# Effect of co-digestion on energy-economics in anaerobic digestion of rice straw and dairy manure

**Authors**

Muramreddy Jugal Sukhesh[a.] , Polisetty Venkateswara Rao[b]

[a] Research Scholar, Civil Engineering Department, National Institute of Technology, Warangal, Telangana, India-506004

[a] Associate Professor, Civil Engineering Department, National Institute of Technology, Warangal, Telangana, India-506004 Ph: +91-9420161800, Corresponding email: pvenku@gmail.com (Corresponding author)

## Abstract

There is a notable surge in the generation of organic wastes globally originating from municipalities, agricultural and food based industries due to increase in urbanization and consumption standards. Anaerobic digestion (AD) is an environmentally friendly sustainable waste management option as well as renewable energy option. The present work aims at evaluating the effect of mono and co-digestion of rice straw and dairy manure on net electrical and thermal energy production. A biogas plant of 200 $m^3$ volume with combined heat and power (CHP) generation system with heat recovery facility was considered. Four unit operations viz., shredding of organic waste, conveyance of feed material, pumping of the feed/digestate, and maintenance of digester against to the heat losses, were considered in establishing the net energy production. . The net electrical energy production of co-digestion was higher by 69% and 9 %.higher compared to mono-digestion of rice straw and dairy manure respectively. The net thermal energy production was higher in co-digestion by 65 % and 12 % compared to mono-digestion of dairy manure and rice straw respectively. Considering the economy, the payback period upon investment of co-digestion of these two organic wastes resulted in payback period of 4.5 years which is 273 % and 17 % lower than mono-digestion of rice straw and dairy manure respectively. The results are encouraging the co-digestion of rice straw and dairy manure as well as mono-digestion of dairy manure for full scale implementation to extract maximum benefit.

**Keywords:** Anaerobic Digestion, Co-Digestion, Energy, Economy, Payback period.

## 1. Introduction

There is a notable surge in the generation of organic waste globally originating from municipalities, agricultural and food based industries due to increase in urbanization and consumption standards[1]. Anaerobic digestion (AD) is an environmentally friendly organic waste management option as well as renewable source of energy option. Anaerobic digestion solves the environmental problems associated with open burning of organic waste that releases greenhouse gases into the environment[2]. Moreover, finished digestate of organic wastes obtained after anaerobic digestion allows recycling of the nutrients if applied on to the cropland. The recycling of nutrients minimises the requirement synthetic chemical fertilisers leading to improved crop productivity. Keeping in view of the multiple advantages, anaerobic digestion is a preferable option for management of organic wastes.

Even though anaerobic digestion has multiple advantages, it suffers with process limitations such as accumulation of VFAs and ammonia leading to poor methane production [3], [4]. The limitations can be attributed to poor nutrient characteristics of the feed material in anaerobic digestion. To avoid these limitations, several authors [5]–[7] focussed on "co-digestion" which is a digestion of two or more organic wastes in a single anaerobic digestion plant. Moreover, co-digestion eases various organic wastes generated in a particular geographical area with integrated organic waste management. Many laboratory studies reported that synergistic effect in co-digestion of organic wastes improves the methane yield. The utilisation of the generated methane gas in combined heat and power (CHP) facility generates electrical and thermal energy. The generated electrical energy can be used for street lighting, domestic purpose for economy development of community. The generated thermal energy (after utilising for plant maintenance) can be used for boiling water or any other industrial use in the vicinity that requires thermal energy. Also, the improved methane generation with co-digestion could reduce pay back periods upon investment, subsequently wide spread practice of anaerobic digestion technology. It is also reported that co-digestion is more economical than pre-treatments as pre-treatments requires an extra energy [8]. In order to adopt the co-digestion of organic wastes, an energy economic assessment is required to quantify the benefits in terms of net energy generation, unit cost of energy production (kWh) and payback period upon investment. Although there are enormous approaches in lab scale indicating the enhancement in methane production, limited information exists regarding energy economics involved in assessing the economic feasibility. Most methods lead to high methane production, but they are not economically viable because the cost they consumed is higher than that of enhanced methane production. Thus, the comparison of input energy spent and output of energy in the anaerobic digestion allows us to estimate the economic viability. The present work is aimed to evaluate net energy production and economic feasibility in anaerobic mono and co-digestion of rice straw and dairy manure.

## 2. Materials & Methods

### 2.1. Design parameters & assumptions

The design of anaerobic digestion plant and necessary auxiliaries employed in it influences energy and economy at commercial scale level. In the present study, energy and economy of anaerobic digestion is assessed based on a plant size of 200 $m^3$ with a working volume of 160 $m^3$ operated in a mesophilic condition ($30^O$ C). The working volume of the digester was calculated based on recommended HRT of 40 days [5] .The recommended OLR of 3 g VS/l/day [9] was considered in assessing the performance. Feed substrate was diluted with water, returning a volume of 4 $m^3$ of feed substrate (based on assumed density of feed materials 1100kg/$m^3$). It is also make note that the water requirement depends on the moisture content. For the case of rice straw anaerobic digestion requires 5.3 L of water /kg of rice straw being fed due to its low moisture content (8%). The anaerobic digestion of dairy manure requires 0.3 L of water /kg of organic waste being fed which is the lowest due to its high moisture content (84%).Whereas, co-digestion of rice straw and dairy manure requires 2.6 L of water /kg of organic waste being fed.

The methane yield in anaerobic digestion of rice straw, dairy manure and co-digestion of rice straw and dairy manure was adopted from our previous study [5]. As methane production obtained experimentally at laboratory batch scale is not be possible to obtain in full scale plant due to scale up factor, 80% of methane production obtained at laboratory scale was considered [10].The obtained methane feeds a combined heat and power (CHP) generation system to convert produced biogas to electrical and thermal energy. The thermal and electrical efficiencies of the CHP unit are based on typical values for commercial units. The CHP unit has an electrical efficiency of 35% and thermal efficiency of 50% with heat recovery facility was considered [11]. The lower heating value (LHV) of methane is 39.62 MJ/$m^3$. It is also assumed that two organic wastes are generated at a constant rate throughout the year and are supplied at free of cost by the waste management authorities. The design parameters of the anaerobic digestion plant are listed in Table 1 Design parameters of full scale anaerobic digestion plant Table 1.

*Table 1 Design parameters of full scale anaerobic digestion plant*

| | **Rice straw** | **Dairy manure** | **Co-digestion** |
|---|---|---|---|
| **Organic waste input t/day** | 0.6 | 3.0 | 1.1 |
| **Specific methane production (mL $CH_4$/g VS added)** | 152 | 216 | 240 |
| **OLR (g VS/l/day)** | 3 | 3 | 3 |
| **HRT (days)** | 40 | 40 | 40 |
| **Digester filling co-efficient** | 0.8 | 0.8 | 0.8 |
| **CHP electrical efficiency** | 30 % | 30 % | 30 % |
| **CHP thermal efficiency** | 50 % | 50 % | 50 % |
| **Process temperature** | 30 $^OC$ | 30 $^OC$ | 30 $^OC$ |
| **Ambient temperature** | 25 $^OC$ | 25 $^OC$ | 25 $^OC$ |

### 2.2. Net energy production of the anaerobic digestion plant

The net energy production of the anaerobic digestion system was assessed by subtracting the energy consumed for internal maintance of plant from the gross energy produced. The energy consumed is calculated based auxiliary equipment employed in shredding of organic waste, pumping of the feed and digestate, conveyance of the feed material to the feed preparation tank and heating the digester against heat losses. A net energy savings in electrical and thermal energy were assessed as follows.

Net energy production= gross energy produced ($E_m$) - energy consumed ($E_{aux}$)

Four unit operations are considered in establishing the net energy balance. Three unit operations are shredding of organic waste, pumping/withdrawal the feedstock/digestate into/from the digester, conveyance of the feed material from the silo to feed tank , maintenance of digester against to the heat losses (5$^O$ C) consumes energy (Deublein, DieterSteinhauser, Angelika, 2010). Energy required for agitation in the bioreactor was neglected due to their low energy requirement (<2 %) [11], [8].

**2.2. Shredding:** The organic substrates need to be shredded homogeneously for efficient methane production. In the current study, a shredder of capacity 9 kW that shreds 400 kg of organic waste in one hour with an efficiency of 0.5 is considered [11]. The difference in electric power requirements with variation in texture of organic waste was neglected. The manures such as dairy manure and chicken manure does not require digestion as they are in fine particulate form.

**2.3. Pumping system:** A centrifugal pump with a wide chamber and a submerged motor was considered. The pump will be able to deliver the feeding material of density 1100 kg/m$^3$ with a flow capacity of 10 m$^3$/h. The efficiency of centrifugal pump is assumed to be 0.5 and the capacity of the motor is 0.5 kW [12].

2.4. **Conveyance:** Two series connected screw conveyors between the silo and feed tank, each with a motor capacity of 5 KW was considered. The conveyor is operated once in a day for 1h/day with a capacity of 1m$^3$/h.

**2.5. Heat input:** Thermal energy is needed to maintain heat losses during winter and night hours. The shortfall in temperature of 5$^o$C i.e. ambient temperature of 25$^O$ C was assumed that could frequently arise in winter and night hours in Warangal District. In considering heat losses, the temperature of the feed substrate and ambient temperature were assumed to be same. To attain 30$^o$ C , supplementation of heat to reach 30$^O$ C and compensation against heat losses were considered. The thermal energy is required to raise the temperature of the feed material and to maintain the heat losses from the reactor wall when the ambient temperature is low .

Thermal energy consumption ($Q_H$) = To heat the feeding substrate +To maintain the temperature against heat losses

$$= \mathbf{m_F . Cp . (T_R - T_A) + U . S . (T_R - T_A)}$$

Where, $m_F$ = quantity of feeding substrate (i.e.4,000 kg/day), Cp=Specific heat capacity of the substrate (4187 J/kg K), U= Overall heat transfer coefficient (0.5 w/m$^2$.K) Deublein et al, S=Surface area of digester (200 m$^2$).The overall heat transfer coefficient (U) in the above equation was calculated. Heat transfer coefficient depends on the thermal conductivity and thickness of material and in addition to the temperature difference. The net available energy was calculated by subtracting thermal energy consumption gross thermal production. Schematic diagram of the full scale plant is shown in Figure 1.

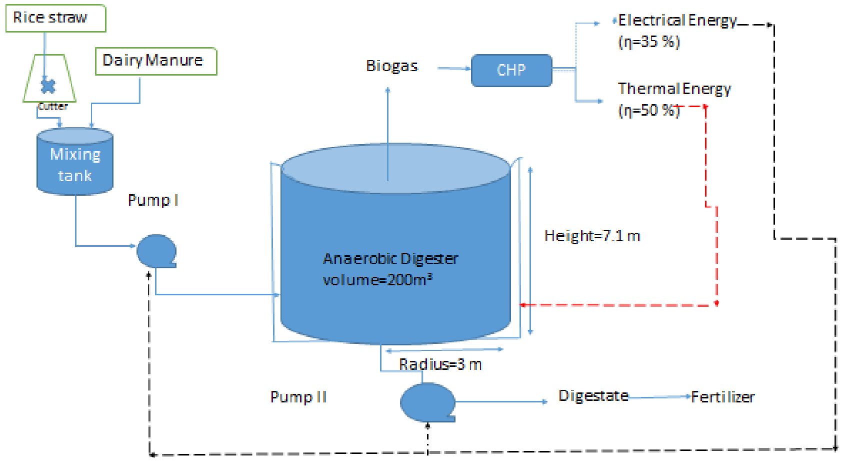

*Figure 1Schematic diagram of Full-scale anaerobic digestion plant*

### 2.3. Economy of the anaerobic digestion plant

The results obtained at previous section are employed for economic evaluation. Two different scenarios are considered. First scenario is the direct use of the produced energy by the household community and corresponding cost of electrical energy per unit production was calculated. Second scenario is the dispatching the produced net electrical energy to the electric grid in accordance with the price of electrical energy.

In order to evaluate the economy of the digester, cost of digester of HDPE material was considered to be Rs 13, 00,000 /- of (Rs 6.5 /- /litre), the cost of pulveriser and conveyor to be Rs 2,00,000 /-, and CHP unit with heat recovery facility to be 5,00,000, amounting total cost of the full scale digester to be Rs 20,00,000 /- . Annual Operation & Maintanance cost is considered to be 10 % of total capital cost ( 4% O&M cost, 4 % Utilities cost, and 2 % labour cost) (eficio et al 2014).The costs of utilities included materials supply, water supply and waste disposal The total labour cost was fixed to 0.5 workers. The income from the sale of the supply was calculated by multiplying the electrical energy produced and cost of unit energy (Rs 6.25 /-).

The total annual costs ($C_T$ ) borne by the plant for the production of electricity was calculated for both scenarios. The both scenarios were considered with an assumption that no subsidy being offered in renewable energy generation. The total annual costs ($C_T$) is calculated as

$$C_T = Capital\ \cos t.CCR + C_{O\&M}$$

Where, CCR is the capital charge rate calculated based on interest rate (10%) and operating life of digester (n=20 years) which is as follows

$$CCR = \frac{i}{1-(1+i)^{-n}}$$

### 2.3.1 Cost of energy

In India, the cost of one unit (Kwh) of electrical energy is Rs 6.25 /-. The cost of one unit (Kwh) electrical energy was evaluated through the ration between annual cost and annual electrical energy production ($E_T$ ). The net produced thermal energy is assumed to supply at free of cost thermal energy usage can not be guaranteed all the time in the vicinity of the anaerobic digestion plant. Price of the organic wastes were assumed to be zero as their management is nuisance.

$$Cost\ of\ energy (CE) = \frac{C_T}{E_T}$$

## 3. Results & Discussion

### 3.1. Net energy production of the anaerobic digestion

The net electrical energy production of co-digestion was assessed by subtracting the electrical and thermal energy requirements of the full-scale plant (Table 2). The co-digestion had high net energy balance compared to mono-digestion of dairy manure and rice straw (Table 3.) The net electrical energy production of co-digestion was higher by 69% and 9 %.higher compared to mono-digestion of rice straw and dairy manure respectively (Figure 2). The plant auxiliaries consumed an electrical energy of 3 to 11 % of that of produced electrical energy maximum being the mono-digestion of rice straw (11 %). High electrical energy is consumed in mono-digestion of rice straw relatively due to energy required for shredding in reducing the structure. Moreover, thermal energy consumes about 7 to 11 % that of produced from the CHP unit. As thermal requirements are low, thermal energy production can be used for the external purposes. In the present study an ambient temperature of $25^{O}$ C was considered that required only 7 to 11 % of thermal energy produced indicating that surplus energy can be used elsewhere. The net produced electrical energy can be used internally for agricultural purposes/domestic use or can be supplied to national electric grid.

*Table 2 Electrical and thermal energy requirement for full scale plant operation*

| **Substrate** | **Shredding (kWh/day)** | **Pumping and discharging of feed and digestate (kWh/day)** | **Conveyance (kWh/day)** | **Thermal energy to raise the temperature to $5^{O}$ C (kWh/day)** | **Thermal energy against heat losses (kWh/day)** | **Total electrical energy requirement (kWh/day)** | **Total Thermal energy requirement (kWh/day)** |
|---|---|---|---|---|---|---|---|
| **Rice straw** | 14 | 0.8 | 10 | 23 | 12 | 35 | 25 |
| **Dairy manure** | 0 | 0.8 | 10 | 23 | 12 | 35 | 11 |
| **Co-digestion** | 7 | 0.8 | 10 | 23 | 12 | 35 | 18 |

However, mono-digestion of dairy manure and co-digestion with rice straw resulted about same net electrical energy production. It is due to large electrical energy requirement for shredding of rice straw. All other energy requirements such as conveyance, pumping and thermal energy requirements are nearly same for mono and co-digestions. The thermal energy requirement was not much differed between mono and co-digestion methods. However, the net thermal energy production was higher in co-digestion by 65 % and 12 % compared to mono-digestion of dairy manure and rice straw respectively.

*Table 3 Performance of the full-scale digester plant*

| | **Rice straw** | **Dairy manure** | **Co-digestion** |
|---|---|---|---|
| **Specific methane production (mL $CH_4$/g VS added)** | 152 | 216 | 240 |
| **Electrical energy production(kWh/day)** | 224 | 319 | 354 |
| **Thermal energy production (kWh/day)** | 320 | 455 | 506 |
| **Electrical energy consumption (kWh/day)** | 25 | 11 | 18 |
| **Thermal energy consumption (kWh/day)** | 35 | 35 | 35 |
| **Net electrical energy production (kWh/day)** | 199 | 308 | 336 |
| **Net thermal energy production (kWh/day)** | 285 | 420 | 471 |

The net electrical energy generated can be used for street lighting, domestic purpose for economy development of community. The net heat energy generated (after utilising for digester maintenance) can be used for industrial use that has requirement in the vicinity.

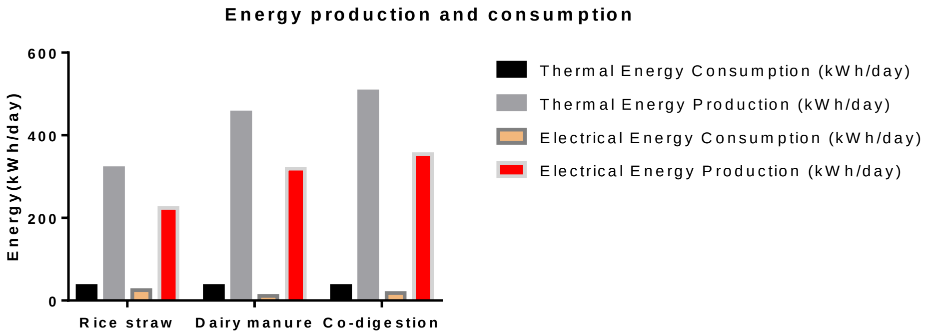

*Figure 2 Net Energy production of mono and co-digestion of rice straw and dairy manure*

### 3.2. Economy of the anaerobic digestion

Based on the full-scale digester design and net energy production obtained as above, a preliminary economic evaluation was carried out (Table 4). Scenario I considered the utilisation of produced electrical energy for the domestic use directly. It is observed that the obtained cost of energy for all type of digestion is is lower than domestic purchase cost in india i.e Rs 6.2 /-.The electrical energy costed is about Rs 5.3 /- and Rs 3.7 /- for mono-digestion of rice straw and dairy manure respectively. Whereas, co-digestion of these two organic substrates resulted in energy cost of 3.3 Rs/- which is .60 % and 12 % higher than mono-digestion of rice straw and dairy manure respectively.

Scenario II considered the supply of the produced net electrical energy to the national electric grid It is observed that the payback period is about 16.8 years and 5.3 years for mono-digestion of rice straw and dairy manure respectively. The co-digestion of these two organic substrates resulted in payback period. of 4.5 years which is 273 % and 17 % lower than mono-digestion of rice straw and dairy manure respectively. Further, the generated net electrical energy generation fetches additional income if used appropriately whose cost is not considered in the study. Thus co-digestion of rice straw and dairy manure as well as mono-digestion of dairy manure are recommended for full scale implementation

*Table 4 Economy of the anaerobic digestion*

| | **Rice straw** | **Dairy manure** | **Co-digestion** |
|---|---|---|---|
| **Scenario I**<br>**(Direct use of energy)** | | | |
| **Total capital cost** | 20,00,000 | 20,00,000 | 20,00,000 |
| **Annual capital charge (11.7 %)** | 2.34,000 | 2.34,000 | 2.34,000 |
| **Annual O& M costs (4%)** | 80,000 | 80,000 | 80,000 |

| | | | |
|---|---|---|---|
| **Labour cost (0.5 worker)** | 1,20,000 | 1,20,000 | 1,20,000 |
| **Total annual cost** | 4, 34,000 | 4, 34,000 | 4, 34,000 |
| **Net electrical energy production (kWh/day)** | 199 | 308 | 336 |
| **Annual Net electrical energy production (kWh/year)** | 72,635 | 1,12, 420 | 1,22,640 |
| **Cost of energy (Rs/kWh)** | 5.3 | 3.7 | 3.3 |
| **Scenario II (Supplied to electric grid)** | | | |
| **Electrical Energy Revenues (Rs/year) EER** | 4,50,337 | 6,97,004 | 7,60,368 |
| **Net cash flow (EER-$C_{O\ \&\ M}$ – Labour cost)** | 2,50,337 | 4,97,004 | 5,60,368 |
| **Pay back period (Discount rate= 10 %)** | 16.8 years | 5.3 years | 4.5 years |

## 4. Conclusions

The net electrical energy production of co-digestion was higher by 69% and 9 %.higher compared to mono-digestion of rice straw and dairy manure respectively. The net thermal energy production was higher in co-digestion by 65 % and 12 % compared to mono-digestion of dairy manure and rice straw respectively. Besides, co-digestion of these two organic substrates resulted in low pay back period. of 4.5 years which is 273 % and 17 % lower than mono-digestion of rice straw and dairy manure respectively. The higher pay back period for anaerobic digestion of rice straw is observed due to low methane production. The results are encouraging the co-digestion of rice straw and dairy manure as well as mono-digestion of dairy manure for full-scale implementation for maximum benefit.

## Acknowledgements

The authors wish to thank Department of Biotechnology, Ministry of Science & Technology Government of India for funding this work (Sanction order No: BT/PR6328/GBD/27/387/2012) and Department of Civil Engineering, National Institute of Technology, Warangal, India for providing support to carry out present work.

## References

[1] D. G. Streets, K. F. Yarber, J.-H. Woo, and G. R. Carmichael, “Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions,” *Global Biogeochem. Cycles*, vol. 17, no. 4, p. 1099, 2003.

[2] M. J. Sukhesh and P. V. Rao, “Anaerobic digestion of crop residues: Technological developments and

environmental impact in the Indian context," *Biocatal. Agric. Biotechnol.*, vol. 16, pp. 513–528, Oct. 2018.

[3] M. Kayhanian, "Ammonia inhibition in high-solids biogasification: An overview and practical solutions," *Environ. Technol. (United Kingdom)*, vol. 20, no. 4, pp. 355–365, 1999.

[4] H. Yuan and N. Zhu, "Progress in inhibition mechanisms and process control of intermediates and by-products in sewage sludge anaerobic digestion," *Renewable and Sustainable Energy Reviews*, vol. 58. pp. 429–438, 2016.

[5] M. Jugal Sukhesh and P. Venkateswara Rao, "Synergistic effect in anaerobic co-digestion of rice straw and dairy manure - a batch kinetic study," *Energy Sources, Part A Recover. Util. Environ. Eff.*, pp. 1–12, Dec. 2018.

[6] P. V. Rao and S. S. Baral, "Experimental design of mixture for the anaerobic co-digestion of sewage sludge," *Chem. Eng. J.*, vol. 172, no. 2–3, pp. 977–986, 2011.

[7] M. Mel, S. I. Ihsan, and R. H. Setyobudi, "Process Improvement of Biogas Production from Anaerobic Co-digestion of Cow Dung and Corn Husk," *Procedia Chem.*, vol. 14, pp. 91–100, 2015.

[8] Z. N. Abudi *et al.*, "Batch anaerobic co-digestion of OFMSW (organic fraction of municipal solid waste), TWAS (thickened waste activated sludge) and RS (rice straw): Influence of TWAS and RS pretreatment and mixing ratio," *Energy*, vol. 107, pp. 131–140, 2016.

[9] D. Li *et al.*, "Effects of feedstock ratio and organic loading rate on the anaerobic mesophilic co-digestion of rice straw and pig manure.," *Bioresour. Technol.*, vol. 187, pp. 120–7, 2015.

[10] B. Ruffino, S. Fiore, C. Roati, G. Campo, D. Novarino, and M. Zanetti, "Scale effect of anaerobic digestion tests in fed-batch and semi-continuous mode for the technical and economic feasibility of a full scale digester," *Bioresour. Technol.*, vol. 182, pp. 302–313, 2015.

[11] E. A. Scano, C. Asquer, A. Pistis, L. Ortu, V. Demontis, and D. Cocco, "Biogas from anaerobic digestion of fruit and vegetable wastes: Experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant," *Energy Convers. Manag.*, vol. 77, pp. 22–30, 2014.

[12] D. Deublein and A. Steinhauser, *Biogas from Waste and Renewable Resources: An Introduction, Second Edition*. 2010.