al., 2021). Of the plethora of protein meat options, chicken meat has been met with an overwhelming demand. In fact, chicken meat has been recognized as the second most staple food item after rice hence acting as the primary protein source in the Malaysian dietary regime (Chijioko et al., 2020). The yearly consumption of chicken per capita in Malaysia is close to 50 kg, which is the first in Asia and third

globally. The rise in chicken meat intake by Malaysians is attributed to the versatility of the meat, the relative low cost in comparison to other meat options, the boost in household income and the acceptance of chicken meat by all religions (Ferlito, 2020). As Malaysia is also rich in ethnical diversity with multiple religions and beliefs therefore, the pattern of food consumption differs from one religion to another particularly in terms of meat intake. For instance, pork is prohibited to Muslims and beef is forbidden to Hindus; such boundaries with respect to religious beliefs makes poultry meat of high demand amongst the meat commodities (Othman and Ruslan, 2020).

The high demand for chicken meat has resulted in a significantly growing issue of manure treatment (Lee et al., 2017). It is estimated that a chicken produces 80 to 100 g of manure daily which is about 3–4% of its body weight (Abdeshahian et al., 2016). Similar to other livestock droppings, chicken manure is a nutrient rich organic waste that contains substantial amounts of nitrogen, phosphorus and potassium and is commonly used untreated as organic fertilizer in agricultural fields. However, excessive use of such fertilizers leads to environmental pollutions such as deterioration of air quality, increased greenhouse

* Corresponding author.

E-mail address: mrashids@utp.edu.my (R. Shamsuddin).<https://doi.org/10.1016/j.clcb.2022.100013>

Received 22 February 2022; Received in revised form 24 May 2022; Accepted 31 May 2022

2772-8013/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

<http://creativecommons.org/licenses/by-nc-nd/4.0/>

gas (GHG) emissions, accumulation of harmful trace metals, eutrophication in water bodies, soil acidification and enhanced nutrient loss primarily nitrogen and phosphorus from soil due to leaching, erosion and runoff prompted by lack of consideration for the nutrient requirements of crops (Zhang et al., 2018). The unpleasant odour triggered by untreated chicken manure draws the attention of flies, pest and rodents which in addition to propagation of pathogens and antibiotic resistance results in an apparent threat to human health (Duan et al., 2019). These factors drive the need to examine alternatives for treatment and use of chicken manure so it can be used sustainably and economically.

When evaluating waste management strategies, the concept of waste-to-wealth is one that has been drawing much attention. The objective of this concept is to encourage a sustainable way of life where waste recovery and valorisation is viewed for its inherent benefits to the environment as well as to improve livelihoods, increase job opportunities and promote new technologies (Xu et al., 2019). Waste-to-wealth efforts are parallel with the circular economy model. The circular economy model is a progressive shift from the linear economy model which operates on the cradle-to-grave flow which capitalizes on single use materials, contributing to adverse environmental effects. The circular economy model on the other hand, minimizes waste by means of recycling and regenerating resources which leads to cleaner production. Adopting the circular economy model will ideally lead to zero-waste and will subsequently generate value chains using renewable energy and natural resources in connected loops instead of resources being consumed and disposed of in linear flows (Lacy and Rutqvist, 2016). Many treatment methods for chicken manure yield circular economy outputs; energy being one of them hence, this calls for a revamp in terms of dealing with chicken manure.

In recent years, energy security has been recognized as one of the main concerns globally due to limited energy supply and its increasing production cost, challenges in energy generation and growing human population that demands for more energy (Zhu et al., 2020). Malaysia's energy source breakdown in the year 2019 observes that up to 94% of energy is derived from fossil fuels. In fact, the nation has developed a high dependence on fossil fuels for energy generation since 2010 (Jones, 2021). Our continued dependency on fossil fuels gives rise to environmental concerns such as carbon dioxide (CO₂) and other GHG emissions. Consequently, such circumstances result in global warming and climate change with adverse effects to humankind and the environment (Zhang et al., 2019). Energy security relies on dependable access to multiple types of energy sources in sufficient quantities and affordable prices which does not reflect their potential effects on the environment and economy (Lee et al., 2022). Generating renewable energy from waste sources such as chicken manure contribute economically towards energy sustainability.

This paper reviews the available treatment processes of chicken manure, including the important considerations and limitations with respect to the physical and chemical properties of the manure. This is as the physical and chemical traits of the manure significantly affect the ease of operation and efficiency of the treatment method. For instance, it has been reported that the moisture content of chicken manure is high (Singh et al., 2018) hence, the treatment method should be able to adapt to this. Accordingly, gasification might not be suitable as feedstock with high moisture content causes feeding and fluidization problems within the process system (You et al., 2016) whereas, anaerobic digestion on the other hand adapts well with feedstock of varying moisture content (Ward et al., 2008). Furthermore, to the best of the authors' knowledge, there has been no comprehensive review comparing the different treatment strategies for chicken manure specifically in the last five years. Review papers on livestock manure or animal manure in general is common while some papers are dedicated to a particular treatment approach. The current manuscript however, delves into different treatment methods for chicken manure while evaluating the ease of the process as well as its drawbacks. Additionally, this review also evaluates the impact of the treatment methods on environmental sustainabil-

ity and the end-products generated based on the waste-to-wealth and circular economy concepts. Apart from recognized methods like composting, pyrolysis, gasification and anaerobic digestion, hydrothermal liquefaction and torrefaction are evaluated as well. Although not common for treating animal manure, these methods are utilized for biomass treatment hence, they are incorporated in this review which adds to its novelty. This should assist decision makers in selecting the most adequate chicken manure treatment method.

2. Treatment methods of chicken manure

Common treatment methods practiced by farmers for chicken manure are using pesticides as well as daily collection and disposal. The practice of direct utilization of chicken manure as an organic fertilizer for soil conditioning puts the environment at jeopardy due to over-fertilization (Tańczuk et al., 2019a). Effective microorganism (EM) supplementation is the addition of mixed cultures of beneficial and naturally occurring microorganisms as inoculants to chicken manure to improve the microbial diversity of soil to which it is applied. One study revealed positive findings on application of EM-treated manure as an organic fertilizer however, the environmental sustainability of this approach has yet to be clearly established (Gunawan et al., 2020). Other alternatives of treating chicken manure are land application and incineration, which have contributed towards leaching of nutrients into waterways, malodours, and particulate emissions, which can adversely affect human health and wildlife (Arena et al., 2015; Maya et al., 2016). The treatment methods reviewed in this paper are composting, pyrolysis, gasification, anaerobic digestion as well as other relatively new approaches. Apart from composting, the other methods are not as common amongst farmers due to lack of expertise and high capital cost even though they can result in useful outputs rather than only serving as treatment method. This review paper can increase the awareness on potential treatment strategies for animal manure, specifically for chicken manure that is projected to increase rapidly in tandem with human population.

2.1. Composting

Composting is where the manure is mixed with other organic matter and bulking agents to facilitate aerobic microbial breakdown and stabilization of organic matter under conditions that expedite the development of thermophilic temperatures to generate an end product that is stable, free of pathogens and suitable for land application (Akdeniz, 2019). The composting process can be segregated into four stages. The first stage is hydrolysis of organic matter such as proteins and sugars by mesophilic microorganisms which grow in the temperature range of 20-45 °C. This microbial activity heats the compost to approximately 65-68 °C, during which, the mesophilic microorganisms are replaced by thermophilic microorganisms. Pathogens are also eliminated at this stage of the process due to the high temperatures (Tuomela et al., 2000). The easily digestible matter is then consumed resulting in the compost temperature decreasing and fungi proliferate degrading the cellulose, hemicellulose and lignin over a period of 3 to 6 months which produces a stable humic material (Sánchez et al., 2017). The compost at the end of the process is often utilized as safe and nutrient-enhanced fertilizer (Li et al., 2020). The degree of composting is dependent on the change in temperature of a composting sample when placed in a dewar or from measuring the CO₂ evolution. Raw compost experiences a temperature change of greater than 40 °C and an oxygen demand of 900 mg per gram volatile matter per hour, while finished compost experience a temperature change of 0-10 °C and an oxygen demand of 1 mg per gram per hour (Godlewska et al., 2017). Composting techniques applied include in-vessel systems, aerated or static bins, dynamic continuous composting and windrows (Sánchez et al., 2017).

Factors such as temperature, moisture, porosity, aeration rate, pH and C/N ratio affect the microbial community and metabolism which

Table 1
Conventional operating conditions and output yield relative to pyrolysis process.

Pyrolysis Process	Solid Retention Time (s)	Heating Rate (K/s)	Particle Size (mm)	Temperature (°C)	Output Composition (%)		
					Oil	Char	Gas
Slow	450–550	0.1–1	5–50	277–677	30	35	35
Fast	0.5–10	10–200	<1	577–977	50	20	30
Flash	<0.5	>1000	<0.2	777–1027	75	12	13

significantly affect the composting process and quality of compost produced (Wang et al., 2018). Moisture needs to be maintained at around 50–60% wet basis, C/N ratio between 25 and 30, pH between 5.5 and 9, temperature between 55 and 63 °C and oxygen content greater than 5%. The pile needs to be bulky to allow ready access of air and have sufficient water holding capacity without blocking the air space and pores (Yu et al., 2015). Chicken manure has low porosity, high moisture content, low C/N ratio and high pH which is overcome by adding high C/N ratio bulking agents such as rice husk, wood chips and sawdust which increases the C/N ratio, pile porosity and aeration channels while simultaneously reducing the water content (Zhang and Sun, 2016).

Addition of compost to soil enhances the organic matter content in soil as well as the soil structure and agricultural productivity due to the additional nutrients in the compost and presence of plant growth-promoting organisms (Luo et al., 2017). Consequently, addition of compost aids food security. More notably, replacing synthetic fertilizer with compost improves soil biodiversity and reduces environmental risk of nutrient leaching (Pose-Juan et al., 2017). Composting contributes favourably to pollution control (Uyizeye, 2019), bioremediation (Ventorino et al., 2019), weed control (Zubair et al., 2020) and plant disease control (Pane et al., 2019). Composting organic waste compared to landfilling prevents ground water from being polluted due to leachate from landfilling organic matter (Ayilara et al., 2020). Stable compost is also much easier to handle in terms of storage and transport compared to raw organic waste which in this case is raw chicken manure (Akdeniz, 2019).

However, composting is a time consuming process, requiring 3 to 6 months to produce a mature compost, hence the footprint of the site is quite large. Odours can be generated from composting piles if the C/N ratio, aeration and water is not managed well, resulting in the piles generating ammonia at low C/N ratios as excess nitrogen is volatilised (Pardo et al., 2015) or the piles become anoxic at low oxygen content resulting in fermentation products such as alcohol and leachate. Additionally, pathogens that are able to tolerate high temperature conditions can sporulate and present a potential health hazard if the compost is derived from food crops (Ayilara et al., 2020).

2.2. Pyrolysis

Pyrolysis is described as the thermal decomposition of biomass in the absence of oxygen resulting in generation of bio-oil, solid biochar and non-condensable gas products. The process is particularly intricate and comprises of both simultaneous and successive reactions when organic matter is heated in a non-reactive atmosphere (Kan et al., 2016). Pyrolysis can be segregated into three primary categories which are slow, fast and flash pyrolysis as depicted in Fig. 1.

The different types of pyrolysis are distinguished with respect to the operating parameters which are inclusive of the heating rate, process temperature, biomass particle size and solid retention time. The relative distribution of products generated is also essentially correlative to the type of pyrolysis and its operating variables as depicted in Table 1 (Hu and Gholizadeh, 2019).

Slow pyrolysis is often used to enhance char yield given a low heating rate and low temperature setting. This is because its vapour residence time is significantly higher in comparison to the other two variations of pyrolysis, anywhere between five minutes to half an hour. During

this period, components in the vapour phase continuously react with each other, favouring solid char formation in addition to other liquids (Al Arni, 2018). The drawback of this approach is its inadequacy to synthesize high quality bio-oil. High retention time results in cracking of the primary product in the process and which often jeopardises the production of bio-oil. Moreover, a significantly lower heat transfer and longer retention time calls for additional energy input (Selvarajoo, 2021).

Fast pyrolysis on the other hand occurs by rapid heating of the biomass to a high temperature in the absence of oxygen. The critical traits of this process are its closely monitored reaction temperature, rapid vapour retention time and swift cooling of vapours and aerosol particularly favourable for rich bio-oil production (Al Arni, 2018). Fast pyrolysis is garnering much attention due to its potential in producing liquid fuels and a variety of commodity and speciality chemicals. The liquid product is economically transported with ease and stored along with effective handling of the solid biomass from utilization. Fast pyrolysis also requires comparatively low investment cost and high energy efficiency compared to other processes, particularly on a small scale (Venderbosch and Prins, 2010).

Flash pyrolysis on the contrary, is a favourable process to produce solid, liquid and gaseous fuel from organic matter enriched biomass which can yield up to 75% bio-oil. Basically, the process is described as rapid devolatilization in an inert atmosphere indicating a high heating rate of the organic matter and a very narrow gas retention time which is less than 1 s to be exact in a high temperature ambience in the range of 450–1000 °C (Patel et al., 2020). Despite the many benefits of flash pyrolysis, there are notable technological constraints which include unsatisfactory thermal stability, presence of solids in the bio-oil synthesized, corrosiveness of the oil, enhanced viscosity of the oil over time due to catalytic action of char, alkali concentrated in the char dissolves in the oil and production of pyrolytic water (Gupta et al., 2021).

There are multiple pyrolysis reactor designs such as fixed bed reactors, fluidized-bed reactors and ablative reactors (Ore and Adebiyi, 2021). All these different reactors have a defined feedstock size limitation to ensure functional heat transfer and trouble-free operational performance. Accordingly, it is essential to prepare the feedstock which in this case is chicken manure in the suitable size. This is often done by mechanical operations such as grinding and cutting. The chicken manure needs to be dried as well such that the moisture content is unmistakably below 10 wt%. This stage is of utmost importance as it prevents adverse implications of moisture on the pH, viscosity, stability, corrosiveness and other liquid properties of the final product. Although introducing mechanical operations and drying enhances the liquid product attained from the process, it increases the production cost as well (Hong et al., 2020). After subjected to mechanical operations and drying, the feedstock is fed into the pyrolysis reactor of choice. The char produced in the reactor emulates the duty of a vapour cracking catalyst. Cyclones are often incorporated into the process flow to separate the char from the reactor after the pyrolysis process has been completed to achieve complete char removal. However, often times, some small char particles pass through the cyclones and ends up mixed in the liquid product. After the solids have been separated, the vapours and gases are quenched quickly to prevent continual cracking of the organic molecules. Pyrolysis liquid condensers are normally utilized for quenching of the vapours in which the vapours are cooled directly with the bio-oil or a hydrocarbon liquid (Xin et al., 2021).

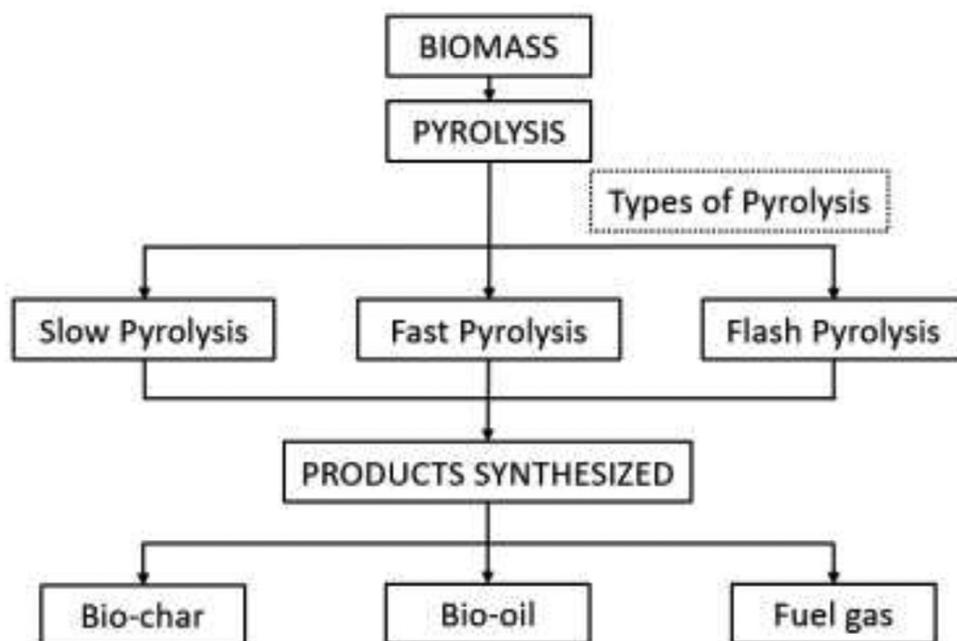


Fig. 1. Different types of pyrolysis processes and the products synthesized (Lee et al., 2019).

The primary products acquired from biomass pyrolysis are bio-char, pyrolytic gaseous species and vapours which condense to liquid products at ambient temperature (Hu and Gholizadeh, 2019). Compositions of pyrolysis product can be enhanced as follows (Uddin et al., 2018): bio-char – lower temperature and heating rate procedure liquid products – lower temperature setting but higher heating rate procedure pyrolytic gaseous species – higher temperature setting and lower heating rate procedure

Bio-oil, a dark brown, viscous organic liquid is the primary yield of interest from pyrolysis. It is mainly constituted of oxygenated components which result in high thermal insecurity and low heating point (Hu and Gholizadeh, 2019). Another undesirable trait of bio-oil is its low pH value in the range of 2–3.7 because of the presence of carboxylic acids. Consequently, bio-oils are more likely corrosive to common structures and highly instable during storage attributed to its ongoing chemical reactions for instance, etherification, esterification and polymerisation to form larger molecules (Kan et al., 2016). Much attention has been drawn to means of enhancing the yield of bio-oil qualitatively and quantitatively with researches emphasizing on reactor designs and configurations taking precedence over other operational parameters. Upgrading of bio-oil is imperative prior to practical utilization in engines (Uddin et al., 2018). For instance, transportation liquid fuel can be synthesized from bio-oil through upgrading by means of high-pressure hydro processing (Elliott et al., 2012) and catalytic cracking technologies (Ibarra et al., 2019). Bio-char on the other hand, is extensively recognized for its efficacy as soil amendment attributed to its enriched plant nutrient content, aiding carbon sequestration which effectively alleviates atmospheric carbon (Vilas-Boas et al., 2021).

The pyrolytic gaseous species, often recognized as syngas constitutes of primarily hydrogen (H_2) and carbon monoxide (CO) with minute quantities of water (H_2O), nitrogen (N_2), (CO_2) as well as hydrocarbons such as methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), tar and ash with respect to the feedstock material and pyrolysis operating parameters. The potential of syngas for utilization as an alternative fuel for industrial combustion processes and internal combustion engines has been evaluated for application such as transportation and power generation (Honus et al., 2018). However, a study on a single cylinder spark ignition engine utilizing syngas as fuel observed a drawback in terms of the emission of nitrogen oxides (NO_x) emission and such circumstances

pose an apparent hazard to environmental sustainability as well as human health (Mustafi et al., 2006).

2.3. Gasification

Gasification is the thermochemical conversion of carbon rich feedstock into combustible product gas utilizing gasifying agents such CO_2 (Widjaya et al., 2018). Gasification consists of four stages as shown in Fig. 2 which are drying, devolatilisation, also known as pyrolysis, combustion and reduction.

The drying stage necessitates the evaporation of free and bound water in the feedstock by heat often supplied by exothermic reactions in the subsequent stages. The temperature is normally between $100\text{ }^\circ\text{C}$ and $200\text{ }^\circ\text{C}$ which satisfies the fundamental function of this stage in the overall process without thermally decomposing the feedstock. This is because the temperature condition does not meet the mark to execute such heavy duties (Patra and Sheth, 2015). The drawback of this stage is the emission of certain air pollutants such as volatile organic compounds. Nonetheless, the inclusion of this step is significant in the case of a high moisture content feedstock. The reason behind this would be that the drying stage prevents feeding or fluidization problems such as agglomerate formation and jamming which are often associated to feedstock with high moisture content such as chicken manure. In the absence of the drying step, the reduced heating value of the product gas adversely effects the overall energy efficiency of the gasification reaction. Such circumstances yield a significantly enhanced tar content in the product gas due to the declining reaction temperature (You et al., 2018). Essentially, the drying rate is controlled by the heat and mass transfer between feedstock particles and their ambient atmosphere corresponding to the temperature difference, particle surface area, moisture and convection velocity of surrounding flows as well as diffusivity of moisture within feedstock particles and moisture (Arima et al., 2018).

The consecutive stage is devolatilisation, otherwise regarded as pyrolysis which has been discussed in Section 2.2. The essence of this stage is further degradation of the feedstock particles into volatile matter and carbonaceous solid residue, also known as biochar under elevated temperature conditions in the absence of oxygen (Wani et al., 2020).

The next stage is combustion which encompasses of complete or partial oxidation of carbonaceous output and certain gas species yield from

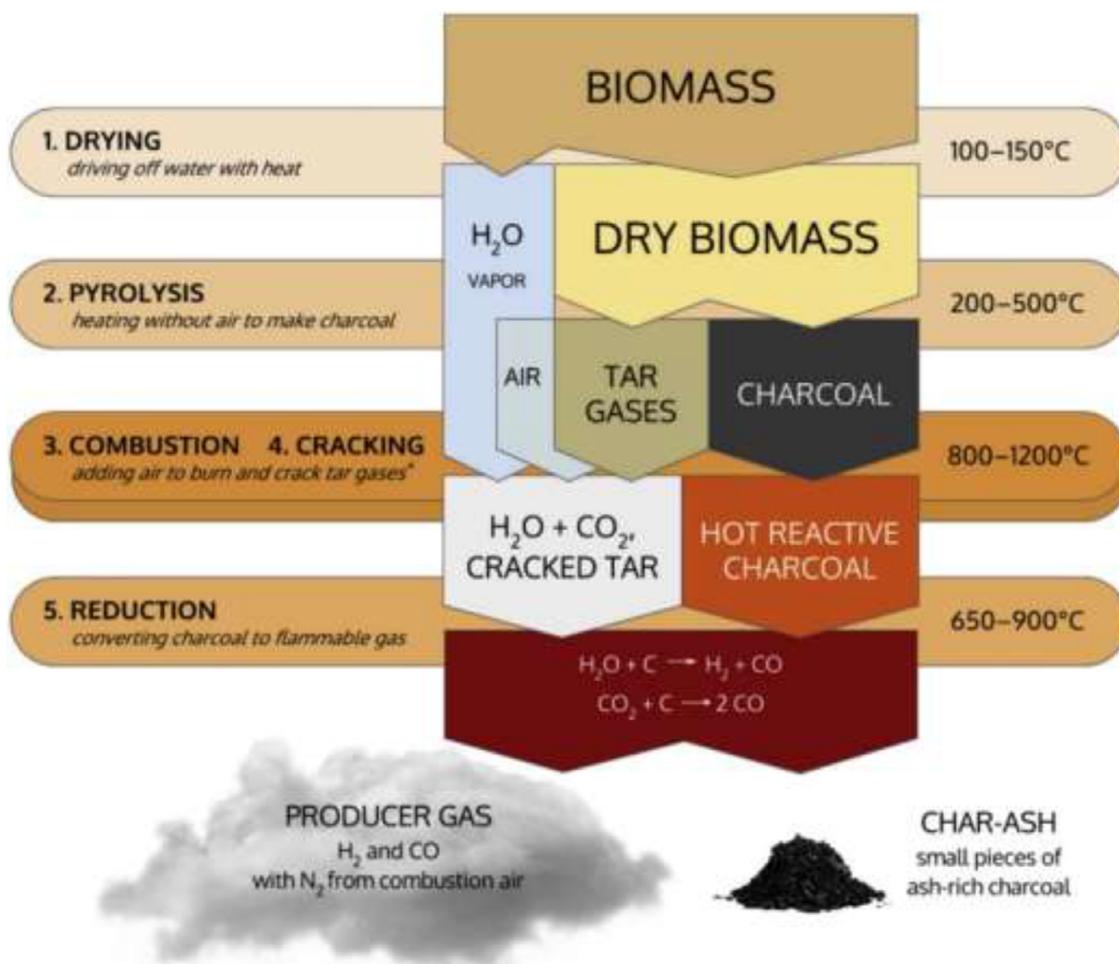
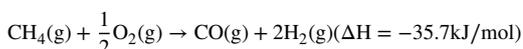
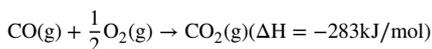
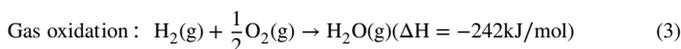
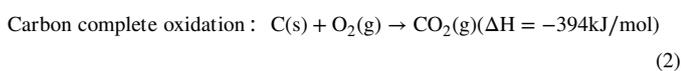
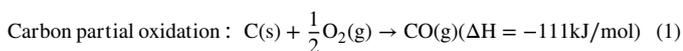


Fig. 2. Consecutive stages of gasification (Safarian et al., 2019).

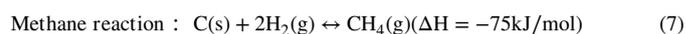
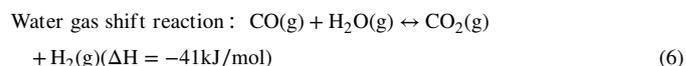
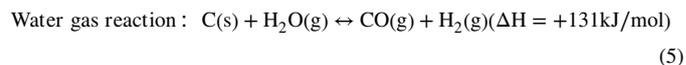
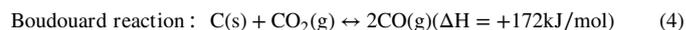
pyrolysis. The products of the combustion reaction are often H_2O , CO_2 , CO and H_2 . This strongly exothermic reaction often occurs between $700\text{ }^\circ\text{C}$ and $1500\text{ }^\circ\text{C}$ (Patra and Sheth, 2015) and is responsible for supplying gasifier heat required in the subsequent reduction reaction as well as the drying and pyrolysis stages of the process which are endothermic in nature (Janajreh et al., 2021). The primary reactions taking place at this stage are expressed as follows;



The oxidation of volatile gas species as illustrated in Eq. (3) occurs rapidly resulting in a large portion of the oxygen being utilized before diffusing to the surface of the biochar, often preventing biochar oxidation as expressed in Eqs. (1) and (2). In the circumstance of a sub-stoichiometric oxygen condition, partial oxidation of carbon occurs dominantly, yielding CO as described in Eq. (1). The steam generated during this stage of the process acts as the reactant for the water gas reaction and water gas shift reaction which will occur during the consecutive stage. Furthermore, oxygen deficiency will also result in remaining

biochar that functions as the reactant for the Boudouard reaction and water gas reaction during the subsequent stage as well (You et al., 2018).

The next stage is the reduction stage whereby the temperature range is approximately $800\text{--}1000\text{ }^\circ\text{C}$ (Janajreh et al., 2021; Patra and Sheth, 2015). The reduction stage is a platform for the biochar to react with H_2O , CO_2 and H_2 from the previous stage to generate a mixture of combustible gases constituting of CO , CO_2 , H_2 , CH_4 as well as light hydrocarbons for instance, acetylene and ethylene. Generally, the reaction of biochar with H_2O occurs faster in comparison to the reaction of biochar with CO_2 (Cao et al., 2020). The primary reactions taking place are as depicted in Eqs. (4)–(7);



From an environmental conservation point of view, there has been fruitful evidence in favour of gasification in comparison to other conventional methods of disposing chicken manure particularly in terms of net GHG emissions. A life cycle assessment (LCA) drawing comparison between the net GHG emissions when disposing of manure using the common approach, land application and gasification observed significant GHG emissions reduction using the latter approach as compared to

Table 2
GHG emission with respect to the LCA framework for land application scenario.

Life cycle stage	kg CO ₂ -eq per tonne dry feedlot manure	Mass (%)
Manure collection	0.99	0.34
Transportation	0.64	0.22
Spreading	1.90	0.64
Manure emissions	292	98.80
Displacing fertilizer utilization	-177	100
Net emissions	119	NA

Table 3
GHG emission with respect to the LCA framework for gasification scenario.

Life cycle stage	kg CO ₂ -eq per tonne dry feedlot manure	Mass (%)
Manure collection	0.99	1.35
Manure transportation	1.02	1.38
Manure emissions	46.90	63.70
Gasification plant emissions	23.40	31.80
Biochar transportation	1.03	1.40
Biochar spreading	0.22	0.29
Avoided electricity generation	-545	76.10
Carbon sequestration	-143	20.00
Biochar effects on agronomy	-28.40	3.96
Net emissions	-643	NA

*Negative net emission value address GHG emission mitigation and vice versa.

the former. Land application decreased GHG emissions by taking over the application of mineral fertilizers for crop cultivation. However, it is vital to note that the surplus in GHG emissions abatement is exclusively attributed to this merit only in the case of land application. Gasification on the other hand, notably reduced GHG emissions through three major aspects which are avoided electricity generation, carbon sequestration and the consideration of biochar effects on agronomy. Overall, the net GHG emissions for one ton of dry feedlot manure using land application and gasification is 119 and -643 kg CO₂-eq, respectively observing the apparent edge of the latter as shown in Tables 2 and 3 (Wu et al., 2013).

Other conventional means of disposing chicken manure include incineration and combustion which also have significant environmental drawbacks as compared to gasification. Incineration for instance, results in 4 times more emissions of sulfur dioxide, SO₂ than gasification which lowers the pH of air consequently resulting in air acidification. Furthermore, opting for gasification to dispose of chicken manure results in 33% less NO_x emissions, observing notably less smog production (Maya et al., 2016). Another study comparing gasification and combustion discovered that PM_{2.5} emissions of the gasification process was 3 times lower than that for the combustion process because of the lower emission of NO_x compounds. Gasification also observed better performance in the non-carcinogens impact category as the vinyl chloride equivalent production was 54 times lower than combustion process (Arenas et al., 2015). On the other hand, there are arguable environmental concerns with respect to the gasification process. Gasification can produce many inorganic and organic contaminants for instance NH₃, hydrogen sulfide (H₂S) and tar (Islam, 2020). These pollutants can significantly affect the post-stream applications of the product gas and cause consequential concerns such as pipeline clogging, catalyst deactivation, conversion efficiency reduction and adverse emissions to the environment (Tańczuk et al., 2019b). With respect to these circumstances, adopting the gasification technology also requires cost allocation for gas cleaning and conditioning.

The mixture of combustible gases, predominantly rich in H₂, CO, CO₂ and CH₄ with minute amounts of low molecular weight hydrocarbons such as C₂H₆ and C₃H₈ is often recognized as syngas (Janajreh et al., 2021). The potential of generating heat and electricity from syngas has been well established (Cao et al., 2020). The quality of syngas is also often time enhanced such that value-added biofuels and

chemicals can be synthesized by either catalytic conversion or anaerobic fermentation; one of which is H₂. H₂ generation can also be significantly enhanced by syngas reforming through catalysed reaction for instance, steam reforming of CH₄ and higher hydrocarbons as well as the water gas shift reaction utilizing Fe and Ni catalysts at the temperature range of 200–1100 °C and pressure range between 1 bar and 30 bar (Chianese et al., 2016).

2.4. Anaerobic digestion

Anaerobic digestion (AD) exploits several groups of bacteria and substrates, exhausted under strict anaerobic conditions specifically, oxidation–reduction potential under 200 mV to convert organic material into biogas, mostly constituting of CH₄ and CO₂. The process consists of four pivotal stages which are fermentation (hydrolysis), acidogenesis, acetogenesis and methanogenesis as portrayed in Fig. 3. Each consecutive degradation stage is facilitated by a different class of microorganism, which partially act in syntrophic interrelation under distinct ambient conditions (Bharathiraja et al., 2018).

Hydrolysis is the stage during which complex, insoluble organic materials such as lipids, carbohydrates, proteins and nucleic acid are hydrolysed into basic water-soluble monomers by exoenzymes excreted by hydrolytic bacteria such as cellulase, cellobiase, xylanase and lipase. The monomers which are the end product of hydrolysis experience acidogenesis by another facultative and obligatory anaerobic bacteria after which these monomers are degraded even further into short-chain organic acids, alcohols, H₂, CO₂ and volatile fatty acids (VFAs) (Bharathiraja et al., 2018). The concentration of the intermediately formed hydrogen ion has a significant effect on the variety of product formed. The products from the acidogenic stage play an imperative role as substrate in the acetogenic stage whereby homoacetogenic microorganisms continuously reduce exergonic H₂ and CO₂ to acetic acid (Kremp et al., 2018). During this stage, organic acids and alcohols are converted into acetate as well and this is crucial to note as acetate acts as a substrate for methane-forming bacteria. Moreover, past studies have also observed that acetogenic bacteria nourish in a symbiotic relationship with methane-forming bacteria (Mutungwazi et al., 2021). This is relevant for the last stage of the AD process which is the methanogenesis which involves two groups of bacteria which are the acetotrophic bacteria that reduces acetate into CH₄ and CO₂ (Szuhaj et al., 2016) and the hydrogenotrophic methanogens that consume H₂ to produce CH₄ (Bharathiraja et al., 2018).

There are a few variables that exhibit apparent effects on the efficiency of the AD process, directly influencing the biogas yield as well. Many studies in the past have stressed on the crucial impacts of temperature on the microbial community, process kinetics as well as stability and methane yield. Psychrophilic temperature conditions for AD have observed deterioration in microbial growth, substrate utilization rates and biogas production in past studies (Xu et al., 2022). Thermophilic temperature setting on the other hand reduce biogas yield contributed by the production of volatile gases such as ammonia which strains methanogenic activities. Accordingly, past studies suggested that in the case of chicken manure as the sole feedstock for AD, mesophilic temperature is more favourable in terms of stability of biogas generation (Bi et al., 2019; Yin et al., 2018).

Another factor affecting the AD process is pH. The pH adequate for hydrolysis is pH 4.0–5.0 whereas for acidogenesis and methanogenesis are pH 5.0–6.5 and pH 6.8–7.5 respectively (Chatterjee and Mazumder, 2019). Chuenchart et al. (2020) has observed that optimum pH range for AD of chicken manure is pH 6.5–7.5 however, the pH of chicken manure falls short as it has been reported to be 6.1 (Singh et al., 2018) hence, there is a need to adjust it prior for optimum biogas generation.

Furthermore, another parameter which affects the biogas yield during the AD process is the organic loading rate (OLR). OLR is described as the amount of volatile solids (VS) or chemical oxygen demand (COD)

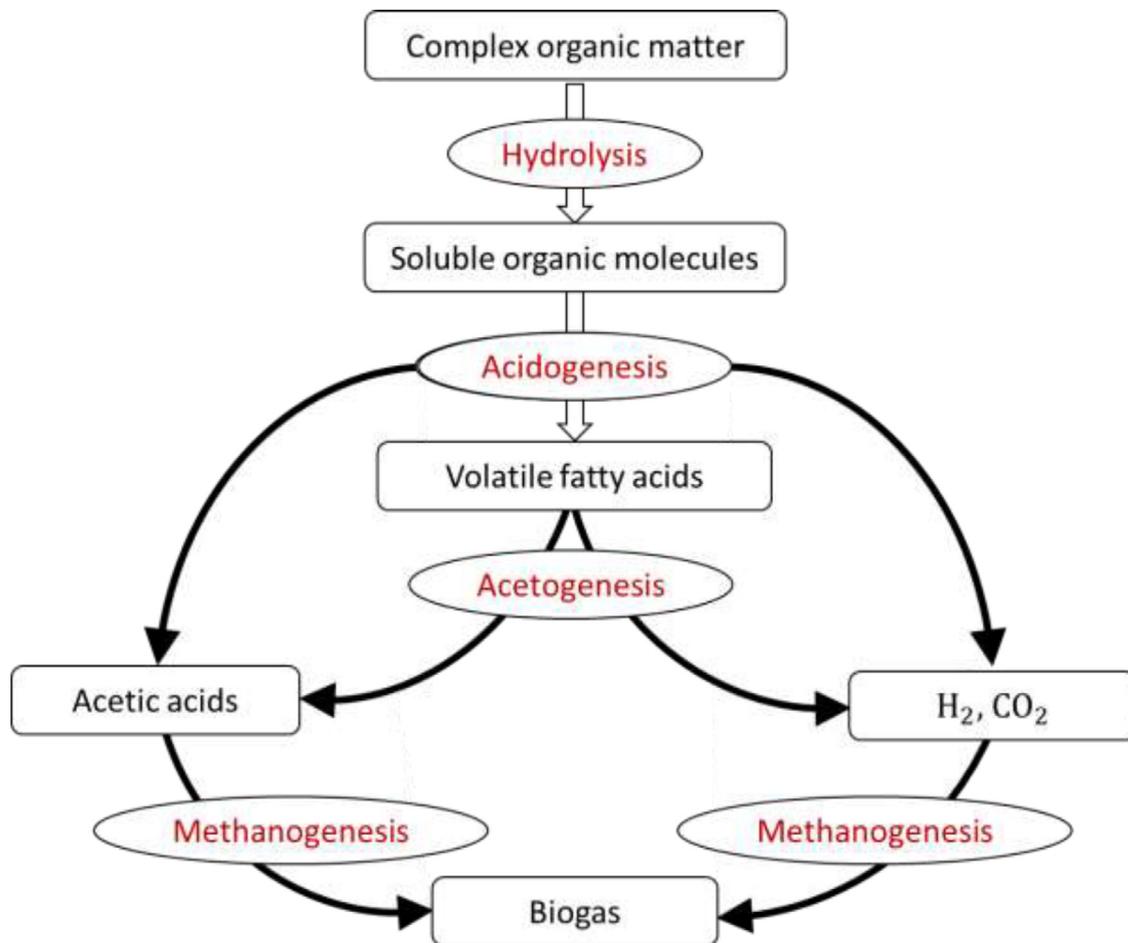


Fig. 3. Different stages of AD for biogas generation (Shamsuddin et al., 2021).

compounds fed daily per unit digester volume (Chandra et al., 2012). Higher OLRs can lessen the digester's size and as the result of this, the capital cost can be reduced as well however, the retention time should be sufficient for AD to take place for biogas production (Jahn et al., 2020). The activity of methanogens can fluctuate considerably with respect to carbon requirements and growth feedback to organic additions. However, the addition of large volumes of new material on a daily basis may cause alterations in the digester's environment and briefly inhibit the bacterial activity during the premature stages of hydrolysis. This bacterial inhibition which may result in disruption to the AD process may occur due to the significantly high OLR leading to higher hydrolysis and acidogenesis bacterial activity than methanogenesis bacterial activity consequently enhancing VFA production which in due course results in an irreversible acidification. Accordingly, the pH of the digester plummets causing the hydrolysis process to be inhibited such that the defective methanogenesis bacteria are not able to transform as much VFA to CH_4 which is why the maximum threshold OLR limit has been extensively studied and observed in previous studies. In a recent study, Bi et al. (2019) observed in an AD system with chicken manure as the sole feedstock under thermophilic temperature condition, the setup with higher OLR ($2.5 \text{ kg volatile solids m}^{-3} \text{ d}^{-1}$) experienced a significant deterioration in CH_4 generation due to NH_4 inhibition in comparison to lower OLR ($1.6 \text{ kg volatile solids m}^{-3} \text{ d}^{-1}$).

Another factor affecting the AD process is the carbon-to-nitrogen (C/N) ratio. Previous studies suggested a C/N ratio in the range of 20–30 or 20–35, with a ratio of 25 being optimum for AD process (Igbum et al., 2019). Cahyono et al. (2021) reported that the C/N ratio of fresh chicken manure is 11.348 indicating that carbon adjusters need to be incorpo-

rated as a co-substrate in the AD process to enhance the C/N ratio. An adequate C/N ratio results in prolonged protein solubilization rate which induces low total ammonium nitrogen (TAN) and free ammonia nitrogen (FAN) concentrations within the system. Hence, ammonia inhibition can be prevented by feeding the anaerobic digester with raw material which exhibits an optimal C/N ratio. However, an excessively high C/N ratio deprives the system of elemental nitrogen to sustain cell biomass and causes accelerated nitrogen decomposition by microbes which leads to significantly reduced biogas production. A system with an extremely low C/N ratio on the other hand faces the risk of ammonia inhibition whereby this circumstance has adverse effects on methanogens leading to inadequate application of carbon sources (Hakimi et al., 2021).

In addition to the factors discussed earlier, retention time also plays an imperative role to ensure the sound performance of AD process. Retention time is the time taken to complete degradation of organic matter. The retention time can be linked with the microbial growth rate and is also heavily affected by the OLR, substrate composition and process temperature (Khan et al., 2016).

Biogas produced through AD is an energy-efficient approach with environmental friendly benefits that has an upper edge over other forms of bioenergy (Hanafiah et al., 2022). Fig. 4 depicts data from 2012 on the potential of biogas generation from different types of farm animals in Malaysia.

Based on the data in Fig. 4, it is apparent that manure produced by the poultry farming industry has a significantly enhanced potential for biogas generation over the manure produced by other types of farm animals. Furthermore, as indicated before, chicken meat is arguably one of the more popular options of poultry meat hence it can be deduced that

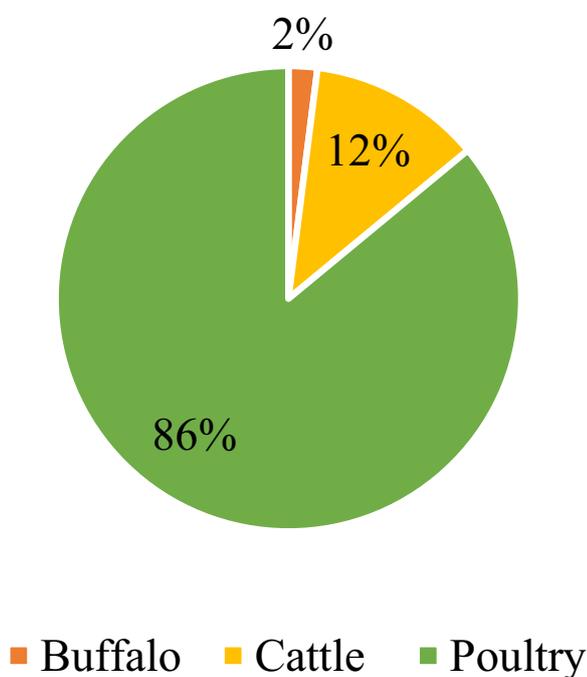


Fig. 4. Biogas generation potential from different farm animal manure in Malaysia in 2012 (Abdeshahian et al., 2016).

Table 4

Estimation of CH₄ generation and energy produced from chicken manure based on population of chickens in Malaysia in 2014.

Parameter	Unit	Value
Chicken population ^a	million birds	772
Chicken manure produced per bird daily ^a	g/day	100
Total mass of chicken manure produced daily	tonnes/day	77,209
CH ₄ generated per kg of chicken manure ^b	m ³ /kg	0.05
CH ₄ generated daily	m ³ /day	3,860,458
Energy produced ^c	TJ/day	139.5
	GWh/day	38.75

^a Chicken population of 772 million in 2014 and assumption of 100 g/day of chicken manure produced per bird acquired from literature study (Kumaran et al., 2016).

^b CH₄ conversion factor is 0.05 m³ CH₄ per kg of chicken manure (Ahmad, 2010).

^c Heat value of CH₄ is 55 MJ/kg (Wongarmat et al., 2021) with gas engine conversion efficiency assumed at 100%.

most of the poultry manure produced is chicken manure (Ahmad, 2015). This finding is crucial as biogas can be used directly for electricity generation and heating as well as a replacement for fossil fuels for instance, as transportation fuel. The valorisation of synthesized biogas, constituting of 65% CH₄, 35% CO₂ as well as small traces of H₂S, H₂ and N₂ is environmentally friendly and energy efficient due to significantly low emission of hazardous substances which otherwise can have an adverse effect on human health. Most of the time biogas is valorised energetically in a combined heat and power (CHP) installation for production of heat and electricity at the same time. These installations normally provide a 33% electrical efficiency and a 45% thermal efficiency (Appels et al., 2011). Table 4 highlights the potential of biogas generation from chicken manure in Malaysia in 2014 given that all poultry farms managed chicken manure through AD.

Moreover, the emission of volatile organic compounds (VOCs) is also minimal since 99% of the VOCs are completely oxidized during combustion which is significantly better in comparison to incineration which emits toxic materials such as dioxins that demand for extensive flue gas purification, effectively increasing the capital investment cost

(Appels et al., 2008). The digestate produced is rich in nitrogen and is often applied in plantations fields as an organic fertilizer (Angouria-Tsorochidou and Thomsen, 2021) which effectively lessens the dependency on energy intensive mineral fertilizers, further reducing GHG emissions.

AD is a microbial conversion approach that favours an aqueous environment which indicates that chicken manure that constitutes of significant water content can be processed without any pre-treatment (Ward et al., 2008). This circumstance is not applicable in the case of many other conversion methods. Combustion, for instance exclusively provides a net positive energy balance if the feedstock consists of water content below 60% and even under those circumstances, a large portion of the energy stored in the feedstock is harnessed for evaporation of the moisture. Additionally, in the case of pyrolysis and gasification, the energetic efficiency of both processes reduces substantially parallel to increase in water content and the presence of water in the synthesized bio-oil is also an undesirable attribute (Van de Velden et al., 2010). In a nutshell, utilization of these methods calls for an energy demanding pre-drying step for wet feedstock which includes fresh chicken manure. Furthermore, AD is not only practical in a large-scale industrial application, it can be incorporated for small-scale utilization as well. This beneficial aspect of AD provides an avenue for life style betterment especially in rural regions and developing countries which has limited or even worse, no energy supply all together. For instance, rural communities in India exploit AD using agricultural wastes and weed as the feedstock to yield cooking gas for household use (Talevi et al., 2022).

2.5. Other treatment methods

The treatment methods discussed in this section are hydrothermal liquefaction (HTL) and torrefaction, both not as commonly applied for chicken manure. Another thing to note is that both these methods do not often yield circular economy outputs directly instead need to be paired with methods scrutinized in the earlier sections.

HTL is essentially a reaction utilizing biomass or organic material as the feedstock in the presence of water, otherwise regarded as the solvent at hydrothermal conditions which is in the temperature range of 250–450 °C and pressure range of 100–350 bar. Under these conditions, water remains in liquid form or relatively dense supercritical state (Castello et al., 2018). Before being treated under HTL, the feedstock undergoes a three-step process which are depolymerisation, decomposition and finally, recombination. Depolymerisation is subsequent dissolving of macromolecules while taking advantage of their physical and chemical traits to ease the process. The high temperature and pressure setting urges the hydrolysis of long chain polymers consisting of carbon, H₂ and O₂ into shorter chain hydrocarbons (Amit et al., 2021). After that, decomposition observes loss of water molecule (dehydration), loss of CO₂ molecule (decarboxylation) and removal of amino acid content (deamination) (Jena et al., 2015). Dehydration and decarboxylation are functional for the removal of O₂ from the feedstock in the form of water and CO₂ respectively. The degradation yield primarily constitutes of polar organic molecules, furfurals, glycoaldehydes, phenols and organic acids that are highly soluble in water. Before HTL, recombination and repolymerization of reactive fragments takes place. Should there be any free H₂ molecules present in the organic matrix for later process, the free radicals will be capped resulting in the stable molecular weight species. However, if there are no H₂ molecules or there is an abundance of free radicals to the point of overwhelming, the fragments will recombine or repolymerize to form high molecular weight char compounds otherwise known as coke formation (Shah, 2015).

Considering that HTL demands for a state of wet reaction, chicken manure is an adequate feedstock for this process due to its significant moisture content (Singh et al., 2018). Additionally, no drying is required which means that operational cost can be effectively reduced. However, it is crucial to note that HTL is often applied for agricultural and forestry waste comprising of plant and plant-based material, otherwise recog-

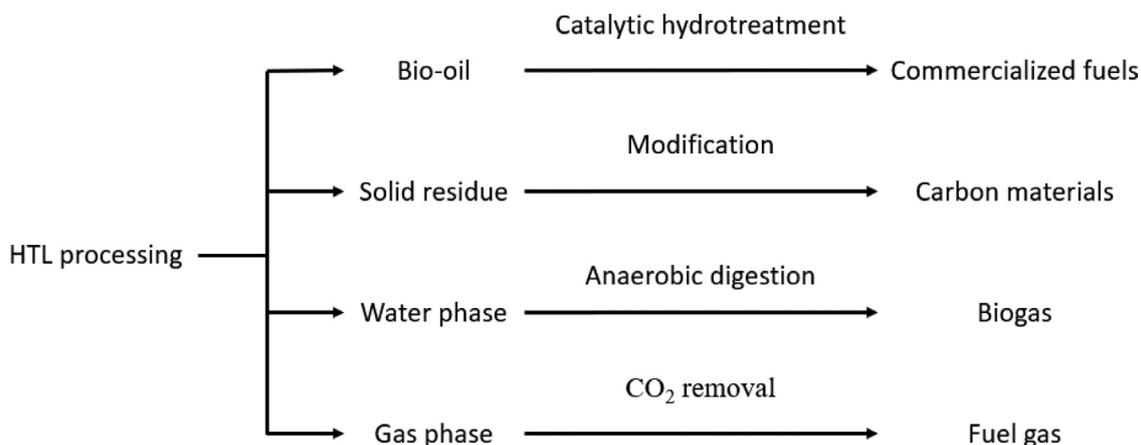


Fig. 5. Circular economy outputs yield from HTL processing (Cao et al., 2017).

nized as lignocellulosic biomass (Cao et al., 2017). The primary purpose of HTL is supposedly to produce bio crude from biomass waste, potentially a substitution for commercial fossil fuels although the economic feasibility is questionable due to the need for higher pressure setups which can be very costly (Gollakota et al., 2018). A proposed solution for this is the addition of catalyst which can inhibit side reactions while lowering temperature and pressure settings (Cao et al., 2020). However, this requires additional cost which may upset the cost reduced on lowering the temperature and pressure conditions. Aside from bio-crude, there are other output that can be acquired from HTL provided that other technologies are integrated within the system as depicted in Fig. 5.

Another treatment that has scarce past research output is torrefaction. Torrefaction, otherwise known as mild pyrolysis encompasses of heating the feedstock at temperatures of roughly 200–300 °C (Akdeniz, 2019) however, with respect to poultry manure, wet torrefaction via the use of fluidized bed technology using superheated steam as a fluidizing medium is recommended as it accelerates manure torrefaction by up to four times (Isemin et al., 2019). The product of interest from the process is biochar which can be further upgraded into activated carbon, an intriguing bioproduct with high specific surface area. Although still at the early stages of investigation, Tabet (2021) observed the biochar obtained from wet torrefaction of chicken manure which was subsequently processed into activated carbon. The activated carbon synthesized had relatively exceptional traits as its specific pore surface area and specific volume of pores were 3392 m²/g and 0.841 cm³/g respectively with a particle size of less than 2 nm. Often times, biochar rich in nitrogen acquired from wet torrefaction of poultry manure serves well as a pH absorbent which indicated that it is a prime candidate for application as sorption materials for water purification from heavy metals or from organic pollutants due to the abundance of surface functional groups (Straten et al., 2018).

3. Conclusion

The paper discussed treatment methods for chicken manure which is produced in abundance compared to other poultry manure due to the high demand of chicken meat as a source of protein. One of the treatment routes reviewed is composting which yields compost, favourable to be utilized as a form of organic fertilizer should it be stable and mature however, there are several drawbacks. For instance, composting is a lengthy process which poses a significant biohazard threat if the compost is not stable and mature. Pyrolysis on the other hand has three variations which are slow, fast and flash pyrolysis corresponding to different operating conditions yielding distinct products which are either rich in bio-oil, bio-char or pyrolytic gaseous species. Gasification is also a treatment route for chicken manure with environmental sus-

tainability attributes in comparison to conventional treatment methods. However, the primary disadvantage of both the aforementioned methods are its energetic efficiencies decreases significantly should there be excessive water content in the feedstock which in this case is chicken manure. Consequently, applying these treatment strategies requires an energy consuming pre-drying stage. Anaerobic digestion on the other hand adapts well with feedstock of relatively high-water content such as chicken manure to harness renewable energy in the form of biogas that is rich in CH₄. Future utilization of this approach is also relatively flexible as adapts well with most geographical locations where the temperature is above 15 °C. Hydrothermal liquification and torrefaction on the other hand, are relatively new treatment methods for chicken manure with comparably scarce and limited past research hence, making it a challenge to foresee if applying these methods are economically feasible.

Declaration of Competing Interest

The authors declare no competing interest. Author Rashid Shamsuddin received research grant from the Ministry of Higher Education Malaysia.

Funding

Funding acquired from Fundamental Research Grant Scheme (FRGS/1/2019/TK10/UTP/02/8) awarded by the Ministry of Higher Education Malaysia to provide allowance to postgraduate student.

CRediT authorship contribution statement

M. Devendran Manogaran: Conceptualization, Writing – original draft, Writing – review & editing. **Rashid Shamsuddin:** Conceptualization, Writing – original draft, Writing – review & editing. **Mohd Hizami Mohd Yusoff:** Supervision, Visualization. **Mark Lay:** Writing – review & editing. **Ahmer Ali Siyal:** Writing – review & editing.

Acknowledgement

Fundamental Research Grant Scheme (FRGS/1/2019/TK10/UTP/02/8) from the Ministry of Higher Education Malaysia is acknowledged. The authors also recognize HiCoE's support to Centre for Biofuel and Biochemical Research, Universiti Teknologi PETRONAS.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ccb.2022.100013.

References

- Abdeshahian, P., Lim, J.S., Ho, W.S., Hashim, H., Lee, C.T., 2016. Potential of biogas production from farm animal waste in Malaysia. *Renew. Sustain. Energy Rev.* 60, 714–723. doi:10.1016/j.rser.2016.01.117.
- Ahmad, M., 2015. Food consumption patterns: findings from the Malaysian Adults Nutrition Survey (MANS) 2014. *Med. J. Malays.* 70.
- Ahmad, M.A.A., 2010. Production of Biogas from Poultry Manure. Universiti Malaysia Pahang (UMP).
- Akdeniz, N., 2019. A systematic review of biochar use in animal waste composting. *Waste Manag.* 88, 291–300. doi:10.1016/j.wasman.2019.03.054.
- Al Armi, S., 2018. Comparison of slow and fast pyrolysis for converting biomass into fuel. *Renew. Energy* 124, 197–201. doi:10.1016/j.renene.2017.04.060.
- Amit, T.A., Roy, R., Raynie, D.E., 2021. Thermal and structural characterization of two commercially available technical lignins for potential depolymerization via hydrothermal liquefaction. *Curr. Res. Green Sustain. Chem.* 4, 100106. doi:10.1016/j.crgsc.2021.100106.
- Angouria-Tsorochidou, E., Thomsen, M., 2021. Modelling the quality of organic fertilizers from anaerobic digestion – comparison of two collection systems. *J. Clean. Prod.* 304, 127081. doi:10.1016/j.jclepro.2021.127081.
- Appels, L., Baeyens, J., Degreve, J., Dewil, R., 2008. Principles and potential of the anaerobic digestion of waste-activated sludge. *Prog. Energy Combust. Sci.* 34 (6), 755–781. doi:10.1016/j.pecc.2008.06.002.
- Appels, L., Lauwers, J., Degreve, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J., Dewil, R., 2011. Anaerobic digestion in global bio-energy production: potential and research challenges. *Renew. Sustain. Energy Rev.* 15 (9), 4295–4301. doi:10.1016/j.rser.2011.07.121.
- Arena, U., Ardolino, F., Di, G.F., 2015. A life cycle assessment of environmental performances of two combustion- and gasification-based waste-to-energy technologies. *Waste Manag.* 41, 60–74. doi:10.1016/j.wasman.2015.03.041.
- Arima, K., Tsuchiyama, Y., Sawatsubashi, T., Kinoshita, M., Ishii, H., 2018. Drying of wet brown coal particles by a steam-fluidized bed dryer. *Dry. Technol.* 36 (6), 664–672. doi:10.1080/07373937.2017.1323337.
- Ayilara, M.S., Olanrewaju, O.S., Babalola, O.O., Odeyemi, O., 2020. Waste management through composting: challenges and potentials. *Sustainability.* 12 (11), 4456.
- Bharathiraja, B., Sudharsana, T., Jayamuthunagai, J., Praveenkumar, R., Chozhavadhan, S., Iyyappan, J., 2018. Biogas production—a review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renew. Sustain. Energy Rev.* 90 (April), 570–582.
- Bi, S., Qiao, W., Xiong, L., Ricci, M., Adani, F., Dong, R., 2019. Effects of organic loading rate on anaerobic digestion of chicken manure under mesophilic and thermophilic conditions. *Renew. Energy* 139, 242–250. doi:10.1016/j.renene.2019.02.083.
- Cao, L., Yu, I.K.M., Xiong, X., Tsang, D.C.W., Zhang, S., Clark, J.H., Hu, C., Ng, Y.H., Shang, J., Ok, Y.S., 2020. Biorenewable hydrogen production through biomass gasification: a review and future prospects. *Environ. Res.* 186, 109547. doi:10.1016/j.envres.2020.109547.
- Cao, L., Zhang, C., Chen, H., Tsang, D.C.W., Luo, G., Zhang, S., Chen, J., 2017. Hydrothermal liquefaction of agricultural and forestry wastes: state-of-the-art review and future prospects. *Bioresour. Technol.* 245, 1184–1193. doi:10.1016/j.biortech.2017.08.196.
- Chandra, R., Takeuchi, H., Hasegawa, T., 2012. Methane production from lignocellulosic agricultural crop wastes: a review in context to second generation of biofuel production. *Renew. Sustain. Energy Rev.* 16 (3), 1462–1476. doi:10.1016/j.rser.2011.11.035.
- Chatterjee, B., Mazumder, D., 2019. Role of stage-separation in the ubiquitous development of Anaerobic Digestion of Organic Fraction of Municipal Solid Waste: a critical review. *Renew. Sustain. Energy Rev.* 104, 439–469. doi:10.1016/j.rser.2019.01.026.
- Chianese, S., Fail, S., Binder, M., Rauch, R., Hofbauer, H., Molino, A., Blasi, A., Musmarra, D., 2016. Experimental investigations of hydrogen production from CO catalytic conversion of tar rich syngas by biomass gasification. *Catal. Today* 277, 182–191. doi:10.1016/j.cattod.2016.04.005.
- Chijioke, N.O., Uddin Khandaker, M., Tikpangi, K.M., Bradley, D.A., 2020. Metal uptake in chicken giblets and human health implications. *J. Food Compos. Anal.* 85, 103332. doi:10.1016/j.jfca.2019.103332.
- Chuenchart, W., Logan, M., Leelayouthayotin, C., Visvanathan, C., 2020. Enhancement of food waste thermophilic anaerobic digestion through synergistic effect with chicken manure. *Biomass Bioenergy* 136, 105541. doi:10.1016/j.biombioe.2020.105541.
- Cahyono, N.A., Shamsuddin, M.R., Ayoub, M., Mansor, N., Isa, N.H.M., Nagoor Gunny, A.A., 2021. Anaerobic co-digestion of chicken manure with energy crop residues for biogas production. *IOP Conf. Ser.* 765 (1), 012044. doi:10.1088/1755-1315/765/1/012044.
- Duan, Y., Awasthi, S.K., Liu, T., Zhang, Z., Awasthi, M.K., 2019. Response of bamboo biochar amendment on volatile fatty acids accumulation reduction and humification during chicken manure composting. *Bioresour. Technol.* 291, 121845. doi:10.1016/j.biortech.2019.121845.
- Elliott, D.C., Hart, T.R., Neuenschwander, G.G., Rotness, L.J., Olarte, M.V., Zacher, A.H., Solantausta, Y., 2012. Catalytic hydroprocessing of fast pyrolysis bio-oil from pine sawdust. *Energy Fuels* 26 (6), 3891–3896. doi:10.1021/ef3004587.
- Castello, D., Pedersen, T.H., Rosendahl, L.A., 2018. Continuous hydrothermal liquefaction of biomass: a critical review. *Ennergies* 11 (11), 3165.
- Ferlito, C., 2020. The poultry industry and its supply chain in Malaysia: challenges from the Covid-19 emergency.
- Godfray, H.C.J., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. *Science* 361 (6399), eaam532410.1126/science.aam5324.
- Godlewska, P., Schmidt, H.P., Ok, Y.S., Oleszczuk, P., 2017. Biochar for composting improvement and contaminants reduction. A review. *Bioresour. Technol.* 246, 193–202. doi:10.1016/j.biortech.2017.07.095.
- Gollakota, A.R.K., Kishore, N., Gu, S., 2018. A review on hydrothermal liquefaction of biomass. *Renew. Sustain. Energy Rev.* 81, 1378–1392. doi:10.1016/j.rser.2017.05.178.
- Gunawan, V.C., Shamsuddin, M.R., Mat Isa, N.H., Julaihi, M.R.M., 2020. Performance analysis of effective microorganisms on chicken manure composting. *Science Eng. Health Stud.* 132–140.
- Gupta, S., Mondal, P., Borugadda, V.B., Dalai, A.K., 2021. Advances in upgradation of pyrolysis bio-oil and biochar towards improvement in bio-refinery economics: a comprehensive review. *Environ. Technol. Innov.* 21, 101276. doi:10.1016/j.eti.2020.101276.
- Hakimi, M., Shamsuddin, R., Pendyala, R., Siyal, A.A., AlMohanadi, H., 2021. Co-anaerobic digestion of chicken manure with the addition of Cymbopogon citratus, Mentha piperita and Citrus sinensis as fly deterrent agents: biogas production and Kinetic study. *Bioresour. Technol. Rep.* 15, 100748. doi:10.1016/j.biteb.2021.100748.
- Hanafiah, M.M., Ansari, I., Chelvam, K., 2022. Life cycle assessment of anaerobic digestion systems: an approach towards sustainable waste management. In: *Sinharoy, A., Lens, P.N.L. (Eds.), Renewable Energy Technologies for Energy Efficient Sustainable Development. Springer International Publishing, Cham, pp. 391–414.*
- Hong, Z., Zhong, F., Niu, W., Zhang, K., Su, J., Liu, J., Li, L., Wu, F., 2020. Effects of temperature and particle size on the compositions, energy conversions and structural characteristics of pyrolysis products from different crop residues. *Energy* 190, 116413. doi:10.1016/j.energy.2019.116413.
- Honus, S., Kumagai, S., Molnár, V., Fedorko, G., Yoshioka, T., 2018. Pyrolysis gases produced from individual and mixed PE, PP, PS, PVC, and PET—Part II: fuel characteristics. *Fuel* 221, 361–373. doi:10.1016/j.fuel.2018.02.075.
- Hu, X., Gholizadeh, M., 2019. Biomass pyrolysis: a review of the process development and challenges from initial researches up to the commercialisation stage. *J. Energy Chem.* 39, 109–143. doi:10.1016/j.jechem.2019.01.024.
- Ibarra, Á., Hita, I., Arandes, J.M., Bilbao, J., 2019. Influence of the composition of raw bio-oils on their valorization in fluid catalytic cracking conditions. *Energy Fuels* 33 (8), 7458–7465. doi:10.1021/acs.energyfuels.9b01527.
- Igbum, O.G., Eloka-Eboka, A.C., Adoga, S., 2019. Feasibility study of biogas energy generation from refuse dump in a community-based distribution in Nigeria. *Int. J. Low Carbon Technol.* 14 (2), 227–233. doi:10.1093/ijlct/ctz011.
- Isemin, R.L., Mikhalev, A.V., Muratova, N.S., Kogh-Tatarenko, V.S., Teplit-skii, Y.S., Buchilko, E.K., Greben'kov, A.Z., Pitsukha, E.A., 2019. Improving the efficiency of biowaste torrefaction. *Therm. Eng.* 66 (7), 521–526. doi:10.1134/S0040601519070048.
- Islam, M.W., 2020. A review of dolomite catalyst for biomass gasification tar removal. *Fuel* 267, 117095. doi:10.1016/j.fuel.2020.117095.
- Jahn, L., Baumgartner, T., Krampe, J., Svardal, K., 2020. Effect of NH₃ and organic loading on the inhibition of mesophilic high-solid digestion. *J. Chem. Technol. Biotechnol.* 95 (3), 702–709. doi:10.1002/jctb.6252.
- Janajreh, I., Adeyemi, I., Raza, S.S., Ghenai, C., 2021. A review of recent developments and future prospects in gasification systems and their modeling. *Renew. Sustain. Energy Rev.* 138, 110505. doi:10.1016/j.rser.2020.110505.
- Jena, U., McCurdy, A.T., Warren, A., Summers, H., Ledbetter, R.N., Hoekman, S.K., Seefeldt, L.C., Quinn, J.C., 2015. Oleaginous yeast platform for producing bio-fuels via co-solvent hydrothermal liquefaction. *Biotechnol. Biofuels* 8 (1), 167. doi:10.1186/s13068-015-0345-5.
- Jones, D., 2021. Global electricity review 2021.
- Kan, T., Strezov, V., Evans, T.J., 2016. Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. *Renew. Sustain. Energy Rev.* 57, 1126–1140. doi:10.1016/j.rser.2015.12.185.
- Khan, M.A., Ngo, H.H., Guo, W.S., Liu, Y., Nghiem, L.D., Hai, F.I., Deng, L.J., Wang, J., Wu, Y., 2016. Optimization of process parameters for production of volatile fatty acid, biohydrogen and methane from anaerobic digestion. *Bioresour. Technol.* 219, 738–748. doi:10.1016/j.biortech.2016.08.073.
- Kremp, F., Poehlein, A., Daniel, R., Müller, V., 2018. Methanol metabolism in the acetogenic bacterium *Acetobacterium woodii*. *Environ. Microbiol.* 20 (12), 4369–4384. doi:10.1111/1462-2920.14356.
- Kumaran, P., Hephzibah, D., Sivasankari, R., Saifuddin, N., Shamsuddin, A.H., 2016. A review on industrial scale anaerobic digestion systems deployment in Malaysia: opportunities and challenges. *Renew. Sustain. Energy Rev.* 56, 929–940. doi:10.1016/j.rser.2015.11.069.
- Lacy, P., Rutqvist, J., 2016. *Waste to Wealth: the Circular Economy Advantage. Springer.*
- Lee, C.C., Xing, W., Lee, C.C., 2022. The impact of energy security on income inequality: the key role of economic development. *Energy* 248, 123564. doi:10.1016/j.energy.2022.123564.
- Lee, J., Choi, D., Ok, Y.S., Lee, S.R., Kwon, E.E., 2017. Enhancement of energy recovery from chicken manure by pyrolysis in carbon dioxide. *J. Clean. Prod.* 164, 146–152. doi:10.1016/j.jclepro.2017.06.217.
- Lee, S.Y., Sankaran, R., Chew, K.W., Tan, C.H., Krishnamoorthy, R., Chu, D.T., Show, P.L., 2019. Waste to bioenergy: a review on the recent conversion technologies. *BMC Energy* 1 (1), 4. doi:10.1186/s42500-019-0004-7.
- Li, J., Wang, X., Cong, C., Wan, L., Xu, Y., Li, X., Hou, F., Wu, Y., Wang, L., 2020. Inoculation of cattle manure with microbial agents increases efficiency and promotes maturity in composting. *3 Biotech* 10 (3), 128. doi:10.1007/s13205-020-2127-4.
- Luo, X., Liu, G., Xia, Y., Chen, L., Jiang, Z., Zheng, H., Wang, Z., 2017. Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. *J. Soils Sediments.* 17 (3), 780–789. doi:10.1007/s11368-016-1361-1.

- Manogaran, M.D., Mansor, N., Noor Affendi, N.M., Baloo, L., Salehuddin, N.F., 2020. Optimisation of diallyl disulfide concentration and effect of soil condition on urease inhibition. *Plant Soil Environ.* 66 (2), 81–85. doi:10.17221/617/2019-PSE.
- Maya, D.M.Y., Sarmiento, A.L.E., Andrade, R., 2016. Gasification of municipal solid waste for power generation in Brazil, a review of available technologies and their environmental benefits. *J. Chem. Chem. Eng.* 10 (6), 49–55.
- Mustafi, N.N., Miraglia, Y.C., Raine, R.R., Bansal, P.K., Elder, S.T., 2006. Spark-ignition engine performance with 'Powergas' fuel (mixture of CO/H₂): a comparison with gasoline and natural gas. *Fuel* 85 (12), 1605–1612. doi:10.1016/j.fuel.2006.02.017.
- Mutungwazi, A., Ijoma, G.N., Matambo, T.S., 2021. The significance of microbial community functions and symbiosis in enhancing methane production during anaerobic digestion: a review. *Symbiosis* 83 (1), 1–24. doi:10.1007/s13199-020-00734-4.
- Nematbakhsh, S., Selamat, J., Idris, L.H., Abdull Razis, A.F., 2021. Chicken authentication and discrimination via live weight, body size, carcass traits, and breast muscle fat content clustering as affected by breed and sex varieties in Malaysia. *Foods* 10 (7), 1575.
- Ore, O.T., Adebisi, F.M., 2021. A review on current trends and prospects in the pyrolysis of heavy oils. *J. Petrol. Explor. Prod.* 11 (3), 1521–1530. doi:10.1007/s13202-021-01099-0.
- Othman, A., Ruslan, N., 2020. Intercultural communication experiences among students and teachers: implication to in-service teacher professional development. *J. Multicult. Educ.* 14 (3/4), 223–238. doi:10.1108/JME-04-2020-0024.
- Pane, C., Spaccini, R., Piccolo, A., Celano, G., Zaccardelli, M., 2019. Disease suppressiveness of agricultural greenwaste composts as related to chemical and bio-based properties shaped by different on-farm composting methods. *Biol. Control* 137, 104026. doi:10.1016/j.biocontrol.2019.104026.
- Pardo, G., Moral, R., Aguilera, E., del Prado, A., 2015. Gaseous emissions from management of solid waste: a systematic review. *Glob. Change Biol.* 21 (3), 1313–1327. doi:10.1111/gcb.12806.
- Patel, A., Agrawal, B., Rawal, B.R., 2020. Pyrolysis of biomass for efficient extraction of biofuel. *Energy Sources Part A* 42 (13), 1649–1661. doi:10.1080/15567036.2019.1604875.
- Patra, T.K., Sheth, P.N., 2015. Biomass gasification models for downdraft gasifier: a state-of-the-art review. *Renew. Sustain. Energy Rev.* 50, 583–593. doi:10.1016/j.rser.2015.05.012.
- Pose-Juan, E., Igual, J.M., Sánchez-Martín, M.J., Rodríguez-Cruz, M.S., 2017. Influence of herbicide triasulfuron on soil microbial community in an unamended soil and a soil amended with organic residues. *Front. Microbiol.* 8 (378). doi:10.3389/fmicb.2017.00378.
- Safarian, S., Unnpörsson, R., Richter, C., 2019. A review of biomass gasification modelling. *Renew. Sustain. Energy Rev.* 110, 378–391. doi:10.1016/j.rser.2019.05.003.
- Sánchez, Ó.J., Ospina, D.A., Montoya, S., 2017. Compost supplementation with nutrients and microorganisms in composting process. *Waste Manag.* 69, 136–153. doi:10.1016/j.wasman.2017.08.012.
- Selvarajoo, A., 2021. Slow pyrolysis of Durio zibethinus rind and the influence of carbonization temperature on biochar properties. *IOP Conference Series: Materials Science and Engineering*, 1092. doi:10.1088/1757-899x/1092/1/012042.
- Shah, Y.T., 2015. *Energy and Fuel Systems Integration*. CRC Press.
- Shamsuddin, R., Singh, G., Kok, H.Y., Hakimi Rosli, M., Dawi Cahyono, N.A., Lam, M.K., Lim, J.W., Low, A., 2021. Palm oil industry—processes, by-product treatment and value addition. In: Inamuddin, Khan, A. (Ed.), *Sustainable Bioconversion of Waste to Value Added Products*. Springer International Publishing, Cham, pp. 121–143.
- Singh, G., Shamsuddin, M., Lim, S., 2018. Characterization of chicken manure from manung region. Paper Presented at the IOP Conference Series: Materials Science and Engineering.
- Straten, J.W., Schleker, P., Krasowska, M., Veroutis, E., Granwehr, J., Auer, A.A., Hetaba, W., Becker, S., Schlögl, R., Heumann, S., 2018. Nitrogen-functionalized hydrothermal carbon materials by using urotropine as the nitrogen precursor. *Chem. Commun.* 2018, 12298–12317. doi:10.1002/chem.201800341.
- Szuhaj, M., Ács, N., Tengöics, R., Bodor, A., Rákhely, G., Kovács, K.L., Bagi, Z., 2016. Conversion of H₂ and CO₂ to CH₄ and acetate in fed-batch biogas reactors by mixed biogas community: a novel route for the power-to-gas concept. *Biotechnol. Biofuels* 9 (1), 102. doi:10.1186/s13068-016-0515-0.
- Tabet, F., 2021. Production of activated carbon from biochar obtained by wet torrefaction of chicken manure as sole feedstock, and in mixture with sawdust in a fluidized bed powered with superheated steam. *Chem. Eng. Trans.* 86, 1519. doi:10.3303/CET2186254.
- Talevi, M., Pattanayak, S.K., Das, I., Lewis, J.J., Singha, A.K., 2022. Speaking from experience: preferences for cooking with biogas in rural India. *Energy Econ.* 107, 105796. doi:10.1016/j.eneco.2021.105796.
- Tańczuk, M., Junga, R., Kolasz-Więcek, A., Niemiec, P., 2019a. Assessment of the energy potential of chicken manure in Poland. *Energies* 12 (7), 1244.
- Tańczuk, M., Junga, R., Werle, S., Chabiński, M., Ziółkowski, L., 2019b. Experimental analysis of the fixed bed gasification process of the mixtures of the chicken manure with biomass. *Renew. Energy* 136, 1055–1063. doi:10.1016/j.renene.2017.05.074.
- Tuomela, M., Vikman, M., Hatakka, A., Itävaara, M., 2000. Biodegradation of lignin in a compost environment: a review. *Bioresour. Technol.* 72 (2), 169–183. doi:10.1016/S0960-8524(99)00104-2, [https://doi.org/10.1016/S0960-8524\(99\)00104-2](https://doi.org/10.1016/S0960-8524(99)00104-2).
- Uddin, M.N., Techato, K., Taweekun, J., Rahman, M.M., Rasul, M.G., Mahlia, T.M.I., Ashrafur, S.M., 2018. An overview of recent developments in biomass pyrolysis technologies. *Energies* 11 (11), 3115.
- Uyizeye, O.C., 2019. Effects of community-accessible biochar and compost on diesel-contaminated soil. *Biorem. J.* 23 (2), 107–117. doi:10.1080/1088968.2019.1603139.
- Van de Velden, M., Baeyens, J., Brems, A., Janssens, B., Dewil, R., 2010. Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction. *Renew. Energy* 35 (1), 232–242. doi:10.1016/j.renene.2009.04.019.
- Venderbosch, R., Prins, W., 2010. Fast pyrolysis technology development. *Biofuels Bioprod. Biorefin.* 4 (2), 178–208. doi:10.1002/bbb.205.
- Ventorino, V., Pascale, A., Fagnano, M., Adamo, P., Faraco, V., Rocco, C., Fiorentino, N., Pepe, O., 2019. Soil tillage and compost amendment promote bioremediation and biofertility of polluted area. *J. Clean. Prod.* 239, 118087. doi:10.1016/j.jclepro.2019.118087.
- Vilas-Boas, A.C.M., Tarelho, L.A.C., Kamali, M., Hauschild, T., Pio, D.T., Jahaniyanfard, D., Gomes, A.P.D., Matos, M.A.A., 2021. Biochar from slow pyrolysis of biological sludge from wastewater treatment: characteristics and effect as soil amendment. *Biofuels Bioprod. Biorefin.* 15 (4), 1054–1072. doi:10.1002/bbb.2220.
- Wang, K., Yin, X., Mao, H., Chu, C., Tian, Y., 2018. Changes in structure and function of fungal community in cow manure composting. *Bioresour. Technol.* 255, 123–130. doi:10.1016/j.biortech.2018.01.064.
- Wani, I., Sharma, A., Kushvaha, V., Madhushri, P., Peng, L., 2020. Effect of pH, volatile content, and pyrolysis conditions on surface area and O/C and H/C ratios of biochar: towards understanding performance of biochar using simplified approach. *J. Hazard. Toxic Radioactive Waste* 24 (4), 04020048. doi:10.1061/(ASCE)HZ.2153-5515.0000545.
- Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L., 2008. Optimisation of the anaerobic digestion of agricultural resources. *Bioresour. Technol.* 99 (17), 7928–7940. doi:10.1016/j.biortech.2008.02.044.
- Widjaya, E.R., Chen, G., Bowtell, L., Hills, C., 2018. Gasification of non-woody biomass: a literature review. *Renew. Sustain. Energy Rev.* 89, 184–193. doi:10.1016/j.rser.2018.03.023.
- Wongarmat, W., Reungsang, A., Sittijunda, S., Chu, C.Y., 2021. Anaerobic co-digestion of biogas effluent and sugarcane filter cake for methane production. *Biomass Convers. Biorefin.* 12 (3), 1–12. doi:10.1007/s13399-021-01305-3.
- Wu, H., Hanna, M.A., Jones, D.D., 2013. Life cycle assessment of greenhouse gas emissions of feedlot manure management practices: land application versus gasification. *Biomass Bioenergy* 54, 260–266. doi:10.1016/j.biombioe.2013.04.011.
- Xin, X., Bissett, A., Wang, J., Gan, A., Dell, K., Baroutian, S., 2021. Production of liquid smoke using fluidised-bed fast pyrolysis and its application to green lipped mussel meat. *Food Control* 124, 107874. doi:10.1016/j.foodcont.2021.107874.
- Xu, C., Nasrollahzadeh, M., Selva, M., Issaabadi, Z., Luque, R., 2019. Waste-to-wealth: biowaste valorization into valuable bio(nano)materials. *Chem. Soc. Rev.* 48 (18), 4791–4822. doi:10.1039/C8CS00543E.
- Xu, X., Sun, Y., Sun, Y., Li, Y., 2022. Bioaugmentation improves batch psychrophilic anaerobic co-digestion of cattle manure and corn straw. *Bioresour. Technol.* 343, 126118. doi:10.1016/j.biortech.2021.126118.
- Yin, D.M., Westerholm, M., Qiao, W., Bi, S.J., Wandera, S.M., Fan, R., Jiang, M.M., Dong, R.J., 2018. An explanation of the methanogenic pathway for methane production in anaerobic digestion of nitrogen-rich materials under mesophilic and thermophilic conditions. *Bioresour. Technol.* 264, 42–50. doi:10.1016/j.biortech.2018.05.062.
- You, S., Ok, Y.S., Tsang, D.C.W., Kwon, E.E., Wang, C.H., 2018. Towards practical application of gasification: a critical review from syngas and biochar perspectives. *Crit. Rev. Environ. Sci. Technol.* 48 (22–24), 1165–1213. doi:10.1080/10643389.2018.1518860.
- You, S., Wang, W., Dai, Y., Tong, Y.W., Wang, C.H., 2016. Comparison of the co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification and incineration-based waste treatment schemes. *Bioresour. Technol.* 218, 595–605. doi:10.1016/j.biortech.2016.07.017.
- Yu, M., Zhang, J., Xu, Y., Xiao, H., An, W., Xi, H., Xue, Z., Huang, H., Chen, X., Shen, A., 2015. Fungal community dynamics and driving factors during agricultural waste composting. *Environ. Sci. Pollut. Res.* 22 (24), 19879–19886.
- Zhang, L., Li, L., Pan, X., Shi, Z., Feng, X., Gong, B., Li, J., Wang, L., 2018. Enhanced growth and activities of the dominant functional microbiota of chicken manure composts in the presence of maize straw. *Front. Microbiol.* 9 (1131). doi:10.3389/fmicb.2018.01131.
- Zhang, L., Sun, X., 2016. Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste. *Waste Manag.* 48, 115–126. doi:10.1016/j.wasman.2015.11.032.
- Zhang, W., Maleki, A., Rosen, M.A., 2019. A heuristic-based approach for optimizing a small independent solar and wind hybrid power scheme incorporating load forecasting. *J. Clean. Prod.* 241, 117920. doi:10.1016/j.jclepro.2019.117920.
- Zhu, D., Mortazavi, S.M., Maleki, A., Aslani, A., Yousefi, H., 2020. Analysis of the robustness of energy supply in Japan: role of renewable energy. *Energy Rep.* 6, 378–391. doi:10.1016/j.egy.2020.01.011.
- Zubair, M., Wang, S., Zhang, P., Ye, J., Liang, J., Nabi, M., Zhou, Z., Tao, X., Chen, N., Sun, K., Xiao, J., Cai, Y., 2020. Biological nutrient removal and recovery from solid and liquid livestock manure: recent advance and perspective. *Bioresour. Technol.* 301, 122823. doi:10.1016/j.biortech.2020.122823.