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Anaerobic Digester and Algal Pond Coupling using Agricultural Residues: Evaluating Productions, Pond Sizing and Nutrient Requirement

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Abstract

This investigation examines application of agricultural residues in making biogas using anaerobic digester and algal pond coupling. Although prior works on integration exist for algal in wastewater treatment, we went on to assess theoretically coupling for energy production, pond sizing and nutrient requirement using 1 tonne/day flow rate of waste. Two systems were proposed: (i) use of waste stream from the anaerobic digester to grow algal biomass and (ii) to recycle the produced algal biomass to the digester. The study showed that applying first configuration gives 515.2 m^3 of biogas with 257.6 (50%) biomethane having 9,273.64 MJ of energy. Using CO_2 waste with commercial nutrient supply to the pond at the appropriate proportion, 443.75 kg algal biomass was produced. Algal pond of depth 0.4 m used was estimated to have capacity of 907 m^3. For the second, co-digestion generates 22.4% increases volume of biogas, leading to 11,913.34 MJ energy generation (23.9% raise). Waste provided half of the nitrogen for algal cultivation. Piecing both configurations together gives a continuous system that, as long as 1 tonne /day feed supply is available, there will be increase in production and reduction in nutrient demand. Approximately 257.65×10^9 m^3 ($9{,}275.27 \times 10^9$ MJ energy) of biomethane by volumes can be generated annually from these agricultural residues globally.

Keywords: *Anaerobic Digestion, Algal Production, Pond Sizing, Nutrient, Biogas, Agricultural Residues*

1. Introduction

There is an increasing demand for energy and this trend is predicted to give even higher increase (IEA, 2006). In the intervening time, there is a rapid decline in the fossil reserves due to the growing consumption profile that we have maintained over the decades. This collective reliance on oil and gas of fossils extract has not been without decimating effect on our planet, but has spiraled and left our ecosystem worse off. The growing awareness of this lingering reality is now bringing about the renaissance of interest in renewable energy as the prospective safe alternative. Consequently, there arises the need to manage these challenges by seeking opportunity in waste as raw material for energy use. Biomass is abundant in nature and could contribute significantly to the success of our clean and renewable energy quest when added to the energy mix matrix (Zhang, 2008 and Raphael & Yang, 2013). Most importantly, waste biomass falls in this cadre as it could go a long way in contributing towards energy provision while concomitantly solving the enduring environmental problems, without short changing the need for food and feed which is paramount to our survival (Bontemps et al, 2009). Globally, the agricultural residues (agrowaste) available for bioenergy application was estimated to be 1,000,173,000 tonnes (dry) for the year 2011 with the detailed reasoning on it presented in Raphael & Yang (2013). That is substantial volumes to consider in meeting a good chunk of our Industrial needs and derive immense benefits (Meghan, 1997). Also, it has the highest opportunities for biogas than other existing waste resources (SGC, 2012). Every region around the world has a fair share of agrowaste that could be utilised for energy purposes, as shown in the Food and Agricultural Organization database (FAO, 2015).

Biogas is a mixture of methane and carbon dioxide. It is an energy rich gas that can be used in various ways such as heating and electricity generation (McKendry, 2002). In addition to biogas, depending on the feed, other gases as ammonia and hydrogen sulphide are produced from anaerobic digestion reactions (Igoni et al, 2008). Meanwhile, anaerobic digestion is a four staged process that basically ferments organic compounds through the use of combination of microbes in the order of hydrolysis, acidogenesis, acetogenesis and methanogenesis (Bouallagui et al, 2005).

In the anaerobic digestion process, biomethane product is the gas of relevance, whose combustion releases less harmful GHG (green house gases) CO_2 with a net carbon neutral effect as its emitted carbon results from the CO_2 uptake by the plant from the environment in growing its biomass. The other components often go out as waste which may require further treatments and utilizations for other remunerations (McKendry, 2002 and Igoni et al, 2008).

On the other side of the divide, there is an algal pond with algal consortium that essentially grows algal biomass using the waste from the digester and nutrients. For example, green algae grow their biomass by assimilation and fixation of mainly carbon (IV) oxide and nitrogen and other nutriant in the presence of sunlight (Orosz & Forney, 2008 and Yang, 2011). This biomass can be harvested and adapted for other energy uses, be it as biodiesel, biofuel or further use to generate biogas from an anaerobic digester as a feed (Orosz & Forney, 2008). This last application is given serious consideration in the context of this investigation as that could be used to further upgrade the biogas from the agrowaste that is profoundly carbohydrate based, considering the fact that algae are famed for possessing high lipid content. Besides, the cultivation of algae for fuel is a prime subject in biomass and bioenergy because aside it having higher yield per hectare and per year than most existing crops do, it only demands nutrients and doesn't necessarily compete for useable land considering that it thrives well in aquatic environment (Goh & Lee, 2010). Typical examples of algae strains are Chlorella, Spirulina, Scenedesmus, Dunaliella, Botryococus and Porphyridium species (Orosz & Forney, 2008).

Presently, there exist different conversion technologies which have been adopted for transforming these renewable resources to fuels (McKendry, 2002; Faaij, 2006; Holtzapple & Granda, 2009 and Raphael & Yang, 2013). This work is specifically looking at the role of anaerobic digestion and algal pond coupled systems as per the advantages that exist in this integration. Anaerobic digestion is a mature technology option that has been applied over the years in treating waste and producing fuel (McKendry, 2002). Waste with or without pre-treatment, is fed into an anaerobic digester, mixed and heated where necessary. In these processes, microorganisms in the absence of oxygen convert these wastes biomass to biogas, leaving behind the undigested portion as digestate. The digestate from agrowaste biomass is mainly lignin laden. Lignin is resistant to enzymatic digestion and retains about 40% of biomass energy (Hatakeyama & Hatakeyama, 2005). Therefore, it could be used for energy production via any of the thermochemical conversion routes or burnt to provide heat where necessary. This system is akin to what happens in a digester operating at psychrophilic temperature or in a non-temperate region where there is the need to maintain the temperature from dropping (Igoni et al, 2008 and Raphael & Yang, 2013).

Previous studies have looked at this kind of integration for waste water treatment as a way of nutrient removal in algal production (Collet et al, 2011; Buchanan et al, 2013 and Fouilland et al, 2014).

This work is, however, assessing its theoretical potential for production and the accompanying specifics with agrowaste as feed. This article has used mass and energy balance to evaluate the production potential, carried out estimation of the suitable pond sizing and assessed nutrient (nitrogen and phosphorus) requirement by the pond using 1 tonne/day flow rate of agrowaste as feed. But this article theoretically examines things from the stand point of material and energy balance in evaluating the opportunity in these combinations using agricultural residue that is readily available annually. Moreover, it combines the first principle with an existing kinetic model to estimate the reactor size for the algal pond. Energy generation from agrowaste stream and/or algal biomass, understanding algal production and its nutrient demand, together with the reactor sizing for the algal pond is accounted for in this study. Mass and energy balances are carried out to understand the significance of running combined system. This is handled under two scenarios: (i) having the waste stream from the anaerobic digester grow algal biomass and (ii) evaluation of the improvements if this produced algae is fed back as a recycle stream to the digester to see the opportunity in anaerobic digester –alga pond coupling. Evaluation of combined system for material and energy production as well as quantification of photobioreactor (PBR) design is the primary reason for this study. In addition, the energy potential for biomass feed is investigated in terms of annual biomethane potential. In essence, the study is aimed at evaluating combined system for material and energy production as well as quantification of photobioreactor (PBR) design.

2. Material and Methods

Biomass of agrowaste to be considered was first identifyed, and their representative compositions and formulas are taken from literatures. Also, the chemical formula for algal biomass was sourced from relevant documented work. Using established equations the theoretical yield to product is obtained and this is followed in doing analysis from end to end between feed and product. For a tonne of feed, the respective material and energy production is found. Subsequently, the CO_2 production from the digester is used in determining the nutrient requirement by algae in the pond. Also, the sizing of the pond is carried out from understanding of production, nutrient demand and algae kinetic in a PBR. Moreover, the developed yield in combination with agrowaste annual data is used to evaluate biomethane potential for this biomass.

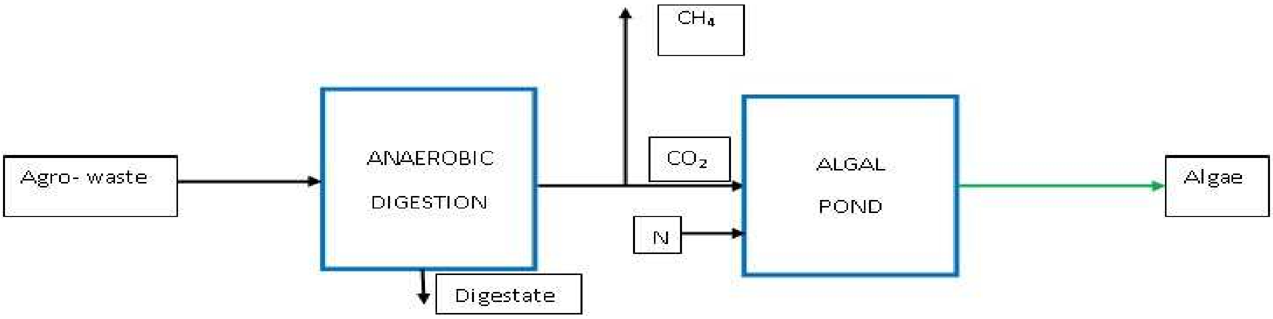

Figure 1. Showing Coupled System with no Recycle Stream

2.1. The Biomass: Agricultural Residues and Algae

Agrowaste weight of composite constituent (35.53% cellulose, 25.98% hemicellulose, 38.49% lignin) used in this article is the average of representative composition of corn stover, barley straw, oat straw, rice straw, wheat straw, sorghum straw, sugar cane straw, sugar beet tops, bagasse and beet pulp biomass used in estimating annual biomass volume in Raphael &Yang (2013) was taken from Drapcho et al (2008). The biomass formula of components is Cellulose ($C_6H_{10}O_5$), hemicelluloses ($C_5H_8O_4$), lignin ($CH_{1.12}O_{0.377}$). The formula for cellulose and hemicellulose are from Drapcho et al (2008) and that for lignin is taken from Holtzapple & Granda (2009). That for algal biomass which is taken to be that type presented in Fraga (2001) which is used in numerous algae biomass modelling and reactions. This formula for whole algal biomass is $C_{106}H_{263}O_{110}N_{16}P$ and its variant that is reduced to $C_{5.0476}H_{12.7619}O_{5.2381}N_{0.7619}$, where the phosphorus is discarded for its negligible proportion in the composition used when the algae is fed as co-substrate to the digester as recycle.

2.2. The Systems

2.2.1. Case A: Coupled System with No Recycle

This set up depicts the first phase of operation. Agrowaste is the only feed entering the digester as the source of biomass for energy generation. After the digestion process the biogas produced exits the reactor and is feed to the photobioreactor. The digestate that is made up of lignin is removed from the bottom of the reactor. An alga grows and increases its biomass by utilizing CO_2 from the anaerobic digester and the external nitrogen feed to it as nutrient (Figure 1).

2.2.2. Case B: Coupled System with Recycle

Following similar description as Case A except the fact that the grown algae here is sent back to the anaerobic digester to add as a substrate, an additional feed in a codigestion process to raise the biogas production and the energy level. This is done with the whole algae biomass combining with same quantity of agrowaste and monitoring the increment. The subsequent output flow rate of CO_2 is adjusted to the right quantity that suits the capacity of the algal pond design from Case A. Furthermore, the ammonia from this present operation now used as the principal supplementary source of nitrogen for the commercial fertilizer source depending on the quantity the codigestion pro-cess is able to afford (Figure 2).

3. Results and Discussion

3.1. The Assessment

3.1.1. The Anaerobic Digester: Mass and Energy Balance

The estimation is on 1000 kg per day (kg/d) of feedstock as basis. For 1000 kg in agrowaste feedstock there is 355.3 kg cellulose, 259.8 kg hemicellulose and 384.9 kg lignin.
In this work the biomass dry matter is taken as its volatile solids (VS) for digestible portion. In a day that means for 1000 kg dry matter, 355.3 kg VS cellulose and 259.8 kg VS hemicelluloses is available for anaerobic digestion with

the lignin remaining as residue which can be used to generate energy via thermochemical conversion.

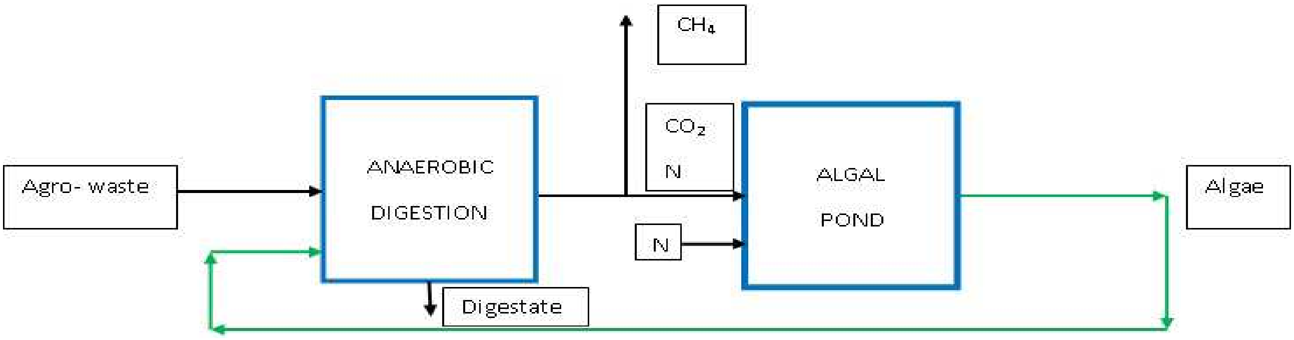

Figure 2. Showing Coupled System with no Recycle Stream

Using Buswell equation (Eq. 1) as contained in Buswell & Mueller (1952) and following estimations in pattern similar to that in Banks (2009).

$$C_cH_hO_oN_nS_s + 1/4(4c-h-2o+3n+2s)H_2O \rightarrow 1/8(4c-h+2o+3n+2s)CO_2 + 1/8(4c+h-2o-3n-2s)CH_4 + nNH_3 + sH_2S \quad \ldots\ldots\ldots\ldots 1$$

Substituting into Eq. 1, the respective feed portions except the lignin we have the respective masses of products. Since 1 mol gas at STP = 22.4 litres and 16 g CH_4 = 22.4 litres estimation was made upon this understanding of ideal gas law for the volumes of methane. In similar manner, the volumes for CO_2 were gotten. The volume of biogas was gotten from the addition of these respective volumes. The complete results for the two digestible components are of agrowaste biomass (cellulose and hemicelluloses)**.**

The energy value estimation for methane and waste are carried out in the following manner in order with Banks (2009). Knowing that the 36 MJ of energy is contained in 1 m^3 of methane, thus, the energy contained in biomass can be calculated by multiplying the volume of methane generated from the biomass with the energy housed in 1 m^3 of methane. The values are entered in Table 1.

On reactor volume, typically, the respective densities of agricultural residues vary greatly, making the establishment of composite density difficult for the bulk biomass. The absence of this information hampered the theoretical assessment of the digester size for this system.

3.2. Algal Pond: Mass and Energy Balance

3.2.1. Nutrients

For this first system setup, it is assumed that the pond has sufficient commercial nitrogen and phosphorus supply as fertilizer, while CO_2 from the anaerobic digestion is the limiting nutrient. Again, it is taken that during sparging the amount of CO_2 supplied and delivered by the conduit to the reactor is completely dissolved and utilized by the algae as substrate. Algae biomass formation results from photosynthesis. This synthesis of algae biomass can be represented by these two chemical equations having ammonium and nitrate as the means of nitrogen (Stumm & Morgan, 1996; Ebeling et al, 2006; and Orosz & Forney, 2008).

$$16NH_4^+ + 92CO_2 + 92H_2O + 14HCO_3^- + HPO_4^{2-} \xrightarrow{hv} C_{106}H_{263}O_{110}N_{16}P + 106O_2 \quad \cdots\cdots 2$$

$$16NO_3^- + 124CO_2 + 140H_2O + HPO_4^{2-} \xrightarrow{hv} C_{106}H_{263}O_{110}N_{16}P + 138O_2 + 18HCO_3^- \quad \cdots\cdots 3$$

Assuming that all nitrogen came from ammonium, we can use Eq. 2 to estimate the amount of macro nutrients (nitrogen and phosphorus) demand and the algae formed using the limiting CO_2 from the anaerobic digester as the feed to the pond. Going by the stoichiometry, the material requirement of the pond is gotten. When nutrient is available without restriction, photosynthesis increases with rising irradiance unimpeded till the maximum growth rate is attained as depicted by Michaelis-Menten kinetics (Richmond & Zou, 1999 and Richmond, 2004). But in a situation where light irradiance is supplied above the saturation level photo inhibition could emanate from the destruct-ion of the algae photoreceptor, bringing about reduction in photosynthetic activity (Qiang & Richmond, 1996 and Cuaresma et al, 2011).

3.3. Algal Pond Kinetics and Sizing

The estimation of the pond volume is done using series of equations and thought in Yang (2011) that is based on High Rate Algal Pond (HRAP) as the PBR using the Eq. 4:

$$\frac{dX_A}{dt} = \frac{F}{V}(X_i - X_f) + r_{gA} - r_{dA} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where:

F: *The mass flow rate of the influent and effluent*
V: *The pond volume*

X_i & X_f: The initial final algae concentration respectively
r_{gA} & r_{dA}: The growth and decay rate of the algae correspondingly

$$r_{dA} = k_{dA} X_A \;\ldots\ldots 5$$

Where:

X_A & k_{dA}: The mass conc. of algae and the decay constant respectively

$$r_{gA} = \mu_A X_A \;\ldots\ldots 6$$

Where:

μ_A: The specific growth rate of algae

The specific growth rate of algae of algae is given by:

$$\mu_A = \vartheta_A \left(\frac{CO_{2D}}{K_c + CO_{2D}}\right)\left(\frac{N_T}{K_{NA} + N_T}\right) f_I \;\ldots\ldots 7$$

Where:

ϑ_A, K_c and K_{NA} are constants
CO_{2D} and N_T: Dissolved CO_2 and total nitrogen respectively
f_I: The light intensity factor

$$f_I = \frac{I_a}{I_s} \exp\left(1 - \frac{I_a}{I_s}\right) \;\ldots\ldots 8$$

Where:

I_s: The saturation is light intensity
I_a: The average light intensity at the pond at a given point

$$I_a = \frac{1}{h}\int_o^h I_o \exp(-K_e h)\,dh \;\ldots\ldots 9$$

Where:

I_0: Surface is light intensity
K_e: Extinction coefficient

$$K_e = K_{e1} + K_{e2} X_A \;\ldots\ldots 10$$

Where:

K_{e1} and K_{e2}: constants where K_e approximates to K_{e1}

By simplifying Eq. 9 to:

$$I_a = \frac{I_o}{hK_{e1}}\left[1 - \exp(-K_e h)\right] \;\ldots\ldots 11$$

Furthermore, the changing day time surface light intensity I_o can be described approximately using a sinusoidal function for the photoperiod under consideration by:

$$I_o(t) = \left(\frac{\Pi}{2}\frac{I_d}{f_p}\right)\sin\left(\frac{\Pi t}{f_p}\right), \;\ldots\ldots 12$$

Where:

I_d: The daily total light intensity at the pond surface
f_p: The fraction of photoperiod in a day
t (unit is day): Their respective values used are gotten from Table 2
f_p: 14/24 and the algal production activity is within 7 days

The necessary parameter values are imputed to complete the estimations are from Table 2.

Substituting f_I and μ_A

Revisiting Eq. 4 at steady state, $\frac{dX_A}{dt} = 0$,

On rearranging we get:

$$\frac{F}{V}(X_f - X_i) = +r_{gA} - r_{dA}$$

At harvesting the X_i assumed negligible compared to X_f so that X_f–X_i becomes X_A

Solving further it simplify to:

$$V = \frac{F}{(\mu_A - k_{dA})}$$

We know:

Pond Area (A) = Volume (V) / depth (h)

The algal pond of h= 0.4 m with estimated V= 907.46 m^3, would have A= 2268.66 m^2

3.4. Coupled System with Recycle and Nutrient Contribution

In one approach, the mass of algae produced from here is fed to the anaerobic digester and the whole alga is considered to be digestible in this system and is also assumed that this is a co-digestion kind of system. A more realistic approach is employed here setting the oil reach algae (50% dry weight) as the digestible biomass with enhanced lipid production at 30 MJ/kg, a conservative value in view of the fact that higher production is found in literatures (Morweiser et al, 2010). It is further assumed that this weight representing volatile solids, is completely convertible to biogas. Also, the phosphorus in the algae formula is discarded for its minute proportion to the other elements. The style followed in material and energy estimation is same as in section 3.1. The calculated values for biogas yield and energy production with algae as co-substrate for the anaerobic digestion process are shown in Table 3.

Table 1. Biogas and Energy Production from Single Agrowaste as Feed

Stream	Component	CH_4		CO_2		Vol CH_4 (m3/d)	Vol CO_2 (m3/d)	Biogas (m^3/d)	CH_4 Energy (MJ/d)
		Mole (mol/d)	Mass (kg/d)	Mole (mol/d)	Mass (kg/d)				
Agro	Cellulose	6.58	105.27	6.58	289.50	147.38	147.38	294.77	5305.79
	Hemicellulose	4.92	78.73	4.92	216.50	110.22	110.22	220.44	3967.85
Overall		11.50	184.00	11.50	506.00	257.60	257.60	515.20	9273.64

Table 2. Showing Model Parameters as well as Design and Operating Parameters of the Pond (Yang, 2011)

Model Parameters	
Parameter	**Value**
μ_A	0.9991 day^{-1}
K_{NA}	0.001 mol Nm^{-3}
K_c	0.001 mol CO_{2D} m^{-3}
K_{dA}	0.05 day^{-1}
K_{e1}	0.32 m^{-1}
I_s	14.63 $MJm^{-2}day^{-1}$

Design and Operating Parameters of the Algal Pond	
Parameter	**Value**
Pond depth (m)	0.4
Hydraulic retention time (day)	7
Temperature (^oC)	20
Surface light intensity($MJm^{-2}day^{-1}$)	18.81
Photoperiod (in 24-hour day)	5-19 hours

Table 3. Biogas and Energy Production from Agrowaste and Algae as Feed

Stream	Ammonia (NH_3)		Methane (CH_4)		CO_2		Vol. CH_4 (m^3/d)	Vol. CO_2 (m^3/d)	Vol. Biogas (m^3/d)	CH_4 Energy (MJ/d)
	Mole (mol/d)	Mass (kg/d)	Mole (mol/d)	Mass (kg/d)	Mole (mol/d)	Mass (kg/d)				
Agro-waste	-	-	11.50	184.00	11.500	506.00	257.60	257.60	515.20	9273.64
Algae	1.00	17.00	3.27	52.38	3.35	147.47	73.33	75.08	148.4	2639.70
Overall	1.00	17.00	14.77	236.38	14.85	653.47	330.93	332.68	663.60	11913.34
Increase (%)	-	-	-	-	-	-	23.90	20.70	22.40	23.90

To complete the operation, maintaining a fixed algae reactor size since the co-digestion process generates more CO_2 than the pond was designed for, the inlet CO_2 from the digester should be adjusted by purging out excess CO_2, or assumed they were never used as only the appropriate volume was consumed by algae in building its biomass during photosynthesis. Again, the ammonia from the co-digestion process was now used to fend for the nitrogen nutrient demand by the pond in this operation and the nutrient contrib.-ution in this case is estimated in similar manner as Section 3.2.1 and entered under co-digestion column in Table 4.

3.5. Discussion

The study revealed that for the first configuration, lone agrowaste feed is capable of producing 515.20 m^3 of biogas with 257.60 m^3 (50%) biomethane having 9,273.64 MJ of energy from the anaerobic digestion process. Next, it was shown that the CO_2 from the biogas can be used for algae production. Upon the CO_2 and commercial nutrient supply to the pond at the appropriate composite nutrient ratio in the presence of sunlight, 443.75 kg algal biomass was produced.

Meanwhile, complete supply of nutrient from extern-al source(s) was needed in this case to cultivate the algae as the agrowaste is essentially carbohydrate based in pristine state after biomass pre-treatment. The algal pond tubular reactor of depth 0.4 m capable of this algal production demonstrated in this work was estimated to have a capacity of 907 m^3 and of cross sectional area 2,269 m^2. Agrowaste have higher potential in terms of annual production volume, whereas its production per unit biomass is low because good portion of its constituents are recalcitrant lignin that anaerobic microorganisms find difficult to digest. Thus, finding economic use, such as heat provision for the systems, for lignin digestate will to a large extent enhance the overall process efficiency.

Table 4. Algae Production and Nitrogen Nutrient

Components	**Agrowaste Alone**		**Codigestion**		**Nitrogen Demand Reduction (%)**
	Mass (kg/day)	**Mole (mol/day)**	**Mass (kg/day)**	**Mole (mol/day)**	
CO_2	506	11.5	506	11.5	
Nitrogen	(-)28*	(-)2*	(+)17*	(+)1*	50
Phosphorus	(-)3.88	(-)0.125	(-)3.88	(-) 0.125	
Algae	443.75	2.625	443.75	2.625	

Denotes signs given to show nitrogen source (commercial (-) and waste (+)

Furthermore, it was found that for the second configuration, where the algal biomass grown in the PBR is harvested and recycled as a co-substrate with agrowaste of same initial feed volume, the co-digestion process generates 148.4 m^3 more volume of biogas which amounts to 22.4% increment. This offers more methane to increase the energy generated from the plant to 11,913.34 MJ. A 23.9% energy increase over earlier production where there was no recycle stream integration. Moreover, in this option, for the feed to the algal pond, the CO_2 level must be adjusted to the pond requirement and maintained to sync with that in first instance of configuration. This time around, part of the nitrogen nutrient was sourced from the ammonia-nitrogen from algal biomass digestion in the digester and the remainder is supplied externally together with the phosphorus. This is able to provide an amount enough to supplant around half the quantity of ammonium-nitrogen demand for algal pond originally gotten commercially. Potentially, biomethane of approximately 257.60×10^9 m^3 volumes ($9{,}274 \times 10^9$MJ energy) can be generated from these agricultural residues annually.

4. Conclusion

The best way to utilize biomass variety to obtain higher delivery has started to take centre stage in the scheme of things for it to be successful and effective at contributing its quota to the renewable energy mix successfully. In this light, anaerobic digester and algal pond coupling is studied and shown to be a reasonable way to optimize biomass for energy. It was found that opportunities exist in these integrated systems considered, especially in the prospect of utilising the algal recycled stream as co-substrate for anaerobic digestion as it ensures higher productions and lowers the external nitrogen nutrient sourcing requirement for the algal pond significantly. Putting together both scenarios as a joint production piece offers a continuous system where, as long as 1 tonne/day feed supply is made over an appropriate interval, there will be the benefit of increase material and energy production, and nutrient demand reduction. Howbeit, pragmatically, lesser production than these should be expected because of the difficulty of the reactor attaining 100% efficiency as complete conversion of the volatile solids by anaerobes may be unattainable for either feedstock examined in this study. This is the preliminary aspect of this research as further work will need to look at the experimental productions, consider costing and other technical orientations of the project to ascertain the feasibility of the system and draw valid comparison with theoretical expectations.

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