Valorization of pineapple peel and poultry manure for clean energy generation

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Abbreviations: Ac-P, acidic pretreatment/pretreated; AD, anaerobic digestion; Al-P, alkaline pretreatment/pretreated; ANOVA, analysis of variance; BP, biomethane potential; C, cellulose; C/N, carbon/nitrogen; CCD, central composite design; CHP, combined heat and power; COD, chemical oxygen demand; DAD, diode array detector; EE, electrical energy; FTIR, Fourier transform infrared; GS, ground sifted; H, hemicellulose; L, lignin; L-C-H, lignin–cellulose–hemicellulose; NS, not sifted; P CR, polymerase chain reaction; PM, poultry manure; PPs, pineapple peels; RSM, response surface methodology; RTE, required thermal energy; TE, thermal energy; TS, total solids; VS, volatile solids.

Abstract
The quest for renewable energy generation is fast increasing globally due to environmental degradation by fossil fuels. The energy production from the anaerobic codigestion of pineapple peels (PPs) and poultry manure (PM) was assessed in the present study. Prior to digestion, the PPs were pretreated using a strong acid (sulfuric acid) and a low-cost mild alkali hydrogen peroxide (H2O2) which was prepared via the adjustment of the pH of H2O2 to 11.5 by adding solution of 5 M NaOH. The physicochemical and structural parameters of the biomass, as well as microbial composition, were evaluated by using standard methodologies, while all structural changes to the biomass after pretreatment were determined using the Fourier transform infrared spectra. The application of alkaline H2O2 pretreatment removed 71.34% of lignin, reduced hemicellulose by 61%, but increased the cellulose content by 39%. The alkaline pretreated pineapple peel (Al-P PP) was able to produce about 91% more biogas than the acid pretreated pineapple peel (Ac-P PP) and 36% more than the two untreated biomass samples. The results of the economic assessment of pretreatment also showed that investment into the use of H2O2 for pretreatment is economically feasible with high net thermal and electrical energy gain, while that of acid pretreatment results in losses. Therefore, alkaline pretreatment application to PPs prior to digestion is hereby solicited in the biotechnological conversion of PPs/wastes for biogas and quality digestate which can be used as biofertilizers or soil enhancers especially in those regions where pineapple production is enormous.

KEYWORDS biogas, biomass, clean and affordable energy, climate action, environmental sustainability, optimization

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INTRODUCTION

The 21st century is experiencing a growing investment and interest in renewable energy technologies as a result of depleting fossil fuel reserves coupled with climate change and its attendant issues (Dahunsi, Oranusi, & Efeovbokhan, 2017). This has led to extensive research on the production of cleaner, environmentally friendly, and sustainable gaseous and liquid fuels from renewable bioresources which include biomass, wastes, and plant and forest residues. Energy generation from these resources is a sustainable way of dealing with large volume of wastes besides the huge potential to eliminate the indirect effects of greenhouse gas emissions from wastes, energy crops, biomass, and landfills (Dahunsi, Oranusi, & Efeovbokhan, 2017a, 2017b, 2017c).

Lignocellulosic materials, such as PPs, are basically composed of cellulose (C), hemicellulose (H), and lignin (L), and this makes them potential materials for alternative energy production especially due to the high hydrolyzable polymer chains. However, the major hindrance to fully maximizing their potentials for biofuel production is the presence of resistant L-C-H matrix which prevents the release of the hydrolyzable carbohydrates for biochemical conversion to energy and for economic viability, hence the need for pretreatment applications (Paudel et al., 2017; Zhao et al., 2018).

The major role of pretreatment is to alter the rigid and structural composition forming the building block of the lignocellulosic material, thereby facilitating the hydrolysis and subsequently bringing about efficient digestion (Dinuccio, Balsari, Gioelli, & Menardo, 2010; Zheng, Zhao, Xu, & Li, 2014). Generally, pretreatment methods can be categorized into physical/mechanical, chemical, biological, and combined (Yao, Bergeron, & Davaritouchaee, 2018) each of which is applied based on the nature of the lignocellulosic materials being studied. Ideally, a pretreatment process should achieve the following: ease the anaerobic digestion (AD) process, do not degrade sugars, solubilize lignin and other structural components, and do not cause inhibition of the digestion process (Zhao et al., 2018).

Ananas comosus (pineapple) is a humid tropical fruit that originated from Paraguay and Brazil located in the Amazon basin of South America from before spreading to the rest of the world. Among all important tropical fruits globally, pineapple is third after banana and citrus and contributes well over 20% of global production of tropical fruits especially because of its richness in sugar, bromelain, citric and malic acids, vitamins A, B, and C, minerals, and considerable amount of calcium, potassium, and fiber (Hemalatha & Anbuselvi, 2013; Joy, 2010). This undoubtedly makes pineapple often used as additional nutritional fruit for health improvement. Globally, the production of pineapple is approximately 24.8 million tons. According to the international reports, the 10 countries with the highest production of pineapple globally are Costa Rica, Brazil, Philippines, Thailand, Indonesia, India, Nigeria, China, Mexico, and Columbia (Hossain, 2016; Food and Agricultural Organization, 2018; The Daily Records, 2018). Nigeria is the 7th global producer and 1st in Africa with about 1,420 thousand metric tons annually. This shows that huge peels accrued from pineapple consumption and processing are generated in Nigeria most of which end up in the dustbin where they serve as a vehicle for transmitting pathogenic microorganisms that in turn adversely affects the health of the populace and therefore requires an urgent action in converting PPs to renewable energy.

In this study, two low-cost pretreatment procedures, that is, use of H₂SO₄ and H₂O₂, were evaluated on PPs being a lignocellulose prior to AD for the purpose of energy generation. Pineapple peels (PPs) were the main feedstock in this study with PM as cofeed. Prior to this research, few other studies have been carried out on the coconversion of different feedstock. These include the codigestion of piggery manure and algal biomass (Chen et al., 2014), microalgae and macroalgae (Dandamudi et al., 2017; Jin, Duan, Xu, Wang, & Fan, 2013), microalgae and lignocellulosic biomass (Gai, Li, Peng, Fan, & Liu, 2016), piggery manure/crude glycerol (Xi, Shahbazi, Shirley, & Wang, 2011), secondary pulp/paper-mill sludge and waste newspaper (Zhang, Champagne, and (Charles) Xu, 2011), spent coffee grounds and lignocellulosic biomass (Yang et al., 2017), and waste activated sludge and sawdust (Nzari, Yuan, Souzanchi, Ray, & Xu, 2015). Most recently are results obtained from the use of thermoalkaline pretreatment to increase solubilization of structural components of biomass leading to biogas production improvement from the coliquefaction of substrates such as Tithonia diversifolia and Chromolaena odorata shoot, Carica papayas fruit peels, Arachis hypogaea hulls, and fluted pumpkin fruit peels with PM (Dahunsi et al., 2016b; Dahunsi et al., 2017a; Dahunsi, Oranusi, Owolabi, & Efeovbokhan, 2016a, 2017b). According to available information, the data contained in this study are the first of its kind on the coliquefaction of PPs and PM. Although few previous researches had evaluated the monodigestion of PPs, there is, however, no documentation on the optimal pretreatment conditions for the optimal energy production from PPs and PM. This study is the first to elucidate both the elemental and structural characteristics and went further to show the structural changes caused to PPs as a result of pretreatment applications. Besides, the appropriate low-cost pretreatment method for PPs was established in this study and this caused the desired solubilization of structural components, especially lignin which equally caused increased biogas yield. The economic feasibility of applying pretreatment to PPs and the combustion rate of the generated biogas were also evaluated in this study. Though PM has been digested singly in several experiments, there were adverse issues of lower gas production due to low ratio between carbon and nitrogen and elevated amounts of ammonia (Dalkılıc &
Ugurlu, 2015). The recommendation from the various studies, therefore, is that PM should be codigested especially with other substrates with ability to yield high energy for higher efficiency (Pagliaccia, Gallipoli, Gianico, Montecchio, & Braguglia, 2016). Therefore, this study aimed at documenting the optimal operational conditions for pretreating PPs in order to obtain maximum biogas yield from its codigestion with PM based on experimental design. If efficiently carried out, the results of this study will bring about the optimal and sustainable use of these waste streams as adequate energy resources. This will also go a long way in helping to analyze, optimize, and subsequently establish the AD system as an efficient treatment method for PPs and PM.

2 MATERIALS AND METHODS

2.1 Sample collection

Pineapple peels were collected from local markets in Omu-Aran, Kwara State, Nigeria, while the PM was obtained from the Research Farm of Landmark University. The PPs were dried until the weight was constant and then ground with a SOLAB, SL-31 knife mill (Brazil). Sieves of 0.075–4.750 mm mesh sizes were then used for sieving so as to determine the particles that are more abundant which were then employed for the initial pretreatments study (Venturin et al., 2018). Thereafter, samples of the ground and sifted (GS) and the not sifted (NS) were stored at 4°C.

2.2 Reagents

All reagents are analytical grades; the H_2SO_4 (98% W/W minimum) used for the acidic pretreatment (Ac-P) was procured from Panoli Intermediates, India, while the 70% (standard grade) H_2O_2 that was used in the alkaline pretreatment (Al-P) was obtained from PeroxyChem LLC. In order to prepare the alkaline solution, the pH of the H_2O_2 was adjusted to 11.5 by adding solution of 5 M NaOH (Li et al., 2012).

2.3 Pretreatment experimental design

Prior to pretreatments, the response surface methodology was used in the experimental design. The first design that was performed was Ac-P with the application of sulfuric acid (H_2SO_4) in a humid steam environment with the variables: time, temperature, % H_2SO_4 concentration, and mass of substrate. The second design was Al-P with the application of H_2O_2 using the same variables with the addition of rotation (rpm) and H_2O_2 concentration (%) instead of the acid. The % composition of the three most important structural components, that is, L-C-H m/m in the pretreated PPs, was the response in the designs.

2.3.1 Acidic pretreatment

This was carried out in an autoclave with humid steam after the application of H_2SO_4. The range of values chosen for each variable was 6, 18, 30, 42, and 54 min of exposure time; temperature of 75, 85, 95, 105, and 115°C; H_2SO_4 concentration of 0.5, 1, 1.5, 2, and 2.5% (v/v); and 2, 4, 6, 8, and 10 g of dry mass according to standard methods with modifications (Sun et al., 2014; Venturin et al., 2018).

2.3.2 Alkaline pretreatment

This was done by applying H_2O_2 in an orbital shaker. The value of the various variables employed was as follows: (a) exposure time (50, 60, 70, 80, and 90 min), (b) temperature (30, 38, 46, 54, and 62°C), (c) agitation (130, 140, 150, 160, and 170 rpm), (d) mass (1.5, 3, 4.5, 6, and 7.5 g), and (e) H_2O_2 concentration (2, 5, 8, 11, and 14% [v/v]). The choice of these values was a modification to previous protocols (Rabelo, Amezquita, Andrade, Maciel, & Costa, 2011; Sun et al., 2014; Venturin et al., 2018) with the addition of 0.5 ml antifoam agent (Biocane FC 500).

2.4 FTIR analyses

The spectra of both pretreated and untreated PPs were obtained by an infrared spectrometer (IRTracer-100; Shimadzu) so as to quantify and substantiate the changes caused to the structures PPs after the application of the different pretreatment procedures (Zhao, Shao, Ma, Li, & Zhao, 2016).

2.5 Analytical procedure

All samples of PPs were analyzed so as to determine the fixed and extractive solids (untreated sample) and the three major structural components, that is, L-C-H (Sluiter, Hames, et al., 2008; Sluiter, Ruiz, Scarlata, Sluiter, & Templeton, 2008b). Evaluation of the extractable materials was carried out in all samples using the Soxhlet apparatus for 6 hr, while the fixed solid was determined after burning sample of PPs using a furnace (Sluiter, Ruiz, et al., 2008). Determination of total L-C-H was done using 0.3 g of dried sample of PPs with 72% H_2SO_4 (3 ml v/v) at 30°C for 1 hr, while the filtrate from this process was employed for carbohydrate determination (Sluiter et al., 2012). Compositions of sugars and acetic acid were determined by liquid
chromatography method, that is, LC-MS. This was done in a DIR-10A refractive index detector operated with a Bio-Rad HPX87H Column with 0.005 mol/L H₂SO₄ as mobile phase. Other parameters were 45°C, 20 μl injection volume, and flow of 0.6 ml/min. Each compound was then determined using calibration curves with corresponding Sigma-Aldrich LC-MS standards (Bazoti et al., 2017). In determining the composition of furfural and hydroxymethylfurfural, the same procedure was used except that to the LC-MS was an attached diode array detector while a C18 column was used with 1:8 acetonitrile/water as the mobile phase. An oven temperature of 30°C was used with 20 μl injection volume and flow of 0.8 ml/min. Calibrations curves were used to determine concentrations as earlier explained.

For the determination of the physicochemical properties of the samples, an inductively coupled plasma mass spectrometry was used as earlier described (Dahunsi, Adesulu-Dahunsi, & Izebere, 2019; Dahunsi, Adesulu-Dahunsi, Osueke, et al., 2019; Dahunsi, Olayanju, & Adesulu-Dahunsi, 2019; Dahunsi, Osueke, Olayanju, & Lawal, 2019). For chemical oxygen demand measurement, the standard method (APHA, 2012) was used. Concentrations of volatile fatty acids were determined by gas chromatography (Clarus 580 GC; PerkinElmer) to which was attached a flame ionization detector. For the determination of total solids (TS) and volatile solids, a standard method by the Finnish Standard Association (1990) was used, while total phenolic content of the samples was determined by using a microtube test which was followed by a 4-amino antipyrine colorimetric test (Monlau, Barakat, Steyer, & Carrere, 2012).

### 2.6 Biogas potential test

Biogas potential (BP) tests were carried out on the substrates used in this study in a bid to determine their maximum biogas production potential. The tests were carried out in a batch system using a set of 250 ml capacity minidigesters closely connected to sets of eudiometer tubes (500 ml each) with 10% (m/v) VS. The standard temperature of 37°C was used according to already described procedure (Steinmetz et al., 2016) for a 30-day retention time. The entire procedure also followed the VDI 4630 (2006) standard.

### 2.7 Codigestion experiment

The anaerobic experiment was carried out in this study using both pretreated and untreated PPs in codigestion with PM based on the best pretreatment results. The

### Table 1 Characterization of pineapple peel and inoculum before and after pretreatments

| Parameter                  | Inoculum | Poultry manure | Cellulose standard | Pretreated pineapple peel | Untreated pineapple peel |
|----------------------------|----------|----------------|--------------------|---------------------------|---------------------------|
|                            |          |                |                    | H₂SO₄ | H₂O₂ | Sifted | Not sifte |
| pH (sample+inoculum)       |          |                |                    | 7.79 ± 0.10 | 7.90 ± 0.10 | 7.80 ± 0.10a | 7.83 ± 0.10a |
| Total solids (% m/m)       | 3.9 ± 0.01 | 253.5 ± 5.02 | 95.1 ± 3.01       | 91.5 ± 0.51 | 90.1 ± 2.01 | 92.3 ± 2.01b | 93.0 ± 0.01b |
| Volatile solids (% m/m)    | 2.3 ± 0.01 | 156.1 ± 5.05 | 95.1 ± 2.01       | 85.9 ± 2.01 | 84.8 ± 1.01 | 89.4 ± 2.01c | 87.1 ± 0.11c |
| Total lignin (% m/m)       | 29.5 ± 2.01 | 5.6 ± 0.01  | ND                 | 26.3 ± 1.30 | 5.1 ± 0.01  | 17.8 ± 0.11d | 18.4 ± 0.21d |
| Cellulose (% m/m)          | 3.1 ± 0.01 | 3.2 ± 0.01  | 99 ± 3.01         | 46.7 ± 0.01 | 43.3 ± 2.01 | 26.6 ± 0.50  | 32.4 ± 0.11 |
| Hemicellulose (% m/m)      | 24.1 ± 0.01 | 1.8 ± 0.01  | ND                 | 5.2 ± 0.01  | 8.3 ± 0.11  | 22.8 ± 1.01  | 23.2 ± 0.10 |
| Fixed solids (% m/m)       | 1.6 ± 0.01 | 0.6 ± 0.01  | 0 ± 0.00          | 1.9 ± 0.05  | 1.3 ± 0.01  | 3.4 ± 0.02   | 3.9 ± 0.10  |
| Extractives (% m/m)        |          | 0.4 ± 0.01   | ND                 | ND           | ND           | 13.7 ± 0.01  | 14.4 ± 0.02  |
| Solids after pretreatment (% m/m) | —           | —           | —                  | 2.9 ± 0.02  | 2.1 ± 0.01  | —            | —            |
| Added sample (g)           | 0 ± 0.00  | 0 ± 0.00     | 1 ± 0.10          | 2.5 ± 0.12  | 2.1 ± 0.10  | 2.4 ± 0.10   | 2.3 ± 0.10   |
| COD (g COD/g VS)           | 162.11 ± 1.12 | 226.9 ± 8.05 | ND                 | 201.26 ± 1.40 | 210.52 ± 0.14 | 206.12 ± 3.00 | 206.08 ± 0.10 |
| BP (Lbiogas/kg VSad)       | 26.1     | 541.2 ± 8.09 | 622.4 ± 3.02      | 361.5 ± 5.10 | 701.5 ± 1.50 | 488.3 ± 3.10f | 520.6 ± 2.10 |
| µmax (Lbiogas kg VSad⁻¹ d⁻¹) | ND      | 202.3 ± 4.02 | 157.2 ± 2.05      | 31.4 ± 0.01 | 245.3 ± 2.10 | 46.9 ± 0.10g | 55.2 ± 0.10 |
| Day of µmax                | ND        | 2–3          | 3–4                | 5–6          | 1–2          | 4–6          | 3–4          |

**Note:** Values shown in table are means of triplicate analyses with respective standard errors; superscripts with same letters are statistically the same by Tukey’s test at 5%.

**Abbreviations:** BP, biogas potential; ND, not determined; µmax, maximum biogas generation rate.
computer-controlled batch anaerobic digester (Edibon) was used, while the sludge sample taken from a previous mesophilic digester treating cattle manure was used as inoculum (Steinmetz et al., 2016). Results of the experiment in both pretreated and untreated PPs were compared. Also, the result of the untreated sifted PPs experiment was compared with that of the not sifted experiment in order to determine possible effect of sifting on the overall biogas yield. The determination of the biogas composition and quality in terms of methane, carbon dioxide, and hydrogen sulfide was carried out using infrared and electrochemical sensors (BIOGAS 5000).

2.8 | Economic assessment of PPs pretreatments

To evaluate the economic feasibility of Ac-P and Al-P applications to PPs, the balance between the energy generated and how it is consumed was assessed. The cost of procuring thermal energy (TE) and chemicals (H\(_2\)SO\(_4\) and H\(_2\)O\(_2\)) was compared with the additional energy anticipated from the extra biogas produced due to pretreatment of PPs. The required thermal energy (RTE) in kWh/t TS for pretreating one ton TS of PPs was calculated as shown:

\[
RTE = \frac{m \times L_s \times (Q_{\text{final}} - Q_{\text{initial}})}{3,600},
\]

where \(m\) = mass of the mixture of PPs and H\(_2\)O which equals 1,000 kg; \(L_s\) = specific heat of H\(_2\)O (4.18 kJ/kg C\(^{-1}\)); \(Q_{\text{initial}} = 25^\circ\text{C};\) \(Q_{\text{final}} = 55^\circ\text{C}\).

The US cost of H\(_2\)SO\(_4\) and H\(_2\)O\(_2\) was used.

2.9 | Combustion test

This was done with the aim of assessing the combustibility of the produced biogas using a specially designed biogas stove. Previous methods (Alfa, Adie, Iorhemen, Okafor, & Ajayi, 2013; Owamah, Alfa, & Dahunsi, 2014) were employed in which water was boiled with the biogas, and the time taken to boil water was recorded which equals the energy value and combustibility of the respective biogas.

2.9.1 | Analysis of microbial community

In order to determine the diversity of microorganisms (bacteria and archaea), samples were taken from the raw substrates, mixed sludge, and digestates for the analyses of microbial community of the digesters. A total of 45 ml was taken from each sample at 5-day interval starting from the fifth experimental day and refrigerated at −20°C. Extraction of the total genomic DNA from all samples was carried out using a standard method (Vilchez-Vargas et al., 2013) followed by a conventional polymerase chain reaction (PCR) in order to capture the whole bacteria in each sample by using specific primers, that is, P338f and P518r (Boon, De Windt, Verstraete, & Top, 2002; Muyzer, Dewaal, & Uitterlinden, 1993). After DNA extraction, the qualities of the DNA and products of the PCR were verified using gel electrophoresis after which a real-time PCR was conducted employing a StepOnePlus™ Real-Time PCR System (Applied Biosystems). This gave room for the analyses of the entire bacteria and methanogens which include members of Methanobacteriales, Methanomicrobiales, and Methanosarcinaceae (Desloover et al., 2015). The real-time PCR products were checked for quality by examining all parameters obtained from the software.

2.9.2 | Data analyses

The central composite design was employed in evaluating the pretreatment procedures. After the experiments, all responses were analyzed with a 95% (\(p \leq .05\)) confidence interval. Comparison of mean was then carried out by analysis of variance (ANOVA) and Tukey’s test.

3 | RESULTS

3.1 | Characterization of PPs (untreated)

The results of sieving of the ground PPs show average particle sizes ranging from 0.856, 0.600, 0.434, 0.215, and 0.132 mm obtained from 61.6 ± 1.5%, 21.6 ± 1.0%, 16.7 ± 2.0%, 12.2 ± 2.2%, and 6.7 ± 0.9% of sample, respectively. The most common fraction was from the 0.600 mm mesh size, and this was used for the various tests, while others were discarded because they had <0.1% of the total samples sieved. From the chromatographic analyses carried out on the untreated (not sifted) PPs, the composition of the structural materials is 19.4 ± 0.21, 32.4 ± 0.11, 23.2 ± 0.10, and 3.9 ± 0.10 for total L-C-H and fixed solids, respectively (Table 1). For the untreated (sifted) sample, the values obtained are 17.8 ± 0.11, 26.6 ± 0.50, 22.8 ± 1.01, and 3.6 ± 0.02 for the four structural components, respectively. However, about 20% of the PP composition was not quantified by the HPLC analysis and was therefore called extractives. Statistically, no significant difference (\(p > .05\)) was found between both untreated PP fractions (Table 2).
### 3.2 Characterization of pretreated sifted PPs

#### 3.2.1 Acidic pretreatment

As seen in this study, the acidic pretreatment using diluted H$_2$SO$_4$ brought about the absolute solubilization of the initial hemicellulose present in the PPs as shown in Table 3. A close examination showed the breakdown of the various chemical bonding in the biomass which includes hydrogen and covalent bond as well as van der Waals forces. Another visible effect of the diluted sulfuric acid on the biomass was the depolymerization of the hemicellulose component by the hydrolysis of xylose to different monosaccharides. However, these effects were not recorded for lignin and cellulose whose concentrations increased after the Ac-P.

Based on the experimental design of the Ac-P, the PPs were optimally treated with 2% (w/v) H$_2$SO$_4$, at 121°C and 4.01 g dry mass over a period of 1 hr. With this, the lignin content increased from 17.8 ± 0.11 to 26.3 ± 1.30% m/m (32.3%) and cellulose increased from 26.6 ± 0.05 to 46.7 ± 0.01% m/m (43%), while the hemicellulose composition decreased by 77%, that is, from 22.8 ± 1.01 to 5.2 ± 0.01% m/m.

Three different responses were studied, that is, composition, of L-C-H due to pretreatment application via effect analysis, with 95% confidence interval, three of the four variables: Temperature, acid concentration, and time of exposure were significant ones. Mathematical models were derived based on these results so as to maximize the cellulosic content and to reduce the hemicellulose and lignin components in the PPs that would have brought interference during digestion. The ANOVA was used, and the three mathematical models were

| Parameter | Inoculum | Cellulose standard | Pretreated pineapple peel | Untreated pineapple peel |
|-----------|----------|--------------------|---------------------------|-------------------------|
| Ash content (%) | 5.45 ± 1.02 | ND | 6.11 ± 0.01 | 4.72 ± 0.01 |
| Moisture content (%) | 91.81 ± 3.02 | 5 | 85.51 ± 2.01 | 81.52 ± 1.01 |
| Total carbon (g/kg TS) | 265.21 ± 0.10 | ND | 629.52 ± 5.22 | 425.11 ± 6.02 |
| Total nitrogen (g/kg TS) | 48.00 ± 2.02 | ND | 30.40 ± 0.22 | 23.20 ± 0.02 |
| C/N | 6/1 | - | 21/1 | 18/1 |
| Acetate (g COD/g VS) | 1.04 ± 0.10 | ND | 0.11 ± 0.10 | 0.06 ± 0.10 |
| Propionate (g COD/g VS) | 1.04 ± 0.02 | ND | 0.15 ± 0.03 | 0.09 ± 0.11 |
| TVFAs (g COD/g VS) | 2.42 ± 0.10 | ND | 1.21 ± 0.10 | 0.12 ± 0.10 |
| Ammonia (mg/g VS) | 4.77 ± 1.01 | ND | 2.01 ± 1.10 | 2.09 ± 1.10 |
| Uronic acids (% VS) | 1.71 ± 1.11 | ND | 2.82 ± 1.10 | 2.82 ± 1.10 |
| Soluble sugars (% VS) | 4.00 ± 2.10 | ND | 8.14 ± 0.11 | 4.11 ± 0.10 |
| Phenols (mg/L) | 4.61 ± 2.10 | ND | 0.005 ± 0.01 | 0.001 ± 0.01 |
| Total phosphorus (g/kg TS) | 6.20 ± 0.02 | ND | 4.86 ± 0.12 | 3.20 ± 0.11 |
| Potassium (g/kg TS) | 7.10 ± 0.11 | ND | 7.6 ± 0.11 | 4.26 ± 0.01 |
| Phosphate (g/g TS) | 3.00 ± 0.02 | ND | 4.10 ± 0.11 | 2.04 ± 0.01 |
| Sulfate (g/kg TS) | 2.40 ± 2.00 | ND | 106.00 ± 6.10 | 55.00 ± 2.00 |
| Calcium (g/kg TS) | 82.01 ± 0.10 | ND | 523.0 ± 1.42 | 339.4 ± 0.42 |
| Magnesium (g/kg TS) | 93.00 ± 0.10 | ND | 67.00 ± 2.02 | 39.60 ± 0.02 |
| Manganese (g/kg TS) | 1.14 ± 0.22 | ND | 0.018 ± 0.04 | 0.013 ± 0.01 |
| Iron (g/kg TS) | 1.16 ± 0.11 | ND | 1.91 ± 0.03 | 0.42 ± 0.01 |
| Zinc (g/kg TS) | 3.50 ± 0.02 | ND | 35.40 ± 0.03 | 19.90 ± 0.02 |
| Aluminum (g/kg TS) | 0.77 ± 0.11 | ND | 1.42 ± 0.10 | 0.25 ± 0.02 |
| Copper (g/kg TS) | 4.81 ± 0.10 | ND | 4.34 ± 0.12 | 2.11 ± 0.10 |

Note: N = 120.

Abbreviations: COD, chemical oxygen demand; C/N, carbon/nitrogen ratio; TVFAs, total volatile fatty acids.
validated at $p < .05$ which enabled the construction of contour curves with their respective 3D plots for the composition of L-C-H. The coefficient of determination ($R^2$) values of 94.5%, 96.1%, and 98.3% for the three structural components represent a good predictive ability of the models (Figure 1).

### 3.2.2 Alkaline pretreatment

The results obtained in this study showed a departure from that of Ac-P in that Al-P with $H_2O_2$ brought about high solubilization of lignin, while the hemicellulose component of the biomass was partially solubilized. However, the composition of cellulose increased after the alkaline treatment as shown in Table 4. The optimal condition was 7.5% (w/v) at 30°C, agitation at 130 rpm, and 3 g of dry mass for 1 hr, 15 min. Under this condition, total lignin content decreased from 17.8% to 5.1% m/m (71.34%), and cellulose increased from 26.6% to 43.3% m/m (39%), while hemicellulose decreased from 22.8% to 8.8% m/m (61%).

In obtaining the statistical effects of the variables for both the total lignin and hemicellulose contents, only two variables (exposure time and $H_2O_2$ concentration) had a significant effect on the pretreated PPs with 95% confidence level. However, only one variable ($H_2O_2$ concentration) was significant ($p < .05$) in maximizing the cellulose component at 95% confidence as shown in Figure 2. The experimental design so used helped in identifying the significant variable so as to maximize the increase in cellulosic content and lignin reduction in the pretreated PPs.

**TABLE 3** Structural composition of crushed and sifted pineapple peel after $H_2SO_4$ pretreatment and actual values of the independent variables

| Run | Exposure time (min) | Temperature (°C) | $H_2SO_4$ concentration (%) | Dry mass (g) | Lignin (%) | Cellulose (%) | Hemicellulose (%) |
|-----|---------------------|------------------|-----------------------------|-------------|------------|---------------|------------------|
| 1.  | 43.77               | 120.00           | 2.00                        | 4.01        | 32.39      | 19.35         | 11.07            |
| 2.  | 42.02               | 118.00           | 2.03                        | 3.99        | 34.61      | 20.58         | 10.14            |
| 3.  | 43.01               | 119.00           | 2.02                        | 4.02        | 33.51      | 19.19         | 11.13            |
| 4.  | 43.25               | 121.00           | 2.03                        | 4.03        | 33.28      | 20.23         | 11.01            |
| 5.  | 45.33               | 119.00           | 2.01                        | 3.94        | 32.44      | 20.25         | 11.00            |
| 6.  | 44.60               | 118.00           | 2.04                        | 4.36        | 32.75      | 20.73         | 11.23            |
| 7.  | 43.56               | 119.00           | 2.01                        | 3.64        | 33.45      | 19.45         | 11.25            |
| 8.  | 45.00               | 120.00           | 2.00                        | 3.75        | 33.45      | 19.25         | 11.51            |
| 9.  | 44.97               | 119.93           | 2.02                        | 4.06        | 34.35      | 19.09         | 10.50            |
| 10. | 45.00               | 120.00           | 1.99                        | 4.15        | 32.42      | 20.28         | 11.28            |
| 11. | 44.79               | 120.00           | 2.00                        | 4.43        | 31.16      | 19.36         | 10.43            |
| 12. | 44.13               | 120.00           | 1.98                        | 3.85        | 33.21      | 19.05         | 10.29            |
| 13. | 43.87               | 120.00           | 2.00                        | 4.55        | 33.24      | 20.44         | 11.04            |
| 14. | 44.09               | 120.00           | 1.97                        | 4.01        | 33.19      | 19.32         | 10.26            |
| 15. | 43.00               | 120.00           | 2.00                        | 3.47        | 33.21      | 19.53         | 10.37            |
| 16. | 44.07               | 119.46           | 1.99                        | 4.15        | 31.43      | 19.92         | 10.92            |
| 17. | 44.13               | 117.01           | 2.00                        | 3.13        | 32.15      | 20.04         | 11.23            |
| 18. | 42.79               | 119.16           | 2.00                        | 4.19        | 33.16      | 18.26         | 11.27            |
| 19. | 44.51               | 120.00           | 1.97                        | 5.19        | 32.60      | 20.15         | 10.91            |
| 20. | 43.87               | 119.40           | 2.00                        | 3.80        | 32.54      | 19.32         | 10.03            |
| 21. | 44.07               | 120.00           | 1.90                        | 4.34        | 33.16      | 19.08         | 11.03            |
| 22. | 40.22               | 120.00           | 2.00                        | 3.10        | 32.42      | 20.21         | 11.24            |
| 23. | 42.35               | 118.95           | 2.00                        | 2.37        | 33.09      | 20.31         | 11.14            |
| 24. | 44.16               | 120.00           | 1.90                        | 5.68        | 33.43      | 19.28         | 12.03            |
| 25. | 42.00               | 119.90           | 2.00                        | 5.78        | 34.21      | 19.29         | 12.81            |
| 26. | 43.65               | 119.98           | 2.00                        | 3.74        | 33.09      | 21.28         | 12.03            |
| 27. | 43.35               | 120.00           | 1.78                        | 5.73        | 32.03      | 21.04         | 11.90            |
| 28. | 42.00               | 120.00           | 1.93                        | 4.50        | 32.23      | 22.54         | 11.23            |
| 29. | 42.11               | 120.00           | 2.00                        | 3.89        | 33.45      | 22.71         | 12.26            |
| 30. | 43.68               | 120.00           | 1.73                        | 4.09        | 33.36      | 20.13         | 12.15            |
3.3 | Assessment of untreated biomass

After the acidic and alkaline pretreatment regimes on PP, the Tukey test was used to do a comparison between the GS and NS PPs and the result showed similar and statistically insignificant composition. This equally showed that sieving had little or no effect on the composition of the biomass with or without pretreatment. Since there was no observable significant difference in the structural composition of the Ac-P and Al-P GS and the NS PPs, the evaluation of both the structural changes that occurred in PPs and biogas biochemical potential was carried out.
3.4  Structural changes in PPs

The FTIR was used to evaluate the structural changes in the molecular arrangement in both pretreated and untreated PPs as shown in Table 5. The bands were located between 3,348 and 2,900 cm⁻¹ which signifies cellulosic chemical bonds in PPs. Due to the enormous increase in cellulose content after Al-P, there was an increase in absorbance (21.3% and 54.1%) for both treated and untreated samples. However, in the Ac-P sample, the cellulosic O–H bonds decreased, thus reducing the absorbance especially at the 3,448 cm⁻¹ band. Another observation in the Ac-P sample was decreased in phenolic lignin at the peak 1,373 cm⁻¹, whereas it increased in the Al-P.

3.5  Biogas production

The results of BP showed that the inoculum had a very low potential to produce biogas as the quantity of gas it produced was not up to 10% of the total biogas produced in all experiments (Ac-P+PM, Al-P+PM, GS+PM, and NS+PM). It was also observed that production from the inoculum was lower than that of the cellulose standard which was higher than the reference 650 LNbiogas kg VSad⁻¹ by well over 80% (Figure 3). To each of the four experiments was added an initial total solid sample of 2.3 ± 0.2 g on average which had different compositions of L-C-H and solids (Table 1). For the Ac-P and Al-P substrates, 0.96 and 0.56 g were the cellulose composition, respectively, thereby making the two samples of the same contents. In terms of biogas production, the Al-P+PM had the highest

| Table 4 | Structural composition of crushed and sifted pineapple peel after H₂O₂ pretreatment and actual values of the independent variables |
|---------|--------------------------------------------------------------------------------------------------------------------------------|
| Run     | Exposure time (min) | Temperature (°C) | Agitation (rpm) | H₂O₂ concentration (%) | Dry mass (g) | Lignin (%) | Cellulose (%) | Hemicellulose (%) |
| 1       | 75.19               | 30.00            | 130.08          | 7.50                    | 3.00         | 18.30       | 38.13         | 18.23             |
| 2       | 74.80               | 32.01            | 128.00          | 7.05                    | 3.12         | 15.04       | 35.82         | 17.18             |
| 3       | 73.87               | 35.00            | 130.03          | 7.27                    | 3.30         | 16.30       | 37.49         | 17.23             |
| 4       | 52.52               | 62.00            | 170.00          | 4.50                    | 9.00         | 14.80       | 34.65         | 17.94             |
| 5       | 56.20               | 60.04            | 150.00          | 5.50                    | 6.00         | 15.01       | 38.10         | 17.87             |
| 6       | 73.74               | 31.11            | 130.00          | 7.50                    | 3.44         | 16.14       | 35.69         | 17.88             |
| 7       | 55.19               | 59.96            | 149.37          | 3.50                    | 5.00         | 16.20       | 36.60         | 16.72             |
| 8       | 53.56               | 55.25            | 170.00          | 5.94                    | 5.01         | 15.22       | 38.09         | 17.71             |
| 9       | 62.54               | 30.00            | 130.00          | 6.47                    | 3.00         | 15.41       | 36.61         | 17.82             |
| 10      | 60.18               | 62.00            | 156.98          | 7.13                    | 4.00         | 14.94       | 38.34         | 17.51             |
| 11      | 86.90               | 30.00            | 130.01          | 4.26                    | 3.00         | 15.03       | 36.15         | 17.97             |
| 12      | 77.21               | 35.01            | 140.00          | 4.45                    | 3.91         | 15.52       | 36.26         | 18.15             |
| 13      | 54.73               | 31.40            | 130.00          | 5.31                    | 3.00         | 15.82       | 36.64         | 17.29             |
| 14      | 66.63               | 30.02            | 140.00          | 4.12                    | 3.00         | 14.04       | 35.03         | 17.74             |
| 15      | 72.76               | 30.00            | 170.00          | 4.48                    | 4.60         | 15.92       | 36.77         | 18.46             |
| 16      | 65.29               | 42.05            | 140.00          | 5.50                    | 3.00         | 16.14       | 35.48         | 17.92             |
| 17      | 58.64               | 30.00            | 170.03          | 3.00                    | 4.95         | 15.23       | 36.92         | 16.23             |
| 18      | 60.33               | 30.00            | 165.03          | 3.54                    | 5.00         | 15.28       | 38.88         | 16.34             |
| 19      | 57.96               | 42.40            | 145.05          | 3.76                    | 3.02         | 15.93       | 36.09         | 17.09             |
| 20      | 57.36               | 30.00            | 140.92          | 4.43                    | 3.99         | 15.03       | 36.51         | 16.27             |
| 21      | 50.73               | 35.10            | 170.03          | 5.54                    | 3.79         | 15.66       | 37.92         | 17.28             |
| 22      | 55.00               | 30.00            | 140.43          | 5.26                    | 3.00         | 14.28       | 37.28         | 15.66             |
| 23      | 78.28               | 30.00            | 130.45          | 5.80                    | 3.00         | 15.24       | 35.63         | 17.29             |
| 24      | 58.07               | 50.10            | 165.93          | 6.91                    | 5.00         | 15.25       | 37.81         | 17.23             |
| 25      | 80.30               | 30.01            | 159.38          | 4.39                    | 3.76         | 13.24       | 36.99         | 16.39             |
| 26      | 59.81               | 62.00            | 139.03          | 6.10                    | 5.71         | 14.93       | 37.54         | 16.28             |
| 27      | 78.81               | 30.01            | 143.23          | 5.03                    | 6.52         | 13.43       | 35.27         | 17.42             |
| 28      | 67.59               | 31.00            | 150.03          | 4.05                    | 5.54         | 14.28       | 36.52         | 17.92             |
| 29      | 69.07               | 60.00            | 168.22          | 4.38                    | 2.03         | 14.92       | 35.43         | 16.90             |
| 30      | 54.19               | 34.02            | 150.18          | 5.51                    | 4.14         | 14.23       | 36.00         | 17.69             |
which compared favorably with the cellulose standard containing only $1 \pm 0$ g of initially added sample. The Al-P+PM was able to produce about 91% more biogas than the Ac-P biomass, whereas the former also produced 36% more biogas than the two untreated samples that were digested. Considering the untreated samples, biogas generation from the NS+PM sample was higher than the GS+PM which was statistically significant according to Tukey’s test, while generation from both surpassed that of the Ac-P biomass.

Overall, biogas produced from the Ac-P+PM, Al-P+PM, GS+PM, and NS+PM samples is $211.7 \pm 7.1$, $667.8 \pm 10.1$, $380.6 \pm 5.4$, and $397.9 \pm 5.6$, respectively. Also, the Al-P biomass produced 57% higher than what was obtained from the cellulose standard and this was achieved on an average of

![Figure 2](image-url)  
**FIGURE 2** Contour lines for the optimization of alkaline pretreatment for pineapple peel
2 days before. Looking at the retention time of 30 days used in this study and the corresponding biogas production, it was observed that total production was achieved in just 10 days, that is, commenced on the 2nd and climaxed on the 11th day; thus, a lower retention time was achieved in this study with a corresponding increase in biogas yield.

The produced biogas from all experiments showed composition ranging between 61 ± 1.4 and 68 ± 0.4 methane, and 24 ± 2.6 and 32 ± 1.5 carbon dioxide, while lower hydrogen sulfide value ranging between 19 ± 1.4 and 23 ± 0.2 was recorded.

### 3.6 | Cooking test

The results obtained from the cooking tests carried out revealed higher cooking rates for both water and rice, that is, 0.05 L/min and 0.0032 kg/min, respectively, obtained from the biogas resulting from the Al-P+PM. The biogas obtained from the Ac-P+PM showed lower rates of 0.12 L/min and 0.0044 kg/min, respectively. This was, however, higher than those produced from the GS+PM and NS+PM experiments with values of 0.12 L/min and 0.0045 kg/min and 0.14 L/min and 0.0046 kg/min. Based on the stove’s configuration, the flow rate of the biogas was determined as 0.0053 m³/min. Overall, the improvement of 58.33% and 27.27% was obtained as cooking rates of both commodities using the biogas produced from Al-P+PM over that from Ac-P+PM.

### 3.7 | Digestate composition

After the anaerobic codigestion experiment, the digestates from all the samples were analyzed to quantify their structural and elemental compositions. From the results, there was increase in the L and C-H complex ratio. The value for the ratios was 0.5–0.9, 0.2–1.6, 0.3–1.1, and 0.4–1.0 for Ac-P+PM, Al-P+PM, GS+PM, and NS+PM experiments, respectively. The lowest ratio was obtained from the Ac-P+PM experiment which also produced the least biogas which further showed that the bulk carbohydrate content of the digester
was not efficiently consumed. In the same vein, the fraction of hemicellulose initially added to the samples was not efficiently consumed especially in the Al-P+PM and untreated samples which has mean hemicellulose contents of approximately 8.8±0.11 and 23.2±0.10, respectively, which further showed less efficiency in carbohydrate utilization.

### 4 | DISCUSSION

The quantities of total L-C-H and fixed solids obtained in this study correspond with earlier results (Cai et al., 2016; Li et al., 2016; Su, Sun, Liu, & Lü, 2006; Venturin et al., 2018). In the experiment of Su et al. (2006) on cornstalk, values of 17.4 ± 0.3%, 36.5 ± 0.3%, 28.9 ± 0.3%, and 5.2 ± 0.8% for the four structural components, respectively, were reported. In Cai et al. (2016), the values of 21.4%, 43.4%, and 19.5% were reported for L-C-H, respectively, when the whole parts of corn were analyzed. For Li et al. (2016), different parts of corn were evaluated for their structural composition and the result showed 20 ± 2%, 34 ± 3%, 24 ± 2%, and 2% of total lignin, glucose (cellulose), arabinose + xylose (hemicellulose), and fixed solids, respectively. Also, in the study carried out by Venturin et al. (2018) on the chemical properties of cornstalk, a total of 18.9 ± 1.4%, 32 ± 0.5%, 23.5 ± 0.5%, and 3.8 ± 0.2% were obtained for lignin, cellulose, hemicellulose, and fixed solids, respectively. These show that
PPs and cornstalk have similar characteristics in terms of structural composition. As seen in this study, both Ac-P and Al-P had enormous effects on the resulting structures of PP. For the Ac-P, the optimum conditions of 2% (w/v) H₂SO₄, 121°C, and 4.01 g dry mass for 1 hr brought about high solubilization of hemicellulose as seen in previous studies (Baadhe, Potumarthi, & Mekala, 2014; Li et al., 2016; Venturin et al., 2018) in which the substrate (cornstalk) was subjected to A-P and the results revealed near-complete hemicellulose removal. However, a striking improvement here was the use of less acid and time reduction with higher solubilization of hemicellulose. At the same time, the increase in the concentration of lignin and cellulose due to acidic treatment agrees with Cai et al. (2016) who used Ac-P on corn and recorded 25% increase in each cellulose and lignin, whereas the hemicellulose content decreased by 87%. Similar results were obtained in other previous studies (Guo et al., 2011; Li et al., 2016; Song, Liu, Yan, Yuan, & Liao, 2014; Wang et al., 2018) in all
of which the hemicellulose component of various ligno-
celluloses was dissolved resulting in the reduction in its
content while those of cellulose and lignin increased after
Ac-P. One of such important studies was carried out by
Fernández-Cegrí, Raposo, De Rubia, and Borja (2013)
with the observation that H_2SO_4 failed to dissolve the lig-
nin content of the oil residue of sunflower. Though the
 cellulose content increased in the pretreated biomass in
this study, there was an obvious modification of the cel-
lulose as a result of exposure to acid, temperature, and
pressure as previously reported for other biomass (Cai
et al., 2016; Li et al., 2016; Zhao et al., 2016).

In contrast to Ac-P, a major observation in the Al-P PPs
was an enormous breaking of lignin bonds. Usually, lignin
is composed of many chemical groups which are also as-
associated with the 1633, 1604, 1734, 1716, and 1516 cm\(^{-1}\)
band which were reduced after A-P of PPs with the excep-
tion of the last band due to its strong association with lignin.
However, all these peaks were seen to have been completely
ruptured or flattened and even disappeared in some cases
after treatment with hydrogen peroxide, thereby leading to
enormous solubilization. Previous studies have reported
similar trends after using various hard and soft alkalis vary-
ing from H_2O_2, NaOH, and KOH (Dahunsi, 2019a, 2019b;
Dahunsi, Adesulu-Dahunsi, & Izebere, 2019; Dahunsi,
Adesulu-Dahunsi, Oseuke, et al., 2019; Dahunsi, Olayanju,
et al., 2019; Dahunsi, Osueke, et al., 2019).

Besides, different studies reported slightly different re-
results when alkaline H_2O_2 pretreatments were applied (Sun,
Li, Yuan, Xu, & Sun, 2013). In the study by Cai et al. (2016),
alkaline H_2O_2 was used to pretreat corn straw and the after-
math was reduction in the L-C-H contents by 19.6%, 32.8%,
and 6.2%, respectively in comparison with the initial values.
In another study, Sun et al. (2013) treated corn straw with
H_2O_2 in which the cellulose and hemicellulose contents in-
creased by 31.4% and 33.3% with a reduction in lignin con-
tent by 38.9%.

Overall, treatment with H_2O_2 in this study brought about
over 80% decrease in the lignocellulosic ratio as against the
increment seen after Al-P with H_2SO_4. These results also
strongly agree with previous studies showing an increase
in structural composition especially lignin after Ac-P (Li
et al., 2016; Yao et al., 2018). This result further corro-
bates the submission of Lizasoain et al. (2017) and Yao
et al. (2018) that pseudo lignin was formed after pretreatment
of corn and wheat stalks under severe conditions character-
ized by extremes of temperatures and pressures and which in
turn reduced biogas generation and sometimes caused com-
plete failure of the AD process.

Most of these inhibitions are caused by different forms of
lignin. For example, the phenolic lignin is not readily absorbed
in AD (Alfa, Dahunsi, Iorhemen, Okafor, & Ajayi, 2014).
During Ac-P in this study, the H_2SO_4 acted preferentially on
the phenolic lignin fraction bringing about changes in the lig-
nin structure, whereas H_2O_2 acted on the entire lignin. Also,
the composition of syringyl ring (1,329 cm\(^{-1}\) band) increased
after pretreatment with H_2O_2 more than what was found in
the untreated biomass (Alfa et al., 2014; Li et al., 2010;
Sun et al., 2013; Wang et al., 2013). For the acetyl lignin
(1,251 cm\(^{-1}\) band), there was a decrease after both Ac-P and
Al-P which was more pronounced in the H_2O_2 treated sam-
ple with about 39.6% (Alfa et al., 2014; Wang et al., 2013).
There was a decrease in peak intensity at 1,059 cm\(^{-1}\) caused
by hemicellulose breakdown which is the hallmark of pre-
treatment with H_2SO_4 (Alfa et al., 2014).

Two kinds of cellulose were prominent in PPs, that is,
crystalline and amorphous cellulose (1,110 cm\(^{-1}/897\) cm\(^{-1}\)).
The ratio between these two showed a 51.3% and 19.4% de-
crease for Al-P and Ac-P, respectively (Cai et al., 2016; Li
et al., 2010, 2016). Venturin et al. (2018) did observe ele-
vated yield of biogas after using H_2O_2 for pretreatment.

A major factor that enhanced enormous biogas gener-
ation from this study was the addition of the cofeed (PM)
which brought about the balance in the feedstock in terms
of carbon and nitrogen ratio as well as supplying adequate
nutrients for the microbial flora of the digester. Poultry ma-
ure is very rich in nutrients, and the availability of these
especially in a microbial-laden environment such as the an-
aerobic digestor is key to the functions and overall success
of AD.

Judging by the biogas production in this study, the Al-
P+PM experiment produced the highest followed by the
NS+PM sample which contains all particle sizes all of
which contributed to the biogas generation as against the
GS+PM sample that produced lesser biogas. As shown in
Figure 3, there was a 51% higher biogas production by the
Al-P+PM above the untreated sample showing that the use
of alkali for pretreatment is very effective. This efficiency
was further demonstrated in the maximum rate of biogas
production which was highest in Al-P experiment coupled
with the days that the maximum biogas production was
achieved among the four different treatments. This justi-
fied and also suggests the need for pretreating lignocellul-
losic biomasses before treatment via AD (Alfa et al., 2014;
Mancini, Papiro, Riccardelli, Lens, & Esposito, 2018).
From the cooking test, the difference seen in cooking time
for each commodity could be a function of the gas quality
in terms of methane content in each case. From digestate
analysis, it is clear that the carbohydrate contents of all di-
gesters were not efficiently utilized during digestion which
corroborates the earlier report of Croce, Wei, Imporzano,
Dong, and Adani (2016).

In using the combined heat and power system for com-
cputing the balance of energy, thermal and electrical effi-
ciciencies of 50% and 35% were used, respectively (Dahunsi,
Olayanju, et al., 2019). The RTE to raise the
temperature of the mixture of PPs and H₂O from 25 to 55°C was therefore determined, while heat loss was neglected (Dahunsi, Olayanju, et al., 2019; Dahunsi et al., 2017a, 2017b, 2017c). For the Al-P experiments, the 1504 kWh/t TS TE gain was higher than the 921 kWh/t TS TE that was initially required to carry out the pretreatment procedure, thus giving a net TE of 583 kWh/t TS. It is possible to increase this net energy up to 80% by the adoption of heat exchanger during pretreatment or for digester heating (Dhar, Nakhla, & Ray, 2002; Zabranska, Dohanyos, Jenicek, & Kutil, 2006). Otherwise, TE can be fully integrated as an effective method of assessing the economics of this study (Fdz-Polanco et al., 2008; Perez-Elvira & Fdz-Polanco, 2012). For the Ac-P PPs, all investments seem abortive seeing that the −200 kWh/t TS TE gain was far below the 1,236 kWh/t TS TE required for the Ac-P with a net TE of −1,436 kWh/t TS.

For the evaluation of electrical energy (EE), only the energy utilized for mixing of substrates was considered, while that used for the mechanical grinding of PPs was neglected since the same mechanical procedure was employed for all samples of PPs prior to AD (Dahunsi, Olayanju, et al., 2019; Dahunsi et al., 2017a, 2017b, 2017c; Menardo, Airdoldi, & Balsari, 2012). For the Al-P experiment, the net EE of 874 kWh/t TS far exceeded the −633 kWh/t TS obtained in the Ac-P experiment. This further confirms the economic suitability of using Al-P as against the use of acids which causes loss in investments. The net TE and EE obtained are suitable for selling to direct users or injected into regional or national energy grids following existing and standard governmental policies.

5 | CONCLUSIONS

The application of alkaline H₂O₂ pretreatment brought about the removal of the lignin content of PPs up to 71.34%, reduced hemicellulose by 61%, but increased the cellulose content by 39% in this study. The Al-P PPs were able to produce about 91% more biogas than the Ac-P biomass and 36% more than the two untreated biomass samples that were digested. Prior to this research, Al-P using the mild alkali H₂O₂ remained grossly unexplored in the treatment of lignocelluloses for the purpose of enhanced biogas production, whereas the use of strong alkalis and acids such as NaOH, KOH, and H₂SO₄ for conventional biomass treatments is well-studied. However, the use of a mild alkali H₂O₂ as reported in this study gave higher biogas yield than all the conventional methods. Therefore, the use of mild Al-P is hereby solicited in the biotechnological conversion of PPs for biogas and quality digestate which can be used as biofertilizers or soil enhancers especially in major pineapple-producing regions of the world.

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CONFLICT OF INTEREST

The author declares no conflict of interest whatsoever.

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