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Biomethanation of Crop Residues to Combat Stubble Burning in India: Design and Simulation Using ADM1 Mathematical Model

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Abstract: Stubble burning in India continues despite the severe consequences on the environment and the massive health crisis in the country. Farmers resort to such practices as a cheap and hasty solution post-harvest, which helps them prepare for their next crops. This study employs a mathematical model, the ADM1 (Anaerobic Digestion Model No. 1), to design a virtual biogas plant in the SIMBA simulation platform. The plant was designed keeping the small-scale farmers in mind, hence, cost-effectiveness, simplicity in design and operation remained a priority. Simulations were performed with different crop leftovers that are widely subjected to on-farm burning in the country such as from rice, wheat, sugarcane, cotton and maize. Simulation trials were performed for each crop residue for nearly two years, to observe the digester performance and possible disruptions over prolonged periods. The optimal feeding ratio and operating conditions for process stability were determined. Simulations revealed generation of nearly 9–10 m^3 methane per day, equivalent to 90–100 kWh electricity. Co-fermentation with animal manures was strongly recommended by the model for process stability and to avoid pH disruptions due to organic acid accumulations. Policy makers and farmers are, thus, encouraged to explore a sustainable alternative to generate energy from stubble.

Keywords: biogas; Anaerobic Digestion Model No. 1 (ADM1); crop residue; stubble burning; mathematical modelling

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1. Introduction

The practice of crop residue burning in India, its impact on deteriorating the air quality and the ecosystem as well as the damage on human health, requires no introduction. India, being one of the largest agricultural lands in the world, holds 157.35 million hectares of land for cultivation [1]. Obviously, along with the several million tons of agricultural produce each year, there remains a huge volume of agricultural leftovers on the fields. An estimated 500–550 million tons of crop residues are produced every year in the country [2] primarily from rice, wheat and millet (forming nearly 70% of the total stubble) while the rest are from sugarcane, cotton, maize, ground nut etc. [3].

While a considerable share of this finds application as animal feed, animal bedding, in thatched roofs etc., a larger portion (nearly 3/4th) remains as waste on the farmlands. Collecting agricultural residues, transporting and storing them becomes labour intensive, expensive and inconvenient especially for the small-scale farmers due to a short window of less than a month to prepare for the next crop [4]. A quick fix solution to manage these huge volumes of agricultural residue is to directly set them on fire. Reports indicate that as much as 23 million tons of stubble alone from rice straw are burnt in North India each year [5]. Such on-farm burning remains a cost-effective approach for the famers, clears the farm for re-use along with providing pest control.

1.1. Consequences of Stubble Burning

The consequence of this broadly favoured practice undeniably is dangerously high levels of air pollution that has even contributed in declaring a public health emergency situation in Delhi [6,7]. Increase in the particulate matter, PM10 and PM2.5 concentrations, when the crop leftovers are burnt on the farm, is also of particular concern to human health [8,9]. Reports show an increase in the particulate matter by 86.7% after the rice harvest, and by 53.2% after the wheat harvest, when the stubble burning occurs in Punjab [8]. The air is then termed anything from toxic to poisonous, with PM2.5 concentrations reaching up to more than 10 times above the WHO air quality guidelines [10]. The northern Indian states, especially the urban areas, even if hundreds of kilometers away, suffer the severe impact of such on-farm burning, especially in winter, due to the already accumulated industrial and vehicular pollutants [7]. Poor visibility is yet another aftermath of such open-fire practices in the NCR (National Capital Region), which has further been linked to numerous road accidents. Along with the serious pollution, it has, also, been connected to a drop in tourism by nearly 25–30% [11].

Recent studies by Venkatamanan et al. [12] calculated the generation of nearly 313.9 Gg of methane, a powerful greenhouse gas, along with heavy quantities of CO_2, CO, NH_3 and N_2O as well as several million tons of PM2.5 and PM10 from stubble burning over northwestern India. Emissions of CO and NO_2 have also been recorded to increase by 7–25% and 22–80%, respectively, across India during crop burning [13]. The release of short-lived climate pollutants, aerosols and soot particles, due to stubble burning, has also been extensively studied and reported [14]. Furthermore, the disturbance in atmospheric chemistry and radiation balance, due to the organic components, such as benzene and polycyclic aromatic hydrocarbons added into the ambient air during stubble burning, have also been confirmed [15,16].

When air quality deteriorates to such an extent, its severe impact on the public health is inevitable, and various studies confirm the same by linking stubble burning to human health deterioration. A study by the Health Effects Institute has attributed about 66,000 deaths in India, due to the PM released as a result of stubble burning [17]. The population faces severe risks of lung complications such as bronchitis, asthma, Chronic Obstructive Pulmonary Disease (COPD), cancer, etc. [18]. Such air quality not only poses a threat to the ones with pre-existing respiratory conditions but also to healthy adults, and has been linked to cardiovascular, neurological and dermatological issues [7]. Current studies, also, indicate poor air quality directly proportional to increasing COVID-19 cases and are associated with high mortality rates [19,20].

The practice of stubble burning does not limit its damaging effects to air, but has also been linked with deteriorating the soil fertility, damaging the microbial population and ecosystem and unbalancing the nutrient budget (resulting in severe nutrient loss), which naturally induce economic losses. The National Academy of Agricultural Sciences reports that the result of open burning only in northwest India accounts for the loss of carbon and nitrogen accounting, roughly, to nearly a loss of INR 2 billion each year [21]. Studies by IFPR (International Food Policy Research) estimated in North India alone, air pollution co-related to stubble burning contributed to a loss of approximately USD 30 billion per year [22]. Scientists and the government are trying to address the stubble menace, but the challenge seems to keep increasing, as more and more farmers choose this option. There is an urgent need for a solution that converts the perspective of considering the agricultural leftovers as a resource and not a waste-product, one that brings additional income and improves soil quality, which further helps the farmers. Due to the absence of an economic or meaningful benefit, farmers continue to choose to set their farms on fire, lacking a useful alternative.

1.2. Biogas/Biomethane from Stubble

Utilising and consuming the enormous quantities of low-cost crop residues can enable effective crop residue management, agreeing with the principles of the circular economy. In India, rice and wheat comprise a major share of the total stubble burnt, 34% and 22%, respectively [11]. While gasifiers have been widely recommended to generate energy from agricultural leftovers [23], biogas, a renewable, carbon-neutral source of energy, has an added advantage of requiring lesser investments in comparison, plus the digester maintenance and operation are relatively simple [24]. During the process of anaerobic digestion, organic matter is converted to a mixture of energy-rich methane (that constitute 50–70% of the total gas), along with carbon dioxide and other gases in traces, thus extracting the energy potential of the substrates. Biogas is a generic term for the gases produced during anaerobic digestion, and the main gases contained are methane and carbon dioxide. The designation biomethane is used to describe the methane part derived from biomass [25]. Biogas can be upgraded to increase the methane content (between 75–99%), by a process of biomethanation, also called biomethane production [26,27]. Different upgrading and scrubbing methods are utilised to enrich the gas to natural-gas quality, which could be used as a vehicle fuel or fed into grids. Since the supply of such bioenergy usually exceeds the on-site demand, they can, also, be stored in the form of liquified biomethane (LBM) or compressed biomethane (CBM). These could be utilised in LNG- and CNG-run vehicles, respectively. In recent years, 'sector coupling' has been, also, gaining momentum, by coupling electricity and gas sectors, where excess electricity stored as H_2 (from water electrolysis usually) is coupled with CO_2 (from biogas plants, landfills etc.) to produce CH_4 [28], also known as power-to-gas (P2G) technology. P2G enables efficient energy storage and enables a bidirectional coupling of electricity (preferably generated from renewable sources) with natural gas grids [29]. With the various advancements in technologies that are available, biogas or the upgraded biomethane formed from the agricultural wastes could benefit small-, medium- and large-scale farmers or industries, based on their individual requirements and capacities. Additionally, the digestate produced in biogas digesters are excellent soil conditioners, recycling and retaining the nutrients such as nitrogen (N), phosphorous (P), and potassium (K), maintaining a healthy humus content in soil. Such an approach can, thus, provide economic benefits to the farmers along with offering environmental protection and effective stubble management [30].

Despite being a sustainable and cost-effective method, the biogas sector in India remains with a large untapped potential. While the rural sector accommodates the maximum number of biogas plants, awareness regarding substrate utilization remains limited to only cattle dung, and the output remains limited to a cooking fuel substitute [31]. Biogas digesters throughout the country suffer reactor failures due to inadequate knowledge, lack of attention paid to regular maintenance and poor dissemination of information and technology [32]. This study intends to broaden the scope of substrate utilization, especially for the small-scale/individual farmers in India, who could co-ferment their animal manures along with the carbohydrate-rich crop leftovers, and the research goal enquired if stubble could be a favorable biogas substrate. Numerous researchers have attempted to determine the biomethane potential of the lignocellulosic crop residues, and the results have been encouraging with polysaccharide-rich substrates. Considering the two major crops subjected to stubble burning, rice and wheat, studies report a methane potential of nearly 390 L/kg vs. [33] and 240 L/kg vs. [34], respectively. These values are comparable to energy crops utilised in large-scale industrial biogas plants for generating energy [35].

Our attempt in this study was to approach towards a waste-to-energy concept, i.e., generation of biomethane from the agricultural crop leftovers, using a mathematical model. A virtual standardised biogas plant was prepared with the help of the Anaerobic Digestion Model No.1 (ADM1) mathematical model. The biomethane potential of different crop residues, typically prone to stubble burning in India, such as from rice, wheat, maize, sugarcane and cotton, was assessed in the SIMBA simulation platform with MATLAB/Simulink software. Substrate characteristics for each crop residue were considered from the literature data, and simulations were performed by feeding each substrate into the designed biogas plant. Several scenarios were compared, and the optimal operational conditions, digester conditions in different scenarios, possible inhibitions and challenges during long-term operation were assessed on the simulation platform. Simulations were performed to outline the most suitable conditions fitting the Indian context, to generate maximum methane from the crop residues left behind every year.

2. Results and Discussion

Mathematical simulations indicated that an encouraging biomethane potential could be expected from the agricultural leftovers or waste. The ADM1 model also was instrumental in designing the standard plant and determining the ideal operational parameters for optimal performance, to limit inhibitions in the longer run. Sudden biogas plant failures due to inhibitory effects are a very common challenge in numerous small-scale biogas units in India, which outweigh the benefits of owning or operating such a plant. This, predominantly, discourages users to consider biogas energy as an option, despite being an environmentally friendly option [32].

The model recommended primarily two things for an optimised performance with such complex, difficult-to-degrade substrates. One was to co-ferment with animal manures, to maintain a high-buffering capacity that prevents pH irregularities in the digester. Previous studies indicate the benefits of co-fermentation of agricultural substrates with animal manures, in enabling stable operation due to the strong buffering capacities offered by manures, which further results in improved methane generation [36]. Co-digestion of manures with agricultural products has demonstrated improved methane yields from 38% to as high as 114%, based on the feedstock and type of manure considered [37,38]. In our case as well, we saw the digester performance improving and attaining stable conditions, when an animal buffer was used along with the carbohydrate-rich crop residues. The other was to feed the plant gradually at least six times, in order to avoid substrate overload. The plant performance significantly improved when fed six times during the course of the day, rather than being fed once or even thrice. When fed with the substrate all at once, volatile fatty acid accumulations (especially of acetic and lactic acid) occurred, which caused digester breakdown within two–three months of operation during the simulation trial. This was solved when the feed volumes were equally divided and fed at regular intervals. The organic load was then, relatively, balanced, and the risks of acid accumulations could be decreased, and the digester operated under stable conditions. Since the biogas plant was designed with a model of keeping small-scale farmers and a cost-effective design in mind, we recommend the commonly built 'fixed dome' or 'floating drum' digesters [39].

Different quantities were attempted to determine the ideal feed quantities for a stable digester operation and optimal performance. Simulations indicated a minimum of 0.1 m^3/d of animal manure in the biogas plant, failing, which the digester resulted in the pH dropping to a value of 4.0. Such low pH values cause severe acid inhibition for the micro-organisms, which, ultimately, leads to complete digester breakdown. Manures, as discussed earlier, have an excellent buffering capacity that prevents pH fluctuations [30].

After numerous trials with all the substrates, to prepare a standardised model that could be applied to other substrates as well, the animal manure was kept constant at 0.1 m^3/d, and different volumes of crop residues were added to determine the ideal ratio with the co-ferment. The goal remained to attain maximum methane concentrations and stability in the biogas digesters in the longer run, so as to prepare a biogas plant that is easy to operate and maintain.

2.1. Methane Production with Rice-Crop Residue

The ADM1 model predicted a stable operation, with rice-crop residue demonstrating a maximum total biogas production of nearly 17.5 m^3, out of which 8.9 m^3 was the methane volume (51%) in the designed farm-scale biogas digester (Figure 1). Increasing the rice-straw-feed volumes resulted in increasing methane production, only until a maximum addition of 0.05 m^3/d, beyond which, there was an abrupt digester breakdown after nearly two months of operation. As clearly seen in Figure 1, feeding a volume higher than 0.06 m^3/d was motivating at the initial stages and provided remarkably higher yields of methane. However, the methane production was misleading at the beginning, since it gradually reduced with time and, then, resulted in an abrupt digester failure. This is a common phenomenon, frequently occurring in real scenarios, and operators struggle to comprehend the reason behind such unexpected system failures. The ADM1 model was investigated further, to understand the cause behind such an occurrence, and organic acid accumulations were determined to be the reason behind it. The model fractions indicated an accumulation of metabolic intermediates during carbohydrate fermentation, such as acetic acid (at a concentration of nearly 12,500 mg L^{-1}), propionic acid, lactic acid, butyric acid, etc. (at concentrations above 5000 mg L^{-1}), which when accumulated and led to the reactor failure. The state of a biogas digester can be reliably interpreted, considering the pH values. In the model, a separate block is utilised to determine the pH values in the anaerobic digester, at any point of time during the simulation trial. The pH values data provided an insight into the reason behind the digester disruptions, beyond a certain feed quantity (0.05 m^3/d in this case), for rice crop residue. As seen in Figure 2, a value between 6.5–7, which is regarded as ideal [40], was maintained in the reactor with all the substrate loads until 0.05 m^3/d, and this could explain the stable performance in the digester. However, when the feeding volumes were increased beyond this, there was a certain point until which the pH was maintained, assumed to be due to the buffering capacity offered by animal manures. However, after nearly 160 days of being constantly fed, the pH eventually dropped to values below 4, the point where methane production abruptly dropped as-well (Figure 1). Heavy acid accumulation leading to a pH drop causes toxicity in the anaerobic digester, thus damaging the microbial population and ecology. Digester acidifications have been reported to cause biogas plant failures in the long run, in numerous studies [41]. In such situations, biogas plants are usually recommended to reduce the organic loading, so as to balance the pH inside the digester back to good health.

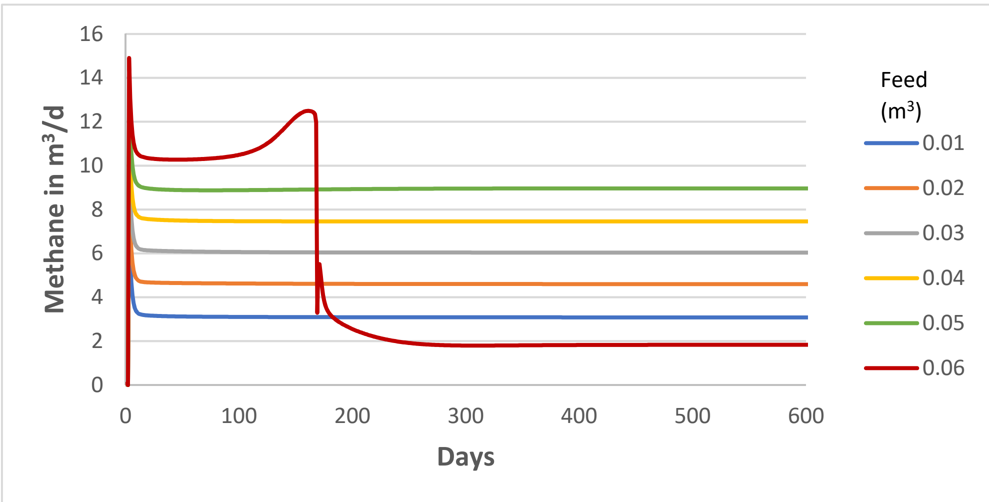

Figure 1. Methane production in the standard biogas plant with different volumes of rice crop residue co-fermented with 100 kg of animal manure.

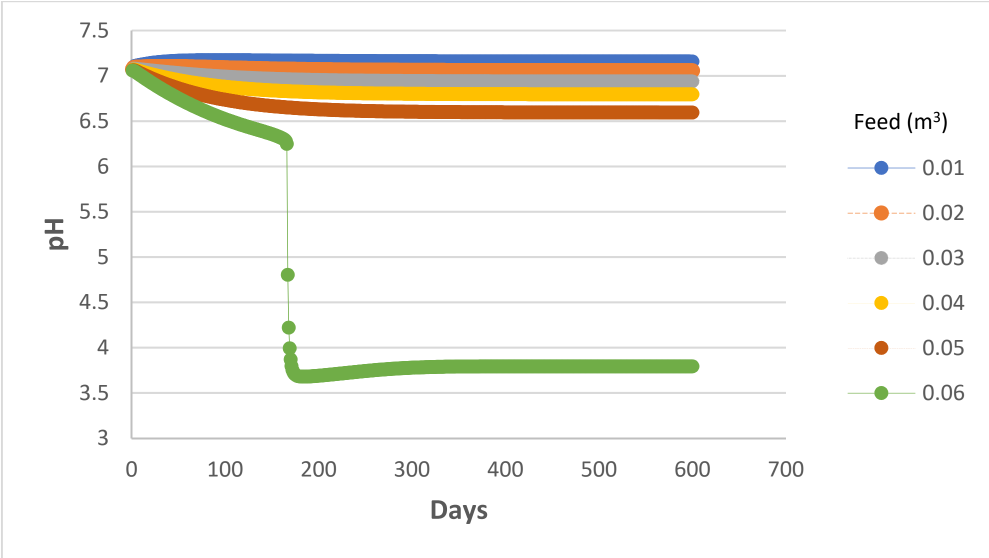

Figure 2. pH values inside the standard biogas digester predicted by the ADM1 model, with different volumes of rice crop residue co-fermented with 100 kg of animal manure.

2.2. Methane Production with Wheat Straw

The virtual biogas plant was designed to test different types of agricultural residues that are openly burnt in India. When tested with wheat stubble, similar trends were observed, where the digester demonstrated a maximum tolerance of 0.04 m^3/d, a slightly lower substrate load than rice stubble, mixed with 0.1 m^3/d of animal manure. When the feed load was increased to 0.05 m^3/d, there, again, was an initial boost in the methane production, which eventually dramatically collapsed within two months of operation in the virtual run (Figure 3). The initial inflection could be explained by the model fractions to be due to an active growth of the biomass, especially the sugar degraders and increasing volatile fatty acid concentrations, which further led to the growth of the respective acid degraders. However, after a few months, the model demonstrated pH drops, such as with rice stubble, due to acid accumulation, especially of acetic acid, which reached a bottleneck and could not be further converted to methane. Additionally, lactic and butyric acid accumulations were also foreseen, thus inhibiting and deactivating the whole microbial population, as reflected by the model fractions. Interestingly, the methane production was similar to that with rice stubble, which is around nine m^3 (and 50% of the biogas yield was CO_2). The higher carbohydrate content in wheat stubble (Table 1) could explain the increased methane generation with the relatively decreased substrate load. The digester, also, demonstrated an equally stable operation even during a longer simulation run of almost two years. This, clearly, encourages considering the lignocellulosic crop stubble as a biogas substrate. Pre-treating and hydrolyzing the complex crop stubble is expected to provide increased methane yields [42].

Table 1. Substrate characterization of the substrates and animal manure considered in this study.

Parameter %	Rice Straw [a]	Animal Manure [c]	Wheat Straw [d]	Maize Stalk	Sugarcane Straw [g]	Cotton Stalk [h]
Dry Matter (DM)	93.63 [a]	9	91.4	94.30 [e]	76.7	94.3
Organic Dry Matter (ODM)	69.38 [a]	80	91.1	76.15 [e]	86.3	95.1
Raw Protein	4.62 [b]	0.74	63.0	3.60 [f]	27.7	6.1
Raw Lipid	40.63 [b]	0.17	16.8	0.52 [f]	9.18	1.67
Raw Fibre	39.95 [b]	1.15	79.85	78.5 [f]	70	88.5
Inert fraction	0.3 [a]	0.5	0.08	13.57 [f]	15	4.9

Source: [a] [37], [b] [38], [c] [43], [d] [40], [e] [41], [f] [42], [g] [43], [h] [44].

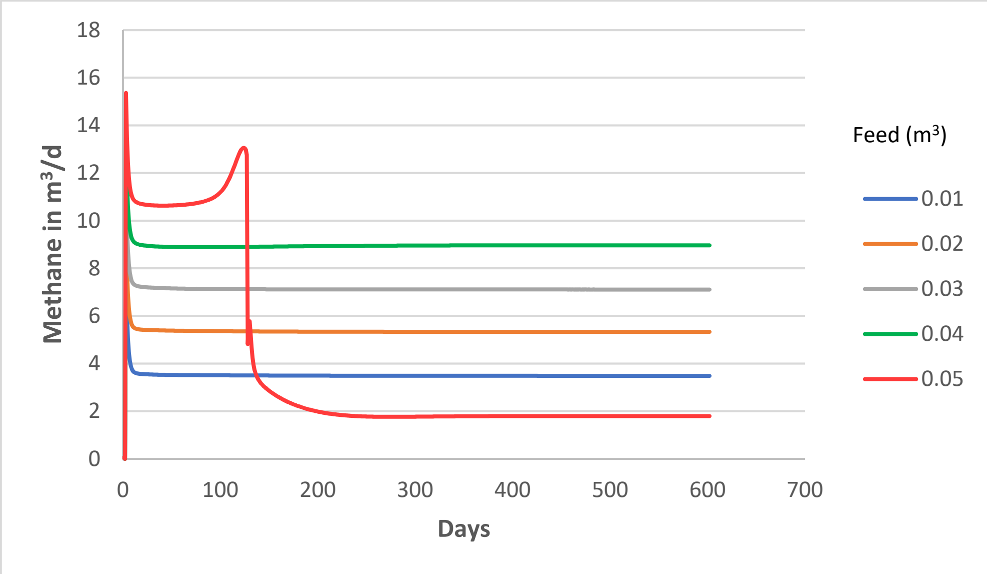

Figure 3. Methane production in the standard biogas plant, with different volumes of wheat crop residue co-fermented with 100 kg of animal manure.

2.3. Methane Production with Crop Residues from Maize, Cotton and Sugarcane

The crop residues such as maize, cotton and sugarcane considered in this study displayed similar trends with stable operation at a pH at around 7, when co-fermented with animal manure. The methane content remained at about 50–51% for each case, which has been widely studied to be reasonable with carbohydrate-rich substrates [44]. Sugarcane crop residue, straw in this case, provided a methane production of nearly 9.11 m^3, when the reactor was fed maximum with 0.05 m^3/d. Cotton stalks and maize stubble could tolerate a maximum load of 0.04 m^3/d, providing methane production of nearly 9.9 m^3 (which is the highest production) and 8.4 m^3, respectively (Figure 4). Feeding above the respective volumes resulted in digester irregularities and abrupt breakdowns, as observed with rice and wheat stubble. Higher carbohydrate content in cotton stalk is held responsible for the increased biogas production. Carbohydrates are characterised with faster degradation rates, and this is a sensitive factor when considering them as a substrate for anaerobic digestion. A higher retention time could answer this, and the designed biogas plant displayed stable conditions, even for a longer simulation run of nearly two years, when the retention time was maintained at nearly 100 days.

A key aspect in order to attain reliable simulations remains in accurate description of the feed entering the system, and the operational conditions considered during practical operation. Several studies confirm the high accuracy (ranging between 70–90%) of the ADM1 model predictions, when validated against real-scenarios [45,46]. A detailed analysis by Fezzani et al. [47] reports a deviation of only 7%, when the model was validated against an experimental reactor. Our previous study reports an accuracy of nearly 98.5%, when the model was validated against an industrial biogas plant [48]. In this study, the model predictions strongly encourage operating agricultural waste-based biogas plants. The energy output expected from the digesters could further benefit the 2.5 million farmers in the country, who resort to open-burning practices due to a lack of alternatives [49]. India continues to grow its agricultural produce, so this would result in increasing crop residues being left behind. This closed-loop approach of creating value from the leftovers in the form of energy and other viable products, such as fertilizers, considers the elements of circular economy. Other sustainable principles supported by this approach include reduced greenhouse gas emissions (CO_2, CH_4, NO_x), improved recycling of wastes, utilization of the heat generated during the process for the digester itself and a reduction in air and water pollution along with prevention of soil degradation. From an economic perspective, this approach can also improve rural economies and support farmers in generating an extra revenue [50]. Biomethane, also known as renewable natural gas, could act as a vector in transitioning towards a decarbonized society. This particular green energy has also been identified as a solution for filling the demand gap and attaining flexible energy, when supply from other renewable energy sources such as solar and wind fluctuate [28].

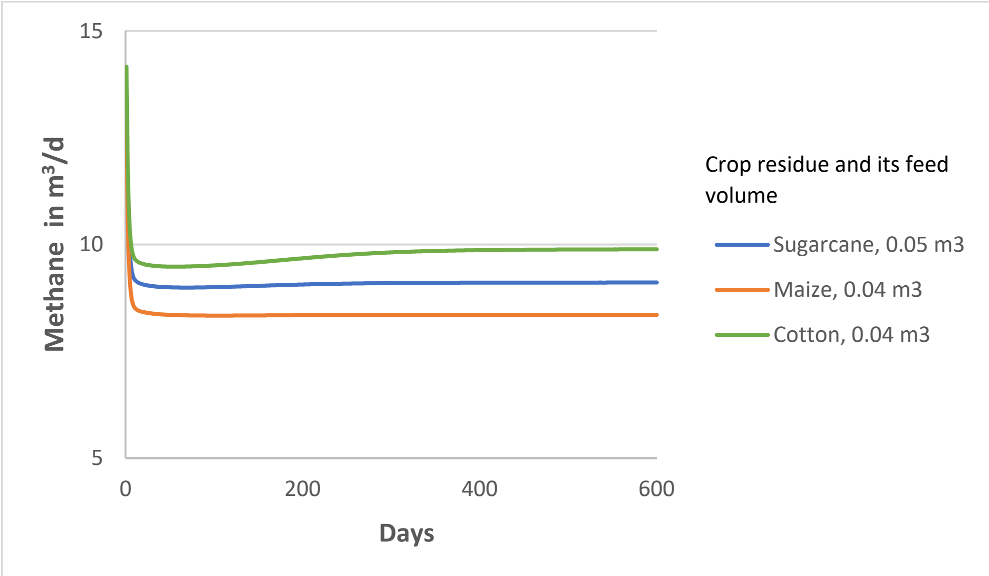

Figure 4. Maximum methane production in the standard biogas plant with crop residues from cotton, maize and sugarcane, each co-fermented with 100 kg of animal manure.

3. Materials and Methods

The ADM1 model was utilised in this study incorporated in the MATLAB software package along with Simulink. Simulink is a block diagram environment with a block library that enables graphical simulations. An easy to construct and operate biogas plant was designed in the virtual environment, using the building blocks from the SIMBA simulation software. Simulations were performed for the different agricultural residues, and the experimentally determined composition of each crop residue was derived from the literature sources. A standard biogas plant was decided for all the agricultural residues, to provide simplicity in design for a varied range of substrates. Optimal conditions, methods facilitating stable operation over longer durations with minimal risks of reactor breakdowns considering different scenarios and parameter settings that enable maximum methane yield were determined.

3.1. Mathematical Modelling

A mathematical model is a computational program with equations for a system including the processes and parameters to comprehend the behaviour of a system in different scenarios. Mathematical models find wide applications in forecasting the performance, to determine the impact of different variables, derive methods and ways to solve problems, optimize the performance of a system, etc., thus decreasing the need to perform elaborate experiments, which further saves time, money and resources [51]. The growing interests in anaerobic digestion both for biogas production and in waste water treatment plants has led to the development of several mathematical models in this field. Such models are helpful in designing, understanding the dynamic time-based behaviour inside an anaerobic digester, predicting possible challenges, optimising the performance and testing various situations, before up-scaling in a real-life scenario [52].

3.2. The Anaerobic Digestion Model (ADM1)

The ADM1 model has been developed by the Task Group of the International Water Association (IWA), with an aim to produce a model for simulating various dynamic anaerobic processes [53]. This mathematical tool was designed to be applicable for research, as a tool to design, operate and optimise anaerobic digestion with different conditions, substrates, parameters, etc. The model considers 31 total processes, 19 biochemical and 2 physio-chemical processes, including enzymatic degradation, thus comprising the reactions occurring in an anaerobic digester, ultimately to form biogas. Outputs from the model are prepared, such that the gas composition, gas production yields, pH in the digester, and concentration of the intermediate products formed, such as volatile organic acids and NH_4, etc., can be determined [53]. There are also different processes incorporated that describe the anaerobic digestion process where organic matter first disintegrates i.e., the complex biological matter breaks down to lipids, proteins and carbohydrates, followed by hydrolysis, where long-chain fatty acids, amino acids and sugars are formed, respectively. This step is followed by acidogenesis, where the formation of different intermediate acids is described, followed by acetogenesis to form acetate and hydrogen and, finally, methanogenesis, where methane is, ultimately, formed [54]. The ADM1 model is considered a powerful tool and has been found competent for simulating biogas plants for small-scale as well as industrial-scale plants, with a broad variety of substrates [55]. Additionally, the model's inclusion of seven types of biomass fractions that degrade the respective components, such as long chain fatty acids, amino acids, sugars, different intermediate organic acids and hydrogen, further strengthens its prediction capability [52]. Since biogas production is essentially meditated by micro-organisms, several biomass fractions have been incorporated, paying attention to their behaviour and role during anaerobic digestion, which has further strengthened the model's capabilities in accurate predictions of the systems. The different biomass degraders, their growth and degradation kinetics, uptake rates and inhibition (such from ammonia, pH, hydrogen, etc.) have, also, been included in the model. With time, the model has been further improvised and updated, to improve its prediction capabilities in our research laboratory, by Biernacki et al. [56]. Wett et al. [57] added a new inert decay product fraction (xp) into the ADM1 model, now known as ADM1xp, which considers nutrient mineralization inside a digester during anaerobic digestion.

3.3. Design of the Biogas Plant

A 15 m^3 biogas plant operated at 38 °C was designed using the SIMBA simulation platform with MATLAB/Simulink incorporating the ADM1xp model (Figure 5). The ADM1xp incorporates the lactic acid parameter as a carbohydrate intermediate, previously developed by the first author, was utilised for this study [58]. The ADM1 model with the SIMBA platform helps in graphically designing the plant, along with combining the numerical equations that describe the anaerobic digestion processes, as incorporated in the model.

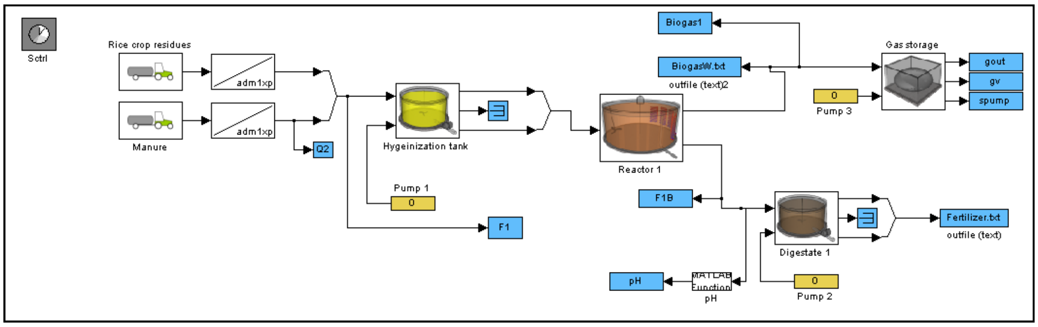

Figure 5. Model description of a crop-residue-based biogas plant designed using SIMBA6 simulation software with Simulink process library.

The biogas plant was designed, such that the liquid volume was maintained at 10 m^3, and the gas collection chamber was 5 m^3. These volumes were decided after several trials with the model, to prepare a standardised design and determine the ideal size for stable operation with a broad range of agricultural residues. Simulation trials also indicated the addition of a buffer, along with such carbohydrate-rich crop residues, in order to avoid pH drops and digester failures. Hence, animal manure was chosen as the inoculum and co-ferment for such a digester. The carbohydrate-rich agricultural residues, when co-digested with nitrogen-rich manures, additionally provide a balanced C/N ratio that has been recognised as a significant factor for optimal conditions inside biogas digesters [59]. The biogas plant was fed, individually, with different crop residues, and their composition was introduced into the model via the converter block of the ADM1 model. The digester was prepared, such that the particular crop residue would be mixed with animal manure and transferred to a hygeinization tank and, then, to the reactor/digester. Digestate from the digester would be transferred to a digestate tank model block, which could be used as fertiliser, while the gas generated shall be transferred to the gas storage model block, where the gas volume and concentration would be monitored during the simulation trials.

Simulations were performed with SIMBA6, based on MATLAB 2013[a] [60]. Trials were performed with each agricultural residue for 600 days. This was considered essential, in order to observe the digester's behaviour over a longer run, and to understand the reactor dynamics with time.

3.4. Model Input Parameters

The parameter set for the ADM1 model plays a significant role in influencing the model's sensitivity, prediction capability and accuracy for real scenarios. Introducing the substrate's characteristics, such as the dry matter and organic dry mass contents, carbohydrate (cellulose, hemicellulose, lignin, etc.), lipid, protein, ammonium contents, etc., into the mathematical model helps in determining the process pathways and performance in the reactor. Bio-chemical reactions, possible inhibitions, growth of particular micro-organisms, pH inside the digester and reaction dynamics during anaerobic digestion are all influenced by the parameters fed into the model.

The standard biogas plant prepared in the model considered co-fermentation of crop residues mixed with animal manure. Animal manure data were considered from the previous experimental works in the same laboratory [56,61]. Substrate characterization data of crop residues such as from rice, wheat, maize and cotton-stalk were determined from experimental data of other researchers (Table 1). Substrate parameters for the co-substrate mixtures were introduced to the model for each crop residue, and simulations were performed.

4. Conclusions

Crop residue burning has gained attention due to the evident air pollution, which has seriously impacted human health and the ecosystem balance. Waste valorization and the circular bioeconomy, by considering the crop residues as a resource, could be an effective approach towards crop-residue management [12]. However, the ground reality remains that despite the implementation of the National Policy for Management of Crop Residues [62], the issues with stubble burning continue to escalate each year, contributing up to 40% of the air pollution in India's urban air [63]. The National Green Tribunal (NGT) has banned stubble burning in several regions, and such open-burning practices are even considered as an environmental crime. Policy makers delve into policies to encourage farmers to prevent such practices and, even, try to reward good behaviour [64], yet the farmers continue to resort to the open-fire method.

Converting the agricultural leftovers to biomethane energy is recommended as an effective mitigation method, which handles the large volumes of stubble and protects the environment from further air and soil pollution, generating a green biofuel that could be converted to heat and electricity [31]. Additionally, the low-value material can be converted to high-quality nitrogen-rich bio-slurry, which would, effectively, replace the dependence on chemical fertilisers, which in itself has a heavy energy demand, thus improving the soil as well as decreasing the carbon footprint [65].

The standard small-scale biogas plant designed in this study was competent in generating approximately 9–10 m^3 methane per day, with all the crop residues considered in the study, which, otherwise, are prone to open burning in India. The methane generated from the plant could further be converted to cooking fuel, heat or electricity, or even upgraded and utilised as transport fuel. Considering calculations that 1 m^3 methane translates to 10 kWh electricity [66], such a stubble-based decentralised biogas plant could generate nearly 90–100 kWh electricity, which is sufficient to power 90–100 bulbs of 100 W for 10 h every day. The different types of crop residues prone to open burning in India, which were considered in this study, were approved by the model to be favorable substrates for generating biomethane. The model predicts a significant energy outcome, from something discarded as waste, and this is expected to motivate the small- and medium-scale farmers to take a step further to utilising their crop residues along with animal manures. The simple design of a biogas plant presented in this study intends to promote the idea of generating biogas without high investment or operational costs, especially for farmers.

In India, addressing stubble burning remains a challenge due to numerous reasons, ranging from increasing crop yields that have increased the stubble production to lack of awareness, lack of effective residue management solutions, lack of incentives and implementation [14]. This urges the necessity of spreading awareness and encouraging farmers to consider alternatives. The recent formation of the Renewable Gas Association of India (RGAI) is a step forward, as this association aims to provide expertise and promote renewable energy [67]. The association identified biogas generation as an effective solution to address the rampant stubble-burning issue in the country. Lately, several initiatives have been taken by the government as well, to supply the fuel demands with bioenergy, preferably from stubble. The Punjab government has agreed with petroleum companies, such as Hindustan Petroleum Corporation, Indian Oil, etc., to produce compressed biogas (CBG) from paddy straw [68]. Biomethane from stubble could, thus, offer a farmer/stakeholder the possibility to either generate energy for self-consumption and/or generate extra income by storing and bottling it in different forms. Further economic benefits from the nutrient-rich organic fertilisers, alongside preventing environmental pollution and harm to the health of the population at large, are, thus, possible.

Operation of biogas plants in practical scenarios, however, comes with certain limitations at the economical, technical, institutional and social levels. While large-scale industrial biogas plants, involving heavy investments and gas production, have been criticised as inefficient compared to other bioenergy sources, upgrading the gas has, also, been found to demand high up-front investments [69]. Another noteworthy limitation remains that biomethane, despite purification and refining, when not accomplished properly, might contain impurities. Such fuels can damage engines, thereby adding to maintenance costs. Practical challenges exist during the distribution of biogas, since these are low-grade and low-value fuels, hence, distribution is feasible only for the upgraded biomethane, but biomethane, when fed into grids, has to qualify under strict quality standards [70]. Storing biomethane in the form of LBM and CBM is gaining attention in India, however, the tendency of LBM, just like LNG, to evaporate necessitates this gas to be utilised within a week [71]. Specific challenges also remain when digesting stubble, since there comes the added challenge of degrading the complex lignocellulosic crop residues, especially that from rice, due to their cell-wall structures. The lignin mesh in rice stubble, surrounding the complex arrangement of cellulose and hemicellulose, makes the microbial degradation difficult, which results in inefficient methane production [72]. In order to attain optimal biomethane yields, pre-treatment, preferably thermochemical treatment of the rigid lignocellulosic biomass in crop residues, is strongly recommended to facilitate better biodegradation [73,74]. Further research will focus on the validation of the ADM1 model against a biogas plant in practical operation. Since the pre-treatment methods utilised so far commonly involve harsh alkaline or acidic chemicals, further attempts shall focus on the determination of economic and environmentally friendly pre-treatment methods for crop residues.

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