Enhancing Hydrolysis and Syntropy Simultaneously in Solid State Anaerobic Digestion: A GRA – Taguchi Based Study and Techno-Economic Assessment for Austainable Bioeconomy

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Research

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Enhancing hydrolysis and syntropy simultaneously in solid state anaerobic digestion: A GRA – Taguchi based study and techno-economic assessment for sustainable bioeconomy

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Abstract

Background: Solid-state anaerobic digestion of agricultural stubble is attractive technology for energy and bioeconomy as well as it may lead to transitioning towards greenhouse gas neutrality; yet hydrolysis and syntropy affects the process and makes it economically nonviable. In this regard, present study investigates the effect of alkali and biochar addition for simultaneous increment of hydrolysis and syntropy for higher methane yield from pearl millet straw. Further, taguchi based design of experiment was coupled with grey relation analysis for multiple output evaluation and detailed techno-economic assessment was performed.

Results: Study showed that 0.5 g/100g pearl millet straw of alkali and 10 g/L of biochar was the optimised dosing along with 20% total solid concentration and 4 as feedstock/inoculum ratio. Statistically, contribution of biochar and alkali was 48 and 21% respectively on the multiple output. The confirmation test revealed that hydrolysis rate constant, *k* for reactor having optimised conditions was 0.0521 d^{-1} while for control, it was 0.0595 d^{-1}. Cumulative methane yield was also increased by 1.8-fold for optimised condition. Techno-economic assessment showed that capital cost and electrical efficiency of combined heat and power unit have dominant effect on the investment. Solid state anaerobic digestion of pearl millet straw with alkali and biochar showed US$ 25652 of net present value and showed to have payback time of 8.2 years with 11% of internal rate of return.

Conclusion: The simultaneous increment of hydrolysis rate and syntrophic activity in optimized condition helped to achieve higher methane yield. Techno-economic assessment showed that shorter payback time and higher internal rate of return, making large scale project profitable and viable which may endorse sustainable bioeconomy with lower greenhouse gases.

Keyword: Methane; Taguchi; Gray Relation Analysis; Syntropy; Hydrolysis; Greenhouse gas, Techno-economic assessment; Bioeconomy

Background

Economic growth of any developing country is directly related to energy and its utilization [1]. India, one of the fastest growing country and economy, was reported to have 634 million tonnes (MT) of lignocellulosic biomass and residues [2]. These lignocellulosic biomass and residues may be utilised as sustainable source of biofuels for bioeconomic development using various biotechnological processes. Also, the agricultural biomass may contribute to energy security of India [3]. Lignocellulosic biomass comprises of cellulose and hemicellulose as polymeric sugars and lignin to protect plant from oxidative stress, pathogens etc. The carbon present in lignocellulosic biomass may be utilised as source of energy in the form of biofuel (here methane) through anaerobic digestion (AD) [4]. The produced biomethane in AD has multiple usage such as cooking fuel in rural areas, source for combined heat and power (CHP) generation or in transportation for greenhouse gas (GHG) neutrality and also for sustainable bioeconomy. The stress on fossil fuels or primary energy provider may be reduced by installing large scale AD plants running on lignocellulosic biomass and building efficient supply chain management of the biomass as well as generated biomethane.

Inherently, lignocellulosic biomass has recalcitrant nature as lignin's present on outer part of biomass that opposes the degradation. This recalcitrant behaviour results in lower biogas yield [5]. Apart from this, steps involved in AD process, govern the overall health and performance of AD reactor and biogas production. The steps of AD are hydrolysis, acidogenesis, acetogenesis and methanogenesis. Each step has its own significant role in AD process for smooth operation of the reactor subsequently resulting in higher methane yield. While complex nature of lignocellulosic biomass limits hydrolysis and growth of cellulolytic microbes, excess hydrolysis may trigger enhanced acidogenesis and volatile fatty acids (VFAs) accumulation which may hamper the methanogens and thus the subsequent methane yield. To enhance the hydrolysis of lignocellulosic biomass various treatment approaches have been explored [3, 5].

Physical (milling, shredding, microwave), biological, biochemical and chemical treatment (alkaline, acidic) are most commonly used technologies for enhancing methane production from lignocellulosic biomass. Alkaline treatment at high temperature is reported as effective in breaking ester bonds and swell the lignocellulosic biomass for enzymatic action [6].

Alkali (e.g., Ca $(OH)_2$, NaOH, KOH and ammonia) is more favourable over acid (e.g., sulphuric acid) treatment of biomass due to removal of amorphous components such as lignin, hydrolysing the acetyl groups of hemicelluloses reducing steric hindrance, and thereby enhancing cellulose digestibility [7]. In addition, the degree of polymerization gets affected by the alkaline treatment resulting in change of surface area and crystallinity. Also, presence of alkali in the treated biomass helps to alleviate pH during acidogenesis phase and subsequently improves methanogenic activity. However, right concentration of alkali should be added as excess addition may raise the pH of the system that may cause lower methane yield [8]. Li et al. [9] examined the effect of KOH and $Ca(OH)_2$ in combined mode for treating corn stover prior to AD. Results revealed that combined effect of alkalis (0.5% KOH + 2% $Ca(OH)_2$) helped to reach up to 271 L/kg volatile solid (VS) of methane and it was 1.77 fold to that untreated corn stover. Liu et al. [10] attempted alkali treatment (2 – 50% KOH) on wheat straw and reported that maximum methane yield was observed at 20% KOH along with enhanced sugar yield. Liew et al. [11] reported effects of simultaneous addition of NaOH (2, 3.5 and 5% loading mixed in inoculum) using fallen leaves in AD and reported that adding 3.5% of NaOH showed a 24-fold increment in cumulative methane yield. However, if simultaneous addition of alkalis such as KOH breaks the threshold, the K^+ ions may disturb the osmotic regulation of microbial cell which may cause the dryness of cell and reduce the turgidity that may lead to lower methane yield [12].

A balanced syntropy between acidogenesis and methanogenesis is also required for smooth operation of AD process apart from increased hydrolysis by treated biomass. Enhanced hydrolysis rate in an AD reactor may decrease the pH due to VFAs accumulation and disturb the archaeal community dynamics responsible for methane production. To overcome the problem of VFA accumulation and subsequently decreased pH, carbon based conducting materials (CBCM) have been endorsed to improve electron transfer between acidogens and methanogens [13]. In anaerobic bioreactor, hydrogen and formic acid can simply be utilized by methanogens via indirect interspecies electron transfer (IIET) given that the partial pressure is favourable to IIET. However, syntropy may get disturbed if partial pressure of hydrogen is high and it may cease the IIET. This leads to VFA accumulation and decrease of pH in AD bioreactor. This only route of interspecies electron transfer in AD may be replaced by CBCM which provides direct interspecies electron transfer (DIET) in the system. Carbon based materials such as activated carbon, biochar, carbon cloth and granulated activated carbon are now extensively reported for reducing acid stress in the AD reactor and improving DIET simultaneously. In an experiment, Wang et al. [14] mentioned that lag phase shrinks by 67% once sawdust biochar was added to AD bioreactor as it diminishes the oxidation of VFA. In the research performed by Paritosh et al. [4] methane yield increased by 2-fold in the solid state anaerobic digestion (SSAD) of wheat straw by employing hardwood biochar. Results revealed that VFA concentration was less in the biochar added reactors while control showed higher VFA accumulation.

In addition to boost the hydrolysis and syntropy due to disruption of lignin and CBCM respectively, total solids (TS) of AD reactor also impact the volumetric methane yield [5]. The reactors having less than 15% TS are termed as liquid anaerobic digestion (LAD) systems while those having more than 15% TS are called as dry or SSAD systems. SSAD has numerous benefits over LAD as it may encompass huge volume of biomass, may shorten digestion period and may reduce the heating load [5]. However, increased TS of lignocellulosic biomass in SSAD reactor may hamper the hydrolysis due to presence of lignin or may enhance the VFA accumulation which affects methanogenesis [15]. Apart from these technical aspects, the profitability, at last, affects the acceptability of any biogas project proposal and its sustainability for bioeconomy as well as the GHG transitioning. A detailed techno-economic assessment of a biogas project is needed for making bioeconomy business a success with lower GHG emissions.

To overcome the above said problems, simultaneous addition of alkali and CBCM may be employed in SSAD of lignocellulosic biomass. The idea was to improve hydrolysis by removing lignin with the help of mild alkali addition and to enable syntropy by adding CBCM simultaneously for higher methane yield in SSAD. Also, in order to optimize the input parameters; along with biotechnological tools, various optimization techniques such as response surface method (RSM), artificial neural network (ANN) and Taguchi's design of experiment (DoE) have been incorporated for robust output [16]. However, selection of Taguchi's (DoE) is fruitful because it helps to examine various input factors as well as their levels with lesser experimental setup [17]. Taguchi's DoE approach measures the output of input variables in signal-to-noise ratio (S/N) and provides qualitative assessment. S/N ratio was selected based on the requirement of the experiments which are smaller-the-better, nominal-the-better or larger-the-better for optimized input parameters. However, the limitation of Taguchi's DoE is that it cannot optimize multiple objective problems. So, in this regard, Grey relation analysis (GRA) was clubbed with Taguchi's DoE for multiple objective optimization. After experimental evaluations, techno-economic assessment was also performed for a sustainable bioeconomy.

Thus, in the present study, a Taguchi's DoE based GRA was performed for biomethane production using mono-digestion of pearl millet straw (PMS) under SSAD. The parameters selected were TS (%), F/I, addition of KOH (g/100g of PMS) and pyrolysis hardwood biochar (PHWBC) (g/L inoculum). Three different levels of all input parameters were selected under the L_9 orthogonal array for the experiment. For analysing the output parameters and for main effect plot and for analysis of variance (ANOVA), Minitab 15 was used as statistical software. Based on the output of Taguchi's DoE; a confirmation test was also performed. The results of confirmation test were used to assess the techno-economic viability of a full scale SSAD plant running on obtained scenarios.

Results and discussion

Experimental setup and observations

L_9 orthogonal array (3^4) employed for experimental setup and output responses were calculated for 60 days of SSAD under batch system. Methane yield, VS reduction, pH of the trials and TVFA/alkalinity ratios were measured after the end of L_9 orthogonal setup of experiment. Cumulative methane yield for all the trials is shown in Figure 1. Experimental investigation showed that maximum methane yield was observed at 20% TS which was 226 L/kg VS in trial R2. It was also observed that trial R2 showed 91 and 38% higher methane yield to that of trial R1 and R3 having same TS content (20%). This may be ascribed to the fact that VS reduction in the case of trial R1 and R3 was 39 and 44% which was 22 and 8% less as compared to R2 respectively (Figure 2). Further, increasing TS content from 20% to 22.5 and 25% did not help to improve the methane yield significantly. The maximum methane yield observed in trial R6 and R8 which was 184 and 174 L/kg VS for 22.5% and 25% TS respectively. This observed methane yield was 52 and 43% lesser as compared to trial R2 respectively. The subsequent VS reduction in R6 and R8 was examined as 43 and 41% which was 1.11 and 1.16-fold less to the best performing trial (R2) (Figure 2). Similar observations were made by Abbassi-Guendouz et al. [18] for SSAD of cardboard with TS ranging between 10-35%. It was reported that rate of methane production was inversely proportional to the TS content in the SSAD reactor increased. It was also contemplated that beyond 30% TS, methane production rate was highly inhibited. Suksong et al. [19] also reported that increasing TS content from 16 to 25 and 30% did more harm than good in SSAD of palm oil mill effluent.

The role of pH is also crucial as pH may help to understand the pattern of methane yield as methanogens are sensitive to change in pH (Figure 2). The suggested pH is 7.4 for AD reactor to function properly [8]. Results obtained were supporting the statement as the lowest pH was observed in the case of R1 which was 6.9 at the end of the experiment. Interestingly, the cumulative methane yield was also lowest in the trial R1 which was 118 L/kg VS (Figure 2). The pH of trial R2 was 7.5 which was near the suggested value and methane yield was also maximum (226 L/kg VS). The second and third highest methane yield have noted the pH 7.8 and 8.8 respectively after the end of experiment which was 0.4 and 1.3 unit more to that of R2. Measurement of TVFA/alkalinity ratio is also required to monitor the stability of SSAD reactor as pH is not sole indicator of reactor's wellness. Simultaneous KOH or NaOH addition may enhance the lignin disruption and subsequently pH drop may be observed due to TVFA accumulation at acidogenesis stage [11, 15]. However, PHWBC may enable a balanced electron transfer network trough DIET within the anaerobic reactor. Furthermore, presence of PHWBC in excess amount may increase the alkalinity of the reactor due to alkaline nature of PHWBC. In this regard, the TVFA/alkalinity ratio may be observed as stress indicator of SSAD reactor [20]. Though this ratio will be unique for each reactor, the ratio of 0.4 and 0.6 is considered as optimal and as excess organic loading in liquid AD [21]. The maximum TVFA/alkalinity ratio was observed as 0.86 at the loading of 0.5% (w/w) KOH and 10 g/L of PHWBC in the case of trial R1 followed by trial R9 as 0.73 at 1% (w/w) KOH and 10 g/L PHWBC respectively (Figure 2). The minimum TVFA/alkalinity ratio was observed in trial R5 (1.5% KOH, and 10g/L PHWBC) which was 0.17. The optimal ratio is reported as 0.4 and the TVFA/alkalinity ratio observed for trial R2, R6 and R8 was 0.37, 0.36 and 0.44 which was nearby optimal value. Interestingly, trial R2, R6 and R8 also showed maximum methane yield in the set of 20, 25.5 and 25% TS respectively. Alike results were observed by Liew et al. [11] in which simultaneous NaOH treatment of corn stover in SSAD not only increased the digestibility but also helped to maintain the buffering capacity of the reactor against excess acid accumulation.

Analysis of Taguchi based GRA

Table 1, 2 and 3 shows the values of normalizing sequence, deviation sequence and grey relation coefficient for GRA respectively. All the output response such as cumulative methane yield, VS reduction, pH and TVFA/alkalinity was normalized first. The normalization of cumulative methane yield and VS reduction is performed as "larger-the-better" using Eq. 5. For pH and TVFA/Alkalinity ratio, "nominal-the-better" was applied using Eq. 7 as pH and TVFA/alkalinity ratio should be in a specific range. The target value in Eq. 7 was given as 7.4 for pH and 0.5 for TVFA/alkalinity ratio [8, 21].

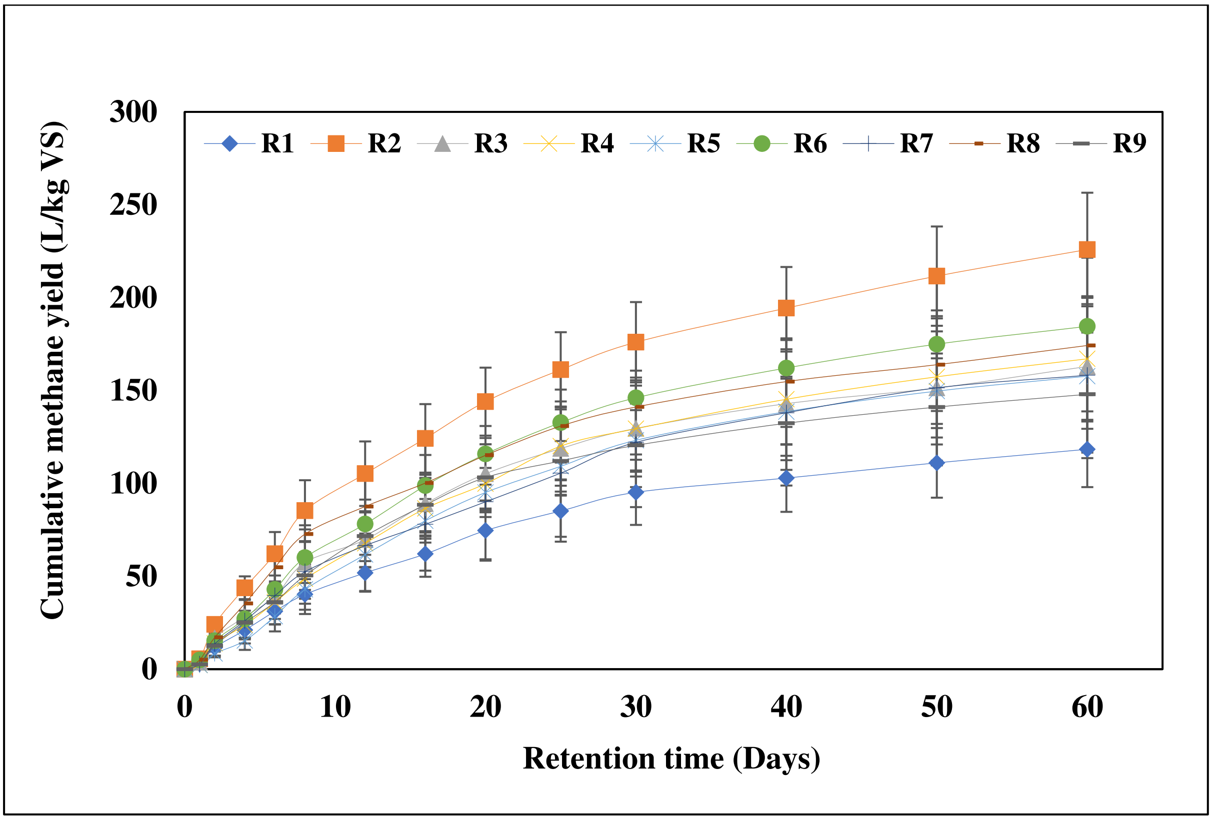
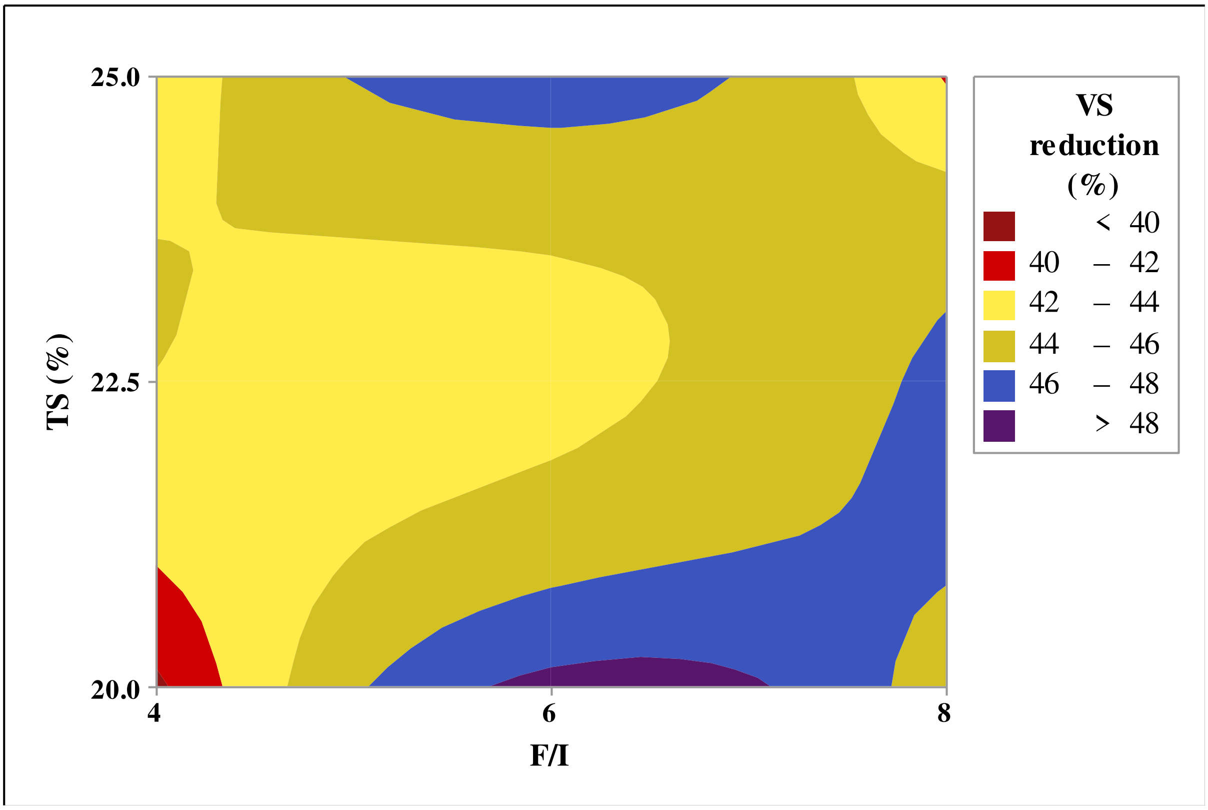
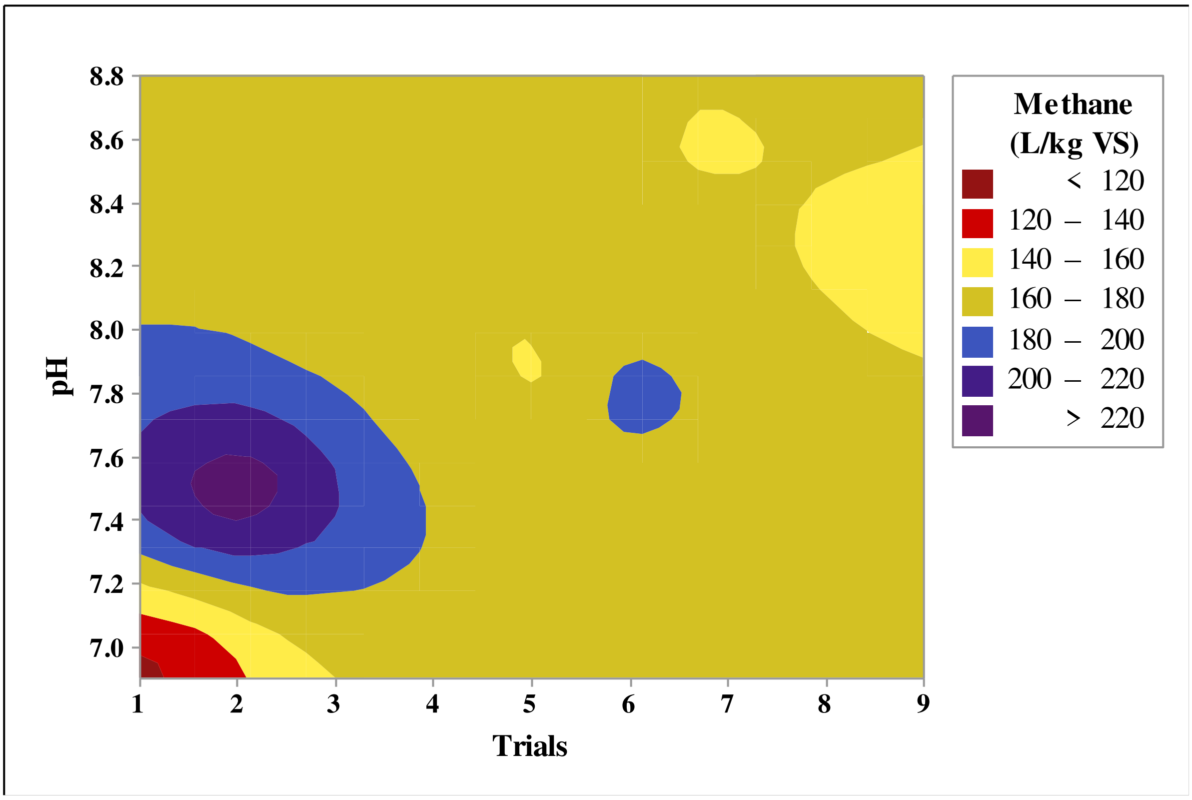


Figure 1: Cumulative methane yield of the trials based on Taguchi's DoE



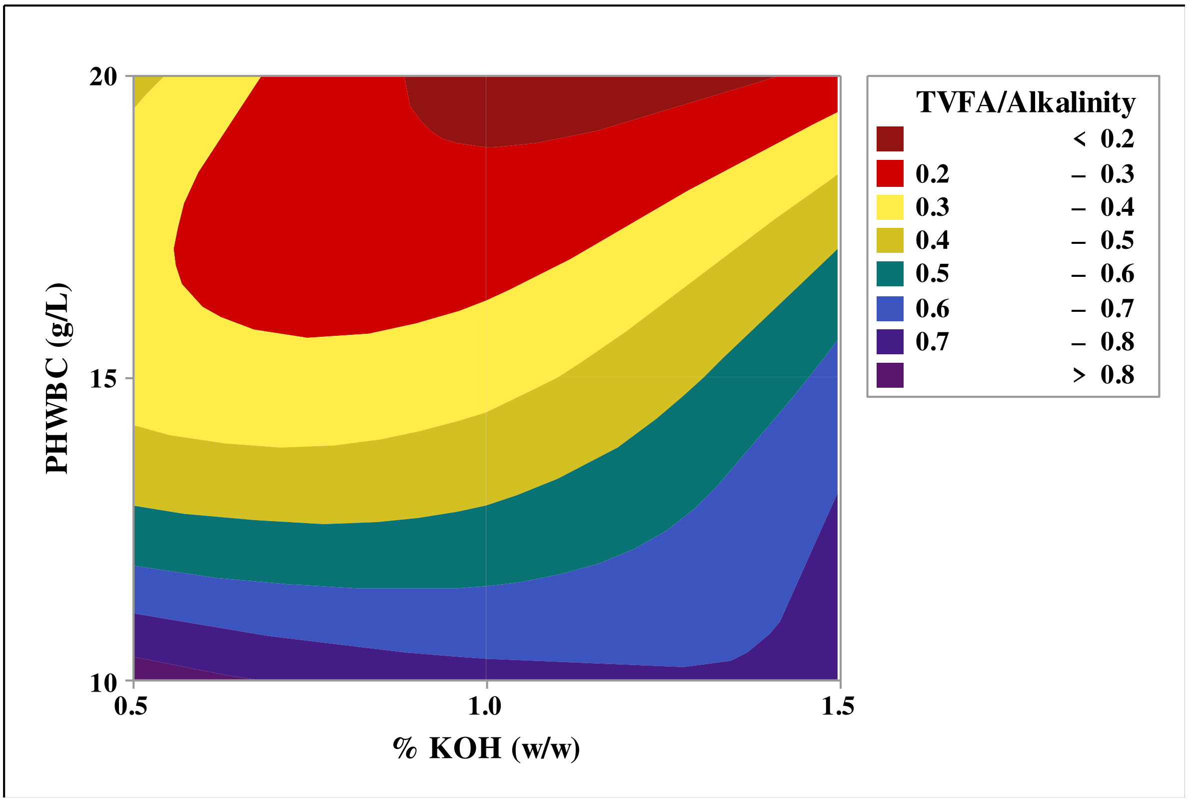
25.0
22.5
20.0
TS (%)
4
6
8
F/I
VS reduction (%)
< 40
40 – 42
42 – 44
44 – 46
46 – 48
> 48

(a)



8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
7.0
pH
1
2
3
4
5
6
7
8
9
Trials
Methane (L/kg VS)
< 120
120 – 140
140 – 160
160 – 180
180 – 200
200 – 220
> 220

(b)



(c)

Figure 2: Surface plot showing (a) relationship among TS, F/I and VS reduction (b) relationship between pH and cumulative methane yield (c) effect of KOH and PHWBC concentration on TVFA/alkalinity ratio

As per the normalized sequence, grey relation coefficient was determined for every individual output using Eq. 8 in which deviation sequence was calculated using Eq. 9. The grey relation grade (GRG) was then determined with the help of grey relation coefficient using Eq. 12 (Table 4). The obtained weighted GRG for all the trials were used for obtaining the optimum condition of the input variables using Taguchi's DoE analysis in Minitab software version 2015. The larger-the-better condition was applied and obtained S/N ratio of input factors. The main effect plot for weighted GRG is shown in Figure 3. It is clear form Figure 4 that 20% TS and F/I of 4 is optimum condition along with 0.5% KOH (w/w) and 10 g/L of PHWBC for enhancing hydrolysis and syntropy simultaneously in SSAD. Based on the obtained optimum condition, a confirmation test was run and discussed in further section.

Table 1: Normalization sequence of responses of trials for GRA

Trial No.	Normalizing sequence			
	Methane	**VS reduction**	**pH**	**TVFAs/ Alkalinity**
R1	1.000	1.000	0.643	0.000
R2	0.000	0.000	0.929	0.625
R3	0.587	0.428	0.143	0.251
R4	0.549	0.510	0.500	0.066
R5	0.634	0.556	0.643	0.401
R6	0.387	0.228	0.714	0.607
R7	0.630	0.674	0.143	0.631
R8	0.482	0.144	0.000	0.827
R9	0.726	0.749	0.357	0.354

Table 2: Deviation sequence of the output factors

Trial No.	Deviation sequence			
	Methane	**VS reduction**	**pH**	**TVFAs/ Alkalinity**
R1	0.000	0.000	0.286	0.827
R2	1.000	1.000	0.000	0.202
R3	0.413	0.572	0.786	0.577
R4	0.451	0.490	0.429	0.761
R5	0.366	0.444	0.286	0.426
R6	0.613	0.772	0.214	0.220
R7	0.370	0.326	0.786	0.196
R8	0.518	0.856	0.929	0.000
R9	0.274	0.251	0.571	0.473

Table 3: Grey relation coefficient of responses for GRA

Trial No.	Grey relation coefficient			
	Methane	VS reduction	pH	TVFAs/ Alkalinity
R1	1.000	1.000	0.636	0.377
R2	0.333	0.333	1.000	0.712
R3	0.547	0.467	0.389	0.464
R4	0.526	0.505	0.538	0.397
R5	0.577	0.530	0.636	0.540
R6	0.449	0.393	0.700	0.694
R7	0.575	0.605	0.389	0.718
R8	0.491	0.369	0.350	1.000
R9	0.646	0.665	0.467	0.514

Table 4: Grey relation grade and signal to noise ratio for response of trials

Trial no.	Output response				GRG	S/N
	Methane	VS reduction	pH	TVFAs/ Alkalinity		
R1	118.39	39.54	6.90	0.86	0.753	-2.46089
R2	226.23	48.55	7.50	0.37	0.595	-4.51524
R3	162.97	44.69	8.60	0.23	0.467	-6.61666
R4	167.06	43.96	8.10	0.17	0.491	-6.17173
R5	157.90	43.54	7.90	0.71	0.571	-4.87151
R6	184.55	46.49	7.80	0.36	0.559	-5.05067
R7	158.24	42.48	8.60	0.63	0.572	-4.85361
R8	174.24	47.25	8.80	0.44	0.553	-5.15311

R9	147.96	41.80	8.30	0.73	0.573	-4.83722

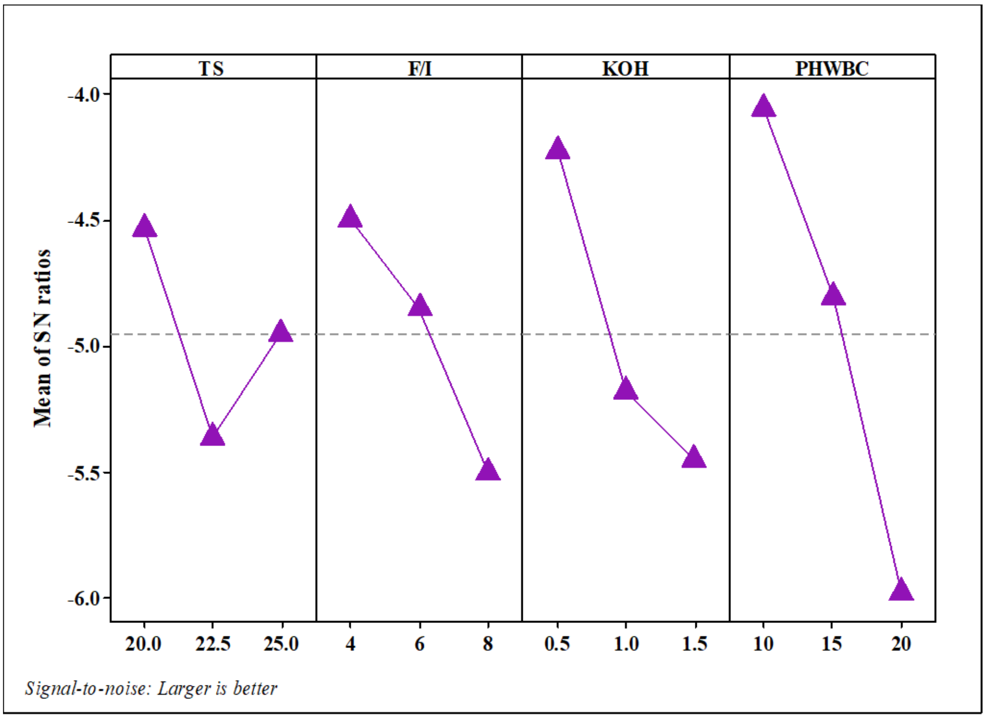


Figure 3: Main effect plot of each parameter on grey relation grade

Analysis of variance

ANOVA was performed to select the most prominent input parameters having severe impact on the process output(s) (Table 5). The most influential factor as per ANOVA analysis was PHWBC having 48.32% contribution on the output parameter. Identical observations were made by Lu et al. [22] in which it was stated that use of powdered biochar doubled the microbial growth and relieved propionic acid accumulation apart from increasing the methane yield. The second most influential factor was KOH having 21.13% contribution. In similar study, simultaneous treatment with NaOH helped in increasing methane yield in SSAD of fallen leaves [11]. The third most influential factor was F/I ratio with 15.35% contribution on the output parameter. It was reported earlier that 2 and 4 F/I optimum in the case of SSAD at mesophilic and thermophilic respectively [22]. The ANOVA results showed that simultaneous alkaline treatment to enhance syntropy and hydrolysis worked well as their contribution ranked first and second.

Table 5: ANOVA for grey relation grade of factors selected for SSAD

Factors	DF	SS	MS	F-Value	P-Value	% Contribution
TS	1	0.002295	0.011482	1.66	0.267	4.46%
F/I	1	0.007896	0.002295	5.71	0.075	15.35%
KOH	1	0.010872	0.007896	7.86	0.049	21.13%
PHWBC	1	0.024865	0.010872	17.98	0.013	48.32%
Error	4	0.00553	0.024865			10.75%
Total	8	0.051458				100.00%

Analysis of confirmation test

Hydrolysis is a rate limiting step and the rate constant can be determined by first order kinetic model [23]. Table 5 shows the result of first order kinetics for the control and optimized conditions. The hydrolysis rate constant (*k*) was observed as 0.0595 and 0.0521 d^{-1} for control and optimized condition respectively. Also, the R^2 was 0.9953 and 0.9987 for control and optimized condition respectively. The results showed that the hydrolysis was improved in the case of optimized condition. Mirmohamadsadeghi et al. [24] also observed that in SSAD of rice straw; rate constant was 0.088 d^{-1} for methane yield after treatment with organic solvent. Similar results were also observed by Bolado-Rodríguez et al. [25] for cumulative methane yield from pretreated (thermal autoclave pretreatment) WS. The first order rate constant for untreated and pretreated WS was 0.100 and 0.055 d^{-1}. In another study, Ferreira et al. [26] reported that hydrolysis was a rate limiting step by modelling methane yield using first order kinetic model. It was observed that hydrolysis rate constant for methane produced from steam exploded WS was 0.085 d^{-1}. Table 6 is showing the comparison of present study to previously reported studies for hydrolysis rate constant based on first order kinetic modelling.

Table 6: Comparison of hydrolysis rate constant (*k*) and cumulative methane yield obtained from first order kinetics with previous study

Feedstock	Treatment type	AD type	k (d^{-1})	R^2	References
WS	Steam explosion	LAD	0.085	0.9890	Ferreira et al., (2013)
RS	Organosolv	SSAD	0.088	0.9180	Mirmohamadsadeghi et al., (2014)
WS	Autoclave	LAD	0.055	0.9976	Bolado-Rodríguez et al., (2016)
WS	Thermal+alkali	LAD	0.056	-	Moset et al., (2018)
PMS	Alkali (KOH)	SSAD	0.052	0.9987	Present study

WS – Wheat straw; RS – Rice straw; PMS – Pearl millet straw

The increment in hydrolysis rate of PMS also manifested in cumulative methane yield improvement. Figure 4(a) depicts the graph of first order model; predicted and experimental methane yield for control and optimized conditions. The experimental cumulative methane yield was 108 and 195 L/kg VS while the predicted was 100 and 170 L/kg VS for control and optimized condition respectively. This shows an improvement of 1.8-fold in the experimental cumulative methane yield. Moset et al. [27] observed an increment of 33% in cumulative methane yield after targeting hydrolysis using thermal and alkali treatment of WS. Similarly, Mirmohamadsadeghi et al. [24] reported an increment of 1.3-fold in methane yield as compared to control from organic solvent treated rice straw in SSAD.

Moreover, application of biochar has also been reported for enhancing methane yield and maintaining syntropy for various feedstocks [13]. Figure 4(b) shows the digester characteristics of control and optimized condition. The pH of control and optimized condition was 6.91 and

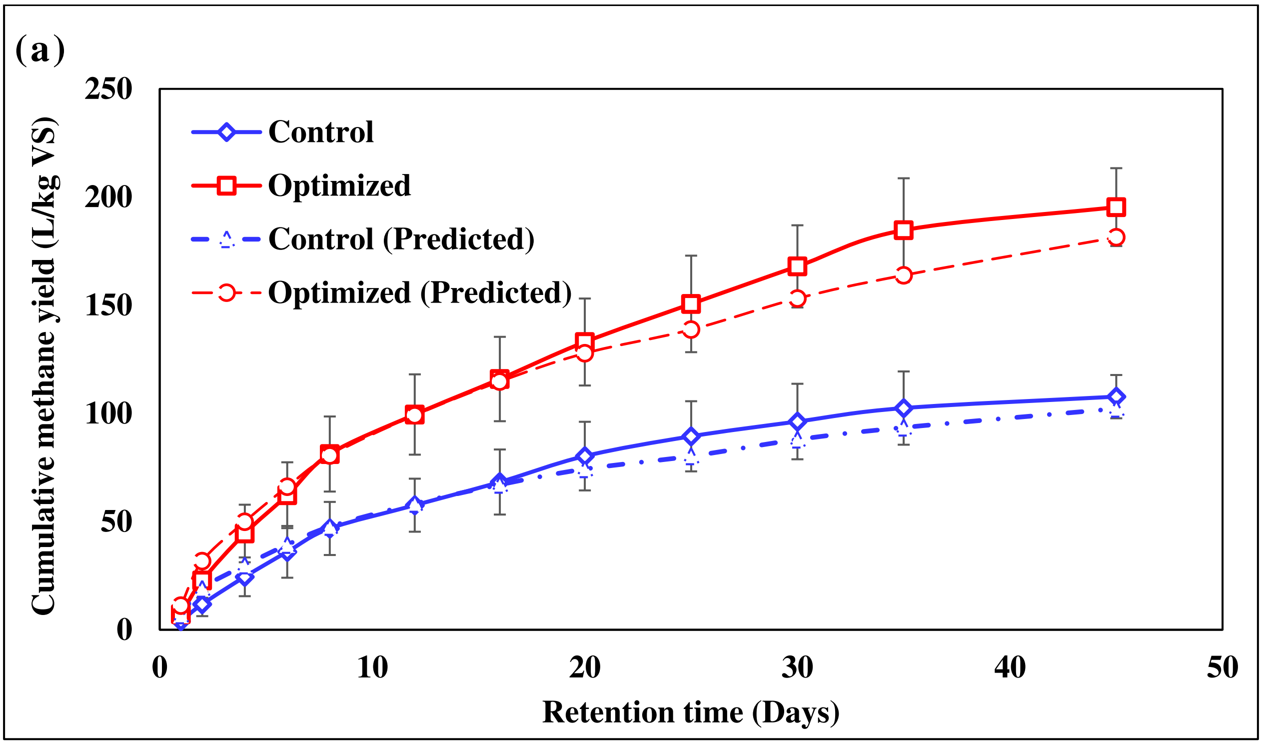
7.49 respectively. The TVFA and alkalinity for control was observed as 2.09 g/L as HAc and 2.74 g/L as $CaCO_3$ respectively. For optimized condition, it was 1.62 g/L as HAc and 4.22 g/L as $CaCO_3$ respectively. These results showed that TVFA accumulation got decreased by 29% while alkalinity increased by 54% apart from increment in pH. Similar results were observed by Lu et al. [28] by employing pine biochar in AD of oil and revealed that pH dropped up to 5.95 while it was 6.49 and 6.29 for powdered and granular biochar added to the reactor respectively. Lu et al. [28] also reported that and microbial population got doubled which helped in increasing the methane yield. In another study, Sun et al. [29] observed that in control, without cow manure biochar, pH dropped up to 6.82 while reactor having 10 g/L of biochar recorded pH as 7.13 thermophilic condition. Sun et al. [29] also, contemplated that presence of biochar could mitigate adverse effect of TVFA accumulation and maintain buffering capacity of the digester. The reactor fed with 10g/L of cow manure biochar showed TVFA as 1.2g/L and alkalinity as 1.9 g/L as $CaCO_3$. However, control showed 1.8 g/L of TVFA and 0.8 g/L of alkalinity as $CaCO_3$. Table 7 shows the comparison of present study with previously reported studies.

Techno-economic assessment

Assessment of economic indicators

Table 8 is showing results of techno-economic analysis. The CAPEX for the full scale SSAD plant included installation of 300 m^3 SSAD plant and equipment and machinery cost. OPEX for the full scale plant includes cost of feedstock, labour cost, O&M cost and transportation cost of straw from farm field to SSAD plant. The revenue model includes revenue generation from electricity to the grid and selling of solid digestate as soil conditioner. The LCOE calculated was 0.128 and 0.1123 US$/$kWh_e$ for untreated and simultaneously treated SSAD reactor. Thus, for both scenarios, the selling price of electricity for revenue generation was increased by 15% to earn profit and selected as 0.147 and 0.13 US$/$kWh_e$ for untreated and simultaneously treated scenario respectively. The selling price of solid digestate as soil conditioner was assumed as US$ 0.035/kg of digestate for both scenarios. However, the selling price of solid digestate may be increased for digestate of simultaneously treated reactor as it would have biochar and it was reported as effective soil conditioner [30]. This will also ensure the viability of the project as lower unit price of electricity will attract the consumer to choose renewable sources over conventional power plant.

The most impactful economic indicator for a project is NPV and effect of different discount rate on NPV for SSAD plant is shown in figure 5. The increase in the discount rate from 5 to 10% have shown decrease in the value of NPV. At 5%, NPV was US$ 20563 and US$ 51,733 for untreated and simultaneously treated SSAD reactor for 25 years of plant life. NPV at 5% was 2 and 20 times more as compared to the NPV at 7.5% for simultaneously treated and untreated full scale reactor respectively. At 10%, NPV for simultaneously treated SSAD rector fell to US$ 7333 while for untreated it was negative. This clearly shows the importance of the discount rate on whole project life.



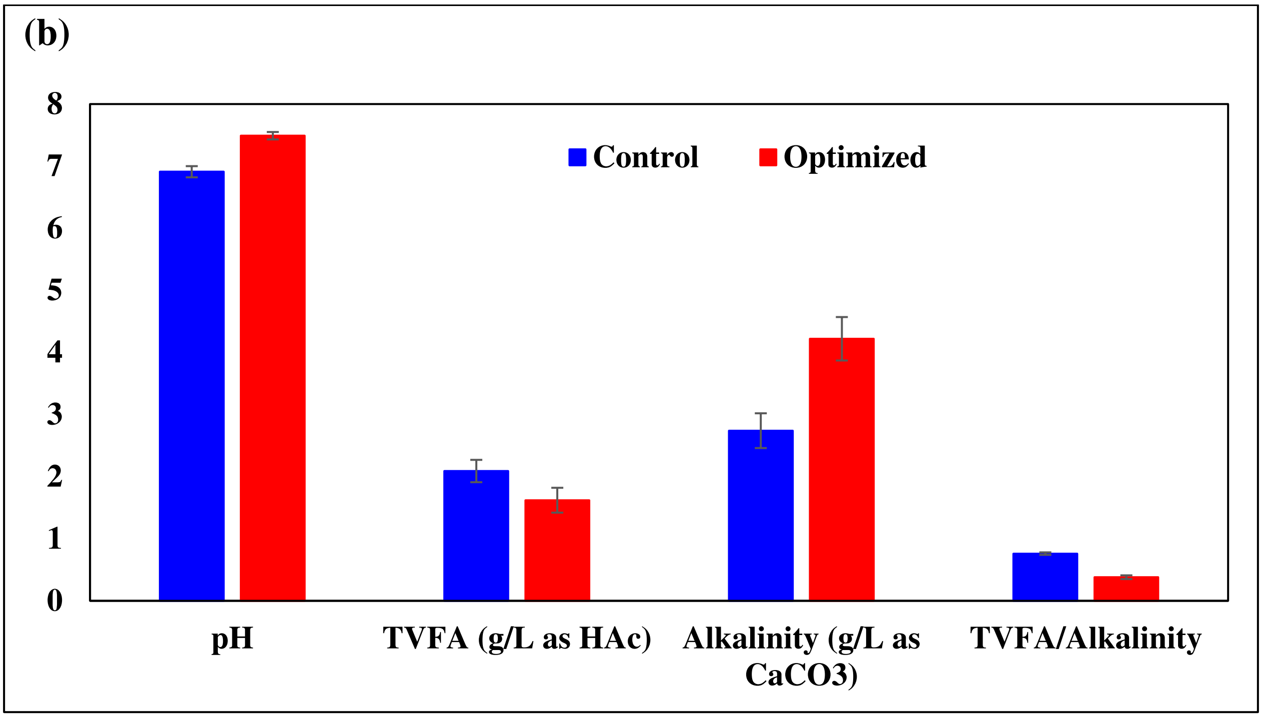


Figure 4: (a) Confirmation test showing experimental and predicted cumulative methane yield and (b) digester characteristics of control and optimized conditions

Table 7: Comparison of cumulative methane yield observed with previous studies

Feedstock	AD type	Targeted process	Methane yield	TVFA/ Alkalinity	Increment	References
WS	LAD	Hydrolysis	273 L/kg VS	-	1.20-fold	Ferreira et al., (2013)
RS	SSAD	Hydrolysis	153 L/kg VS	-	1.34-fold	Mirmohamadsadeghi et al., (2014)
WS	LAD	Hydrolysis	265 L/kg VS	-	1.32-fold	Bolado-Rodríguez et al., (2016)
WS	LAD	Hydrolysis	305 L/kg VS	-	1.33-fold	Moset et al., (2018)

BL	SSAD	Syntropy	401 L/kg VS	0.46	1.47-fold	Sun et al., (2019)
Oil	LAD	Syntropy	854 L/kg VS	-	1.35-fold	Lu et al., (2019)
PMS	SSAD	Hydrolysis +Syntropy	195 L/kg VS	0.36	1.8-fold	Present study

WS: Wheat straw; RS: Rice straw; PMS: Pearl millet straw; BL: Beer lees

A lower IRR and higher PBT will make decision makers, like investors and government authorities, repulsive to the project. A higher IRR shows an attractive project proposal. At 7.5% of the discount rate, the IRR was 7.6 and 11.2% for untreated and simultaneously treated reactors. This shows that despite the additional operational cost of simultaneously treatment (US$ 3650/year for PHWBC and KOH), IRR of simultaneously treated reactor was 3.6% higher to that of untreated approach. The PBT for simultaneously treated reactor was 8.2 years

Table 8: Techno-economic assessment of SSAD plant

Particulars	**Untreated**	**Simultaneously treated**
Capital cost ($/25year)	73000	73000
Raw material cost ($/year)		
PMS	0	0
Inoculum	0	0
Additives (PHWBC + KOH)	0	3650
Operational cost ($/year)		
Maintenance and electricity charges	3650	3650
Labour	2190	2190
Transportation	157.5	157.5
Revenue generated ($/year)		

Electricity	10439.1	16782.7
Digestate	2205	1715
Techno-economic indicators		
LCOE (US$/$kWh_e$)	0.128	0.112
NPV ($)	1088	25652
IRR (%)	7.65	11.29
PBT (Years)	10.9	8.2
DPBT @ 5% (Years)	16.36	10.89
DPBT @ 7.5% (Years)	24.08	13..33
DPBT @ 10% (Years)	Investment can never be paid back at this rate	18.28

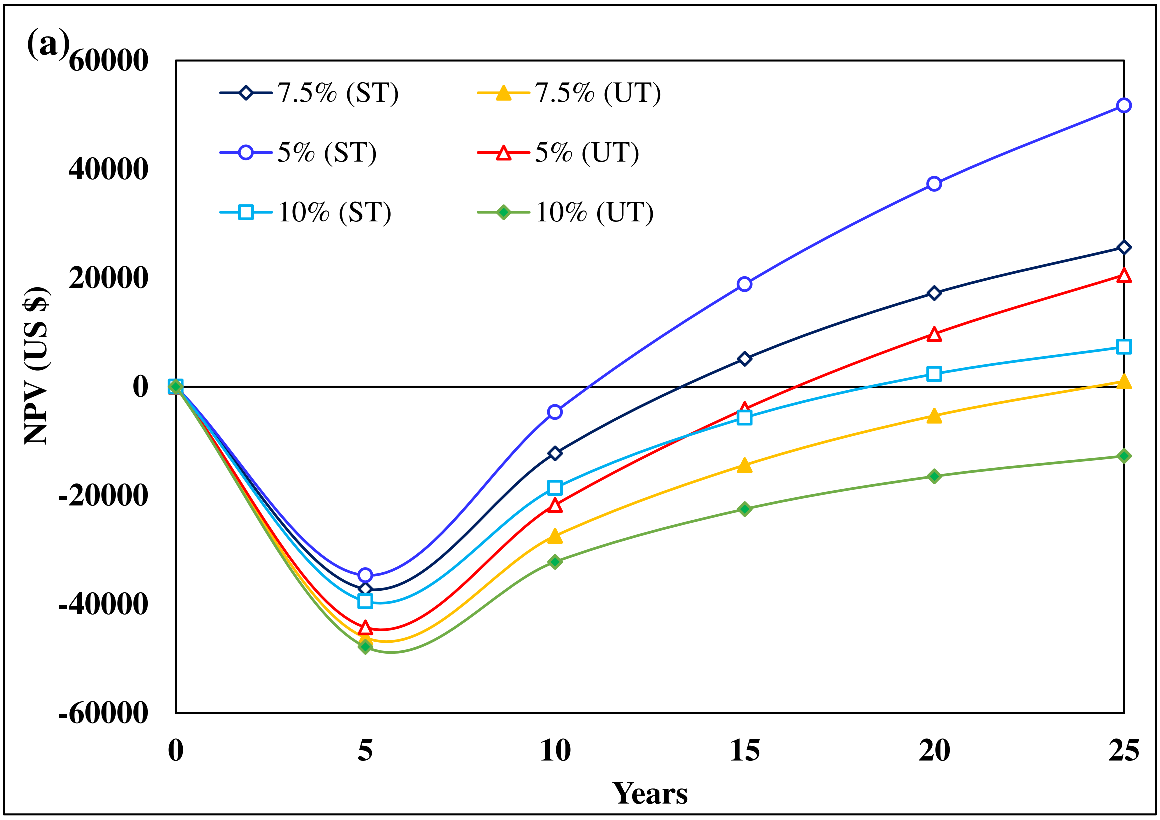
while for untreated condition, it was 11.9 years. This is because the revenue generated by electricity and digestate selling was US$ 146539 more as compared to untreated condition after 25 years of project duration. Similar results were also observed by Li et al. [37] in which SSAD at 20% TS showed payback period of 10.9 years with 11.7% of IRR. However, the payback time may be reduced further if anaerobic codigestion is adopted with PMS to increase the daily methane yield, subsequently increasing electricity production.

Sensitivity analysis

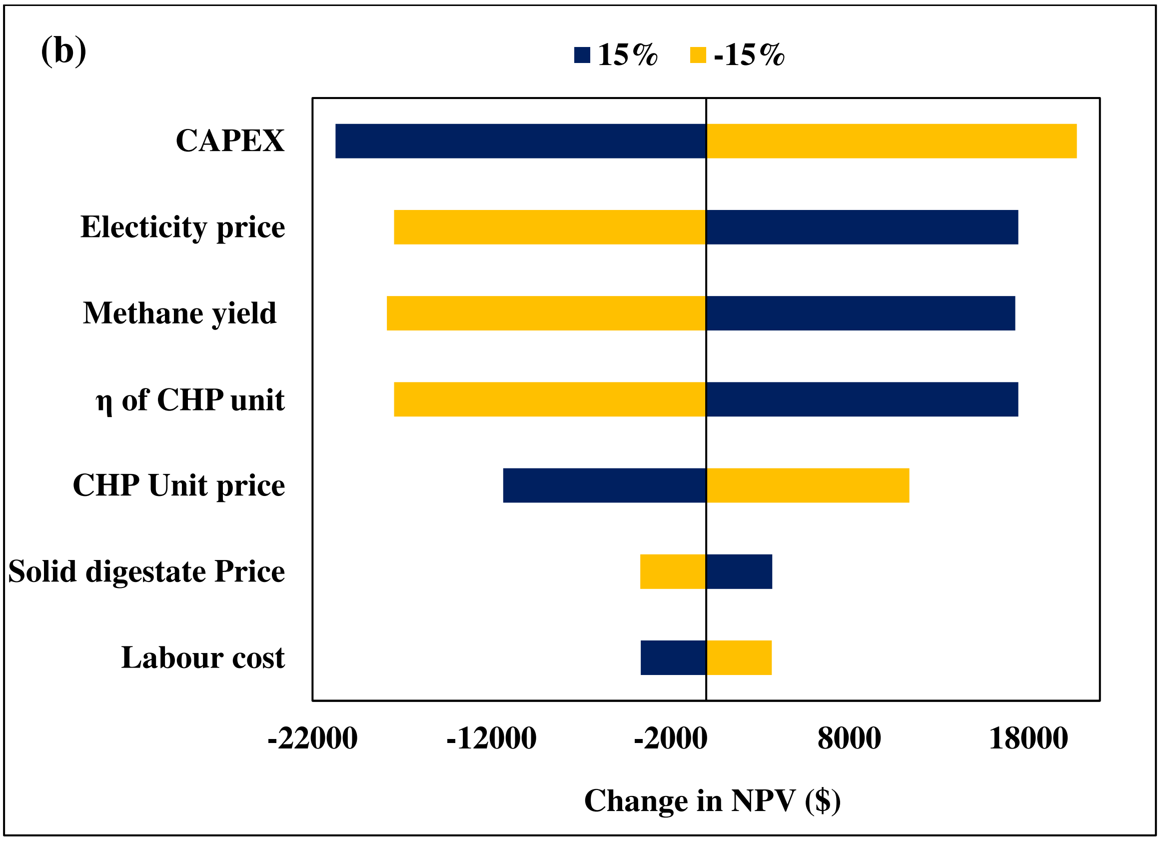
Figure 5 shows the tornado graph of the sensitivity analysis for both untreated and simultaneously treated scenarios. For untreated scenario, CAPEX is affecting the NPV most followed by electricity selling price, methane yield and efficiency of CHP unit. The change in NPV observed due to ±15% change in CAPEX was US$ 20714. This shows that if CAPEX is increased by 15%, the NPV would be negative (Figure 5). The NPV change in the case of

CAPEX was more than 18% when electricity price and efficiency of CHP unit was increased by 15%. Floating of methane yield by ±15% showed a change of $\geq$ US$ 17000 in NPV. These results showed that CAPEX, methane yield, efficiency of CHP unit and electricity price are crucial for this scenario of power generation. All the factors have shown a negative NPV when the values were decreased by 15%. This makes the SSAD plant non-viable economically in the case of no treatment provided for methane increment.

For second scenario, i.e. simultaneously treated reactor, electricity selling price and efficiency of CHP unit showed a change of US$ 28061 on NPV when floated by ±15%. However, this change was only 1% more when methane yield was floated by same percentage. This clearly shows that if methane yield is increased per unit mass, the NPV will also increase in the case of electricity price as methane yield governs the electricity generation. Also, compared to untreated scenario, the change in NPV due to ±15% change in methane yield was more than 59% in scenario of simultaneous treatment. This clearly shows that simultaneous increment of hydrolysis and syntropy will help to achieve monetary benefits despite the fact that OPEX was US$ 3650/year more in the case of simultaneous treatment ($C_{Additives}$).



(a)
7.5% (ST)
7.5% (UT)
5% (ST)
5% (UT)
10% (ST)
10% (UT)
NPV (US $)
60000
40000
20000
0
-20000
-40000
-60000
0
5
10
15
20
25
Years



(b)
15%
-15%
CAPEX
Electicity price
Methane yield
η of CHP unit
CHP Unit price
Solid digestate Price
Labour cost
-22000
-12000
-2000
8000
18000
Change in NPV ($)

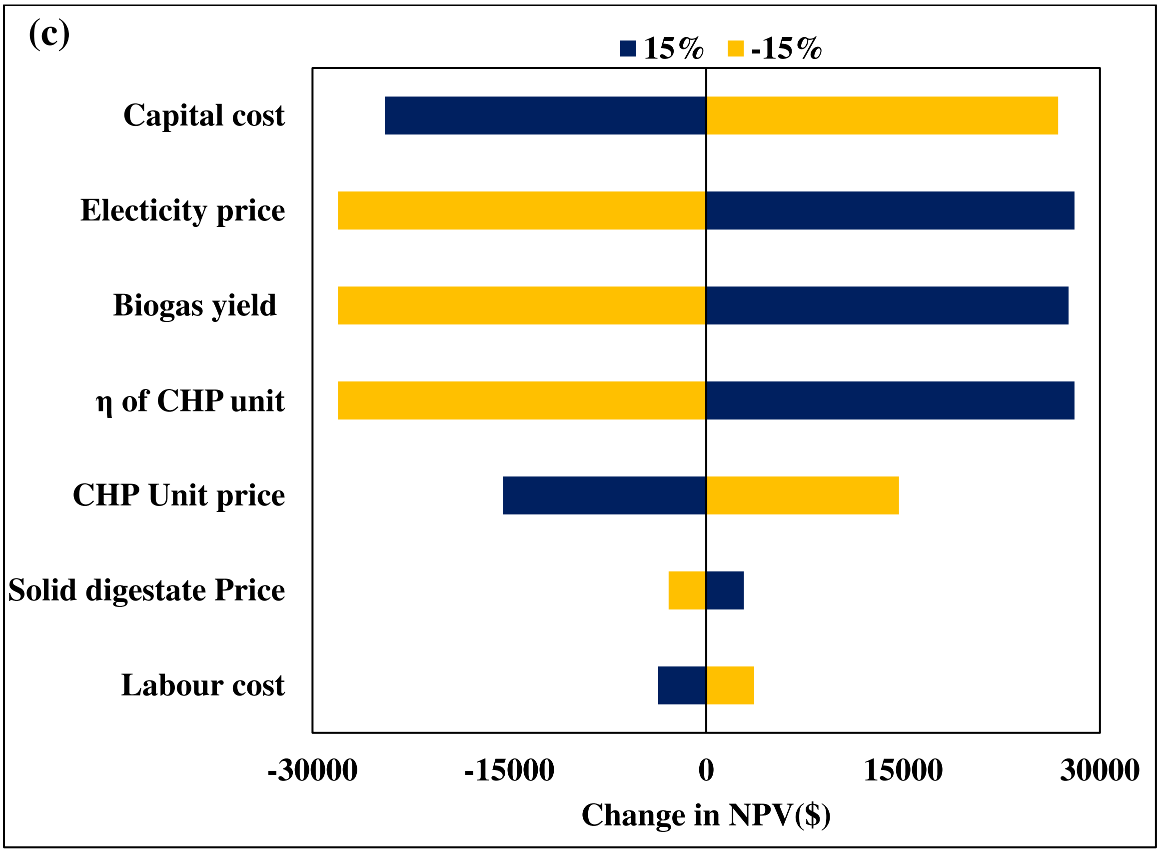


Figure 5: (a) NPV at different discount rate. (ST – simultaneously treated reactor; UT – Untreated reactor); Sensitivity analysis of (b) untreated and (c) simultaneously treated SSAD plant

Conclusions

In this study, hydrolysis and syntrophic activity enhanced simultaneously in SSAD process. The increment in the hydrolysis rate and syntrophic activity helped to achieve 1.8-fold higher methane yield as compared to control. While simultaneous mixing of alkali (KOH on w/w basis) helped to improve the hydrolysis rate, mixing of PHWBC (w/w basis) enabled the syntropy in the SSAD of PMS. The TVFA/alkalinity ratio was 0.36 for optimized condition while for control it was 0.76. However, further research is needed for concrete proof of improved hydrolysis and syntropy during simultaneous treatment like estimation of lignin solubilization and microbial community analysis for evaluating the population of hydrolytic and archaeal community as well as to decipher the deeper biotechnology involved. Techno-economic assessment showed that addition of PHWBC and alkali helped to achieve shorter payback years and higher return rate making a biogas project profitable and paving road for sustainable bioeconomy for reduced GHG emissions. Though, anaerobic codigestion may be adopted to increase the methane yield and energy generation as sensitivity analysis showed that NPV is vulnerable to change in CAPEX and methane yield.

Materials and methods

Selection of lignocellulosic biomass and inoculum

For present study, locally available lignocellulosic biomass; PMS was selected. North-western part of India is rich in PMS and annual production was reported to be 21 million tonnes [2]. Despite the abundant availability, PMS has been least explored for biomethane production. Yadav et al. [32] reported that fungal treatment helped to improve biomethane by 51% over untreated PMS in LAD. In another study by Paritosh et al. [33]; SSAD of PMS was attempted at mesophilic and thermophilic conditions. Results favoured the thermophilic temperature and 25% TS for highest methane yield. The scarcity of literature on PMS compels for its selection in SSAD process and its proper utilization for future sustainable bioeconomy and lower GHG emmisions. PMS was collected from nearby village (Burthal) located in Jaipur (26.79° N, 75.88° E), India during October 2019. The collected PMS was stored in the zip lock bags till further use.

The inoculum as effluent was collected from nearby (Durgapura, Jaipur; India 26.8ºN, 75.7ºE) active biogas plant operating at mesophilic temperature using cow dung. Pre incubation of inoculum was performed (52ºC, 14 days) in incubator prior to its proper use; for taking down the residual methane potential and to activate. Thermophilic condition has been chosen to work with over mesophilic contiopnes as the former leads to higher yields due to increased rate of hydrolysis in SSAD system [5].

Selection of carbon based conducting material and alkali

Biochar, a CBCM, is made by pyrolysiing the biomass, under minimum amount of O_2 [34]. Biochar is with unique properties viz. high surface area, increased porosity and cation exchange capability. Of course these and other characteristics of biochar also depend on type and origin of biomass. The above characteristics make biochar very impactful for adsorbing the inhibitors such as ammonia, pesticides, heavy metals along with DIET. Since biochar have higher surface area it helps in increased bacterial growth in AD [13]. For present study, PHWBC was locally procured (Greenfield eco solution, India). KOH was selected as alkali for simultaneous alkaline treatment of PMS in SSAD experiment as per previous study by the group [15]. The characteristics of PMS, inoculum and PHWBC are depicted (Table 9).

Taguchi design of experiment and solid state anaerobic digestion

To apply Taguchi's DoE in present study for experimental array of orthogonally arranged inputs, four parameters (TS in %, F/I, KOH as g/100g PMS and PHWBC as g/L inoculum) were selected. The input control parameters were varied through three levels (Table 10) minimum number of experiments were calculated. As per Taguchi's DOE, the minimum number of experiments were 9 (L_9) for given number of input parameters and levels (Eq. 1). The inner orthogonal array formulated for selected parameters were shown in table 11.

Minimum number of experiments to be performed = $[(L-1)] * P] + 1$ (1)

Where, $L = Number\ of\ levels$; $P = Number\ of\ parameters$

Taguchi's DoE encompasses three different categories for performance analysis of selected input parameters. These three categories are "Larger-the-better", Nominal-the-better" and "Smaller-the-better" and expressed as "Signal to Noise (S/N) ratio". This S/N is calculated using Eq. 2, 3 and 4.

Table 9: Properties of feed materials for SSAD

Characteristics	Pearl millet straw	Inoculum	Pyrolysis Hardwood biochar
Total solid (%)	93.6 ± 2.7	8.9 ± 0.3	94.1 ± 0.3
Volatile solid (% TS)	92.3 ± 1.9	65.7 ± 0.5	95.3 ± 0.3
pH	/	6.9 ± 0.3	7.9 ± 0.3
Carbon (%)	41.8±2.1	35.3±0.1	ND
Hydrogen (%)	7.9±1.3	4.1±0.9	ND
Nitrogen (%)	0.9±0.3	1.5±0.2	ND
C/N	46.4±1.3	23.5±0.1	ND
Hot water extractives (%)	14.5±1.8	/	/
Cellulose (%)	38.2±2.3	/	/
Hemicellulose (%)	29.6±1.9	/	/
Lignin (%)	17.5±0.8	/	/
Calorific value (Kcal/kg)	3888.6±27	/	7850±48
Electrical conductivity (dS/m)	/	/	1.4±1
Cation exchange capacity (c mol/kg)	/	/	17±1
Phosphorus (%)	/	/	0.2±0.01
Potassium (%)	/	/	2.5±0.2
Calcium (%)	/	/	1.2±.1
Magnesium (%)	/	/	0.05±.003

Table 10: Parameters and their levels selected for Taguchi DoE

S. No.	Parameters	Level 1	Level 2	Level 3
1	Total solid	20	22.5	25
2	F/I	4	6	8
3	KOH (w/w)	0.5	1.0	1.5
4	PHWBC (g/L)	10	15	20

Table 11: L_9 orthogonal array of input control parameters

Trial no.	Input Parameter conditions			
	Total solid (%)	**F/I**	**KOH (w/w)**	**PHWBC (g/L)**
R1	20	4	0.5	10
R2	20	6	1.0	15
R3	20	8	1.5	20
R4	22.5	4	1.0	20
R5	22.5	6	1.5	10
R6	22.5	8	0.5	15
R7	25	4	1.5	15
R8	25	6	0.5	20
R9	25	8	1.0	10

For "Larger-the-better"

$$S/_N = -10\, log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \qquad (2)$$

For "Nominal-the-better"

$$S/_N = -10\, log\left(\frac{\bar{y}}{s_y^2}\right) \qquad (3)$$

For "Smaller-the-better"

$$S/_N = -10\ log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \qquad (4)$$

The batch SSAD was carried out in a glass bottle of volume 600 mL. A total of 9 set were prepared. The PHWBC and KOH were pre-dissolved into inoculum and mixed with straw manually as per table 11. These premixes were put into the glass batch bioreactor bottles (triplicates), closed with rubber septum and sealed. Flushed with nitrogen was done for the anaerobic condition to all the above mentioned bioreactors and then incubated (SANCO, India) at 52 □ 2°C for 60 days. To keep up the proper and uniform mixing the bottles were mixed thoroughly up and down manually at least three times a day.

Grey relation analysis

GRA was developed to measure complicated relationship between input variables both qualitatively and quantitatively [35]. The GRA technique categorizes dynamic characteristics and relative influence of input factor. GRA requires data pre-processing based on the selected criteria. In pre-processing, data are normalized based on "larger-the-better", "smaller-the-better" or "nominal-the-better" conditions using Eq. 5, 6 and 7.

For "larger-the-better"

$$X_i^*(k) = \frac{X_i^0(k) - \min X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \qquad (5)$$

For "smaller-the-better"

$$X_i^*(k) = \frac{\max X_i^0(k) - X_i^0(k)}{\max X_i^0(k) - \min X_i^0(k)} \qquad (6)$$

For "nominal-the better"

$$X_i^*(k) = 1 - \frac{|X_i^0(k) - X^0|}{\max X_i^0(k) - X^0} \qquad (7)$$

Where, $X_i^*(k)$ = Normalized value; $\max X_i^0(k)$ = maximum value of $X_i^0(k)$; $\min X_i^0(k)$ = minimum value of $X_i^0(k)$ and X^0 = target value.; i = number of experiments performed; k =

number of responses obtained. After the normalized value is obtained, determination of grey relation coefficient is next step using Eq. 8.

$$\zeta_i(k) = \frac{\Delta_{min} + \xi\, \Delta_{max}}{\Delta_{0i}\,(k) + \xi\, \Delta_{max}} \quad (8)$$

Where, $\zeta_i(k)$ = Grey relation coefficient, $\Delta_{0i}\,(k)$ = deviation sequence and given by Eq. 9.

$$\Delta_{0i}\,(k) = \left|\left|X_0^*\,(k) - X_i^*\,(k)\right|\right| \quad (9)$$

$$\Delta_{max} = Max_{\forall j \in i}\, Max_{\forall k} \left|\left|X_0^*\,(k) - X_j^*\,(k)\right|\right| \quad (10)$$

$$\Delta_{min} = Min_{\forall j \in i}\, Min_{\forall k} \left|\left|X_0^*\,(k) - X_j^*\,(k)\right|\right| \quad (11)$$

A distinguish factor ξ is used for calculating grey relation coefficient which is expressed as $\xi \in [0,1]$ and generally is equal to 0.5. After calculating gey relation coefficient, grey relation grade (GRG) is determined using Eq. 12.

$$\gamma = \sum_{k=1}^{n} \zeta_i(k) \quad (12)$$

Analytical methods and post treatment analysis

Biogas volume calculation and compositional analysis was performed as per previously reported study [33]. For compositional analysis, biogas was fed to inlet of gas chromatograph (TRACE 1300, Thermo Fisher Scientific, India) equipped with thermal conductivity detector and Helium as carrier gas. Temperature of detector and injector was 150°C and oven was at 50°C throughout the run. The TS, VS and ash content were determined for raw materials and inoculum as per the standard methods [36]. Ultimate analysis (C, H and N) was performed using Elemental Analyzer (FLASH 2000; Thermo Scientific, USA). pH, total volatile fatty acids (TVFA) and total alkalinity were monitored. For the same, sampling was done by blending 5 g of sample in 50 ml of deionised water, it was further centrifuged (10,000 rpm, 15 min) at room temperature (CIS 24 plus, REMI, India) [37]. Titration was performed to quantify the TVFA and total alkalinity as per reported methods [11].

Confirmation test

After performing the Taguchi based DoE and GRA analysis, a confirmation experiment was also performed for 45 days. 2 sets of experiments were performed in which one set was having only premixed PMS and inoculum as control while other set was having KOH and PHWBC added to inoculum and mixed with the PMS. The amount of KOH and PHWBC added to inoculum was the best condition obtained from Taguchi based GRA analysis (0.5 g KOH on w/w and 10 g/L PHWBC). To check whether hydrolysis got improved by alkali addition, first order kinetic model was used to determine the hydrolysis constant using Eq. 13.

$$Y_t = Y_{max} * [\,1 - exp(-kt)] \qquad (13)$$

Where, Y_t = cumulative methane yield (L/kg VS) at time t (d); Y_{max} = maximum cumulative methane production and k = hydrolysis constant (d^{-1}). Further, to check if the syntropy established, TVFA/alkalinity ratio was also determined using method described in section 2.5.

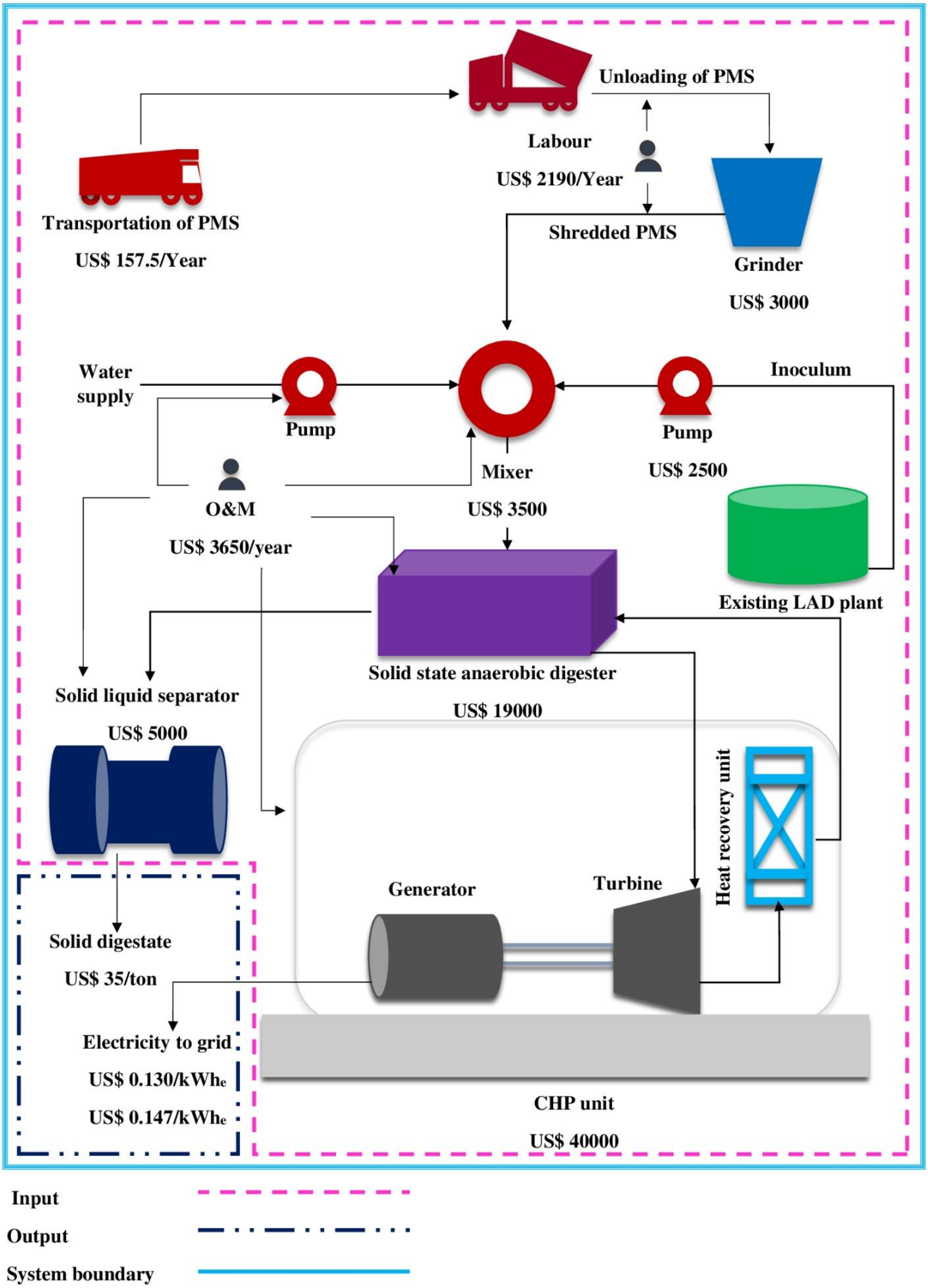
Statistical analysis

Analysis of variance (ANOVA) is statistical tool by which relative influence of selected input factors may be determined on the output response. ANOVA helps to identify the most dominant factor among selected factors on output parameters [38]. It also helps in categorizing the contribution of each factors selected on the multiple output. By knowing the dominant factor, one can control its variation in input condition for overall control on output variations [39].

Techno-economic assessment

Inventory and system assessment

Results of confirmation test was used for techno-economic analysis of a full scale SSAD plant. A garage type rector was assumed for techno-economic analysis in batch SSAD condition. The dimension of the reactor was assumed as 10m x 6m x 5m with wall thickness as 300 mm [15, 40]. The digester was assumed to be used for treating 28 ton of PMS per run and the batch digestion time was adopted to be 45 days. The location of SSAD plant is considered same as mentioned in previously reported study by Paritosh et al. [15] which is near existing full-scale LAD plant running on cow dung. Thus in this case, cost of inoculum transportation is considered as US$0/ton. The distance of the pearl millet farmland is assumed to be 25 km away from the SSAD plant. The PMS was transported using trucks running on diesel as fuel and diesel consumption was taken as 0.06 L/ton of PMS for transporting up to 1 km [41]. The average price of the diesel utilized was assumed as US$ 1 for 1 L [32]. Grinder and mixer were taken into consideration for grinding of the PMS and mixing of PMS with water, inoculum, KOH and PHWBC prior to feeding it into SSAD digester. A CHP unit with genset and heat recovery unit was employed for energy conversion from biogas generated. The electrical and heat efficiency of CHP was assumed to be 40 and 30% respectively [42]. The electricity produced from CHP is assumed to be fed into the national grid while the heat produced from CHP unit is used for digester operation. After the SSAD plant operation is completed, the digestate produced was separated into solid and liquid digestate using solid liquid separator and solid content is assumed as 30% [15]. The entire plant life for running is assumed for 25 years. The discount rate is assumed as 7.5% throughout the plant life. The operating hours are assumed as 24 hr/day x 325 days while 24 hr/day x 40 days for operational expenditure (OPEX) or contingency work (if required). The OPEX is assumed as 5% of the capital expenditure (CAPEX) on yearly basis and includes general maintenance work and electricity cost to run mixer, grinder and pump once in 45 days as SSAD plant is batch system and daily grinding, cutting, mixing and pumping is not required. Labour charges assumed as 3% of CAPEX annually. Civil and material work, insulation, electrical wiring and installation charges of SSAD plant was taken as US$ 63/m^3 of reactor [43]. Land rent is assumed under government subsidy and no other subsidies were considered. The system boundary for techno-economic assessment is shown in figure 6. All the assumptions made for techno-economic analysis is mentioned in table 12.



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539 **Figure 6:** System boundary for techno-economic assessment

Techno-economic assessment and economic indicators

The techno-economic feasibility of the SSAD plant is calculated by evaluating levelized cost of energy (LCOE), net present value (NPV), internal rate of return (IRR), payback time (PBT) and discounted payback time (DPBT) in this study. LCOE represents the unit cost of energy generation (US$/kWh$_e$) incorporating CAPEX and OPEX over the plant life. If the selling price of electricity is less than LCOE, the project will not be profitable. To incur profit, the selling price of electricity should be greater than the LCOE. The LCOE is calculated using Eq. 14 as suggested by Oreggioni et al. [44].

$$LCOE = \frac{\sum_{T=0}^{N} \frac{(CAPEX_T + OPEX_T)}{(1+r)^N}}{\sum_{T=0}^{N} \frac{Energy\ output\ (kWh_e)_T}{(1+r)^N}} \qquad (14)$$

Where, $LCOE$ is the levelized cost of energy, $CAPEX_T, OPEX_T$ are capital and operational expenditure in a year T, r is the discount rate and N is the total plant life.

LCOE calculated (as above) was taken as reference for setting the selling price of electricity/kWh. After calculating LCOE and revenue by selling electricity, NPV was calculated to estimate the time value of money invested in form of CAPEX and OPEX. If the NPV is greater than 0, it shows positive impact of the project in monetary terms. NPV presents a clear picture of cost benefit and project effectiveness by considering value of money in total project life time frame [45]. For the calculation of NPV, Eq. 15 is used as proposed by Budzianowski and Budzianowska [46].

$$NPV = -CAPEX + \sum_{T=0}^{n} \frac{-OPEX_T + R_T}{(1+r)^T} \qquad (15)$$

Where, n is the total plant life i.e. 25 years; r is the discount rate which is assumed as 7.5% for the project; $CAPEX$ is the capital expenditure required for initial investment for equipment purchase and other facilities, $OPEX_T$ is operation expenditure in a year and R_T is the revenue in a particular year T. Eq. 16 is used for calculating revenue (R_T) and operation expenditure ($OPEX_T$) for a year T.

$$-OPEX_T + R_T = -(C_F + C_{Trans} + C_{OPEX} + C_{Labour} + C_{Additives}) + (R_E + R_D) \quad (16)$$

Where R_E *and* R_D are revenue generated from electricity and digestate selling. $C_F, C_{Trans}, , C_{OPEX}, C_{Labour}$ *and* $C_{Additives}$ are feedstock, diesel for transportation, operation and maintenance, Labour and additives cost per year respectively. Cost of additives (PHWBC and KOH) is assumed as 5% of CAPEX. After this, IRR, PBT and DPBT were also calculated using Eq. 17, 18 and 19 respectively [47]. IRR is an important economic indicator for project viability and that discount rate at which NPV becomes zero. Whereas, PBT and DPBT represents the time in which the initial capital cost matches the total cash inflow. PBT represents payback period without discount rate while DPBT considers it.

$$0 = -CAPEX + \sum_{T=0}^{n} \frac{-OPEX_T + R_T}{(1 + IRR)^T} \quad (16)$$

$$PBT = \frac{-OPEX_T + R_T}{CAPEX} \quad (17)$$

$$-OPEX_T + R_T = CAPEX \left[\frac{(r\,(1+r)^{DPBT})}{((1+r)^{DPBT} - 1)} \right] \quad (18)$$

Apart from the discount rate of 7.5% which was used for whole techno-economic analysis, NPV and DPBT at 5 and 10% of the discount rate were also calculated to know the effect of variable discount rate on it. Variation of discount rate gives a clear picture of whole project life regarding investment.

Sensitivity analysis

Energy production and economic performance of entire plant life is sensitive to the variability of input and operational cost [48]. Variation in capital cost, maintenance and labour charges, feedstock cost, efficiency of CHP unit over 25 years, biogas productivity of the SSAD reactor and other related factors may have substantial impact on NPV. For this, sensitivity analysis was conducted for both untreated and simultaneously treated scenario. In a techno-economic study, the sensitivity analysis showed the viability of the assumption made on the NPV if cost of the input parameters fluctuates [47]. The values of all the variables were drifted with ±15% to know whether these fluctuations will have any impact on the NPV of the project over 25 years.

Abbreviations and nomenclature

R_D	Revenue generated through digestate
R_E	Revenue generated through electricity
R_T	Revenue in a year T
$C_{Additives}$	Cost of additives
C_F	Cost of feedstock
C_{Labour}	Labour cost
C_{OPEX}	Operational cost
C_{Trans}	Cost of feedstock transportation
AD	Anaerobic digestion
ANN	Artificial neural network
ANOVA	Analysis of variance
CAPEX	Capital expenditure
CBCM	Carbon based conducting materials
CHP	Combined heat and power

DIET	Direct interspecies electron transfer
DoE	Design of experiment
DPBT	Discounted payback time
GRA	Grey relation analysis
GRG	Grey relation grade
IIET	Indirect interspecies electron transfer
IRR	Internal rate of return
LAD	Liquid anaerobic digestion
LCOE	Levelized cost of energy
NPV	Net present value
O&M	Operation and maintenance
OPEX	Operational expenditure
PBT	Payback time
PHWBC	Pyrolysis hardwood biochar
PMS	Pearl millet straw
RSM	Response surface method

S/N	Signal to noise
SSAD	Solid state anaerobic digestion
TS	Total solid
TVFAs	Total volatile fatty acids
VS	Volatile solid

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Authors' contributions

Kunwar Paritosh: Idea conceptualization, Design of experiment Methodology, Investigation, Techno-economic analysis, Writing - Original Draft. Sanjay Mathur: Formal analysis, Guidance in Taguchi' design of experiment. Nidhi Pareek: Analysis, Review and Editing, Vivekanand Vivekanand: Supervision, Design concept, Resources, Project administration.

All authors read and approved the final version of manuscript.

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Availability of data and materials

All the data generated and analysed are included in manuscript.

Ethics approval and consent to participate

Not applicable—no human subjects involved in study.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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763 **Table 12:** Assumptions made for the techno-economic assessment of full scale SSAD plant

Particulars	Value
Plant configuration for SSAD	
Project life	25 years
Operating days	315 days
Dimension of AD rector[a]	10 m x 6 m x 5 m
Total and working volume of AD reactor[a]	300 and 240 m^3
Temperature[b]	Thermophilic (52°C)
Digestion time[b]	45 days per run
Total run	7800 hours
Operation and maintenance	960 hours
Quantity of materials per batch run	
PMS	28 tonnes
Inoculum	40 tonnes
Water	60 tonnes
KOH	150 kg
PHWBC	434 kg
Machinery and digester as capital cost and	
Grinder[c]	US$ 3000
Solid liquid separator[c]	US$ 5000
SSAD digester with insulation[d]	US$ 19000
CHP unit (80 kW, genset, heat recovery unit)[e]	US$ 40000
Mixer[f]	US$ 3500
Pump and accessories[c]	US$ 2500
Utilities and Other cost	

Cost of PMS[g]	$ 0/tonne
Inoculum[h]	$ 0/tonne
Additives (PHWBC + KOH)	5% of capital cost/year
Diesel[i]	0.06 L/ton/km
Diesel for transportation[j]	$ 1/litre
O & M	5% of capital cost/year
Labour	3% of capital cost/year
Revenue generation (US$)	
Electricity[k]	0.13 and 0.147/kWhe
Solid digestate as soil conditioner[l]	35/tonne

[a][40]; [b][15]; [c][31]; [d][40]; [e]Indian market price @US$ 500/kW; [f]Market price; [g]Biowaste; [h]Plant is located near LAD plant; [i][11]; [j][32]; [k]Calculated based on LCOE; [l]Prevaling market price in India

Figures

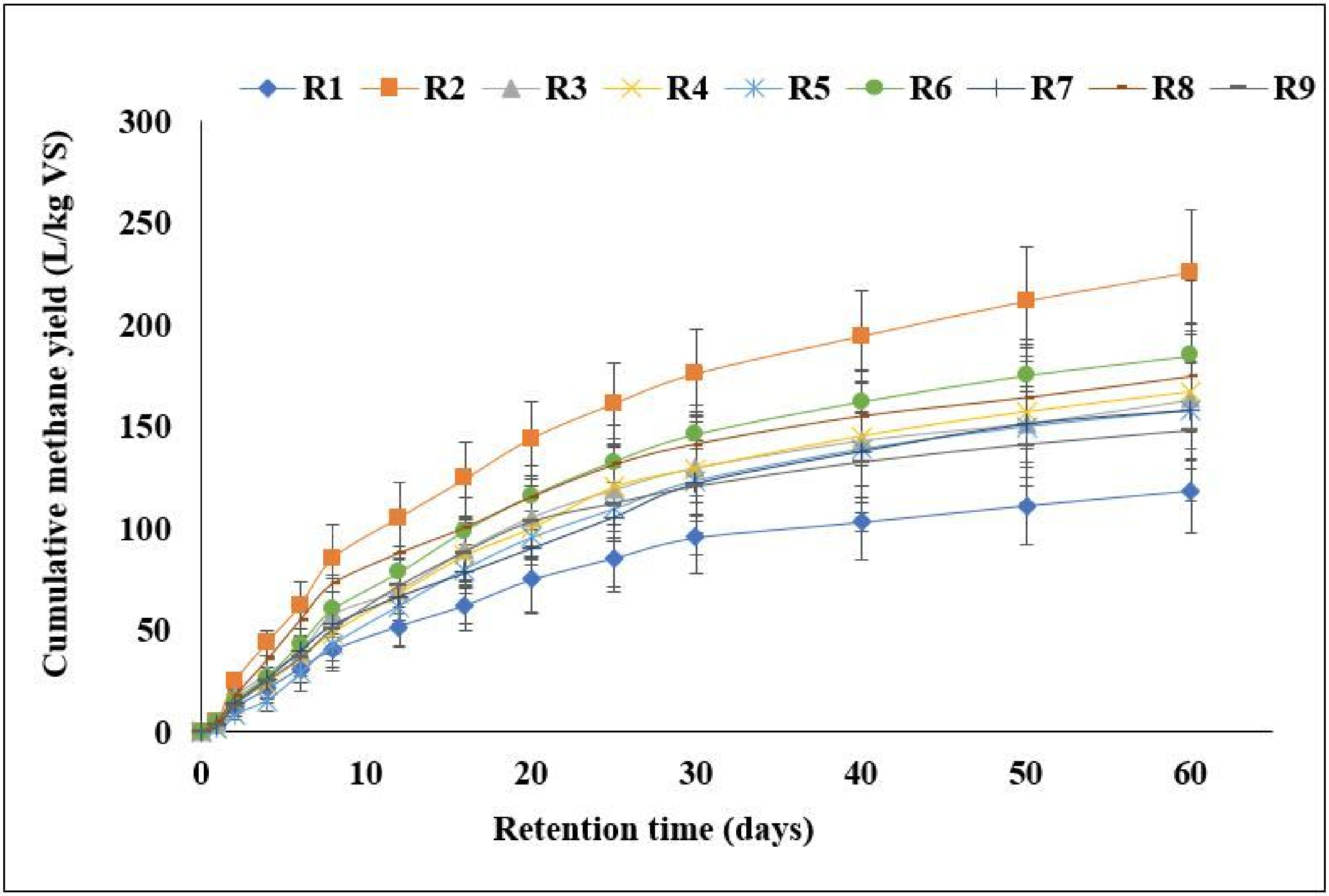
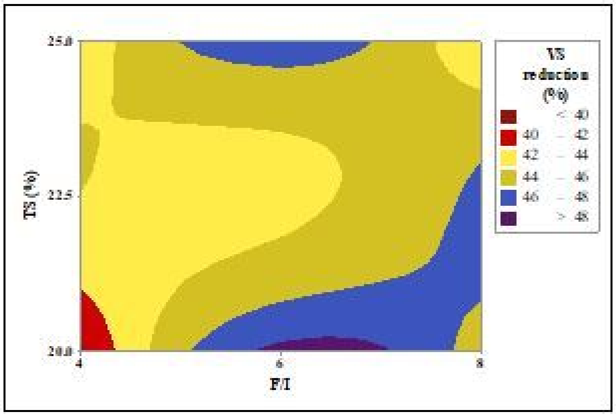
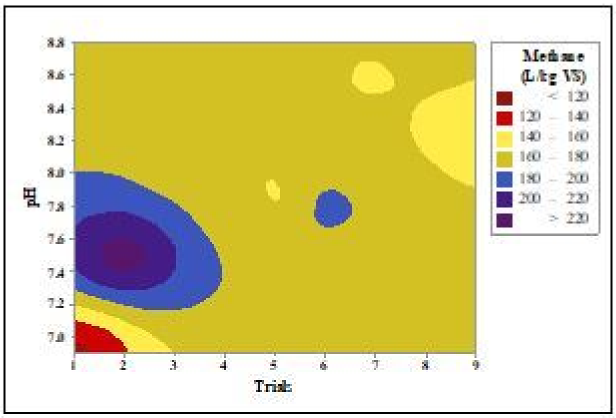


Figure 1

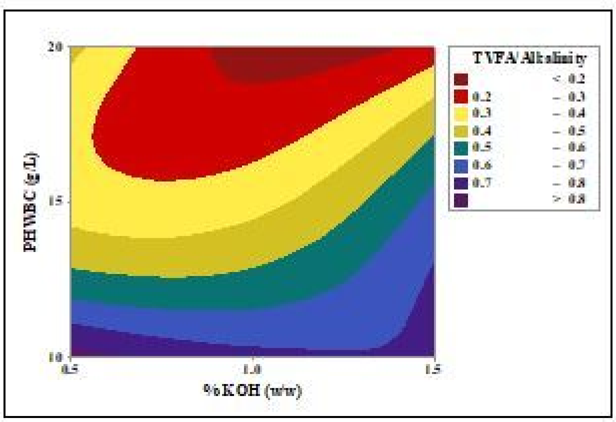
Cumulative methane yield of the trials based on Taguchi's DoE



(a)



(b)



(c)

Figure 2

Surface plot showing (a) relationship among TS, F/I and VS reduction (b) relationship between pH and cumulative methane yield (c) effect of KOH and PHWBC concentration on TVFA/alkalinity ratio

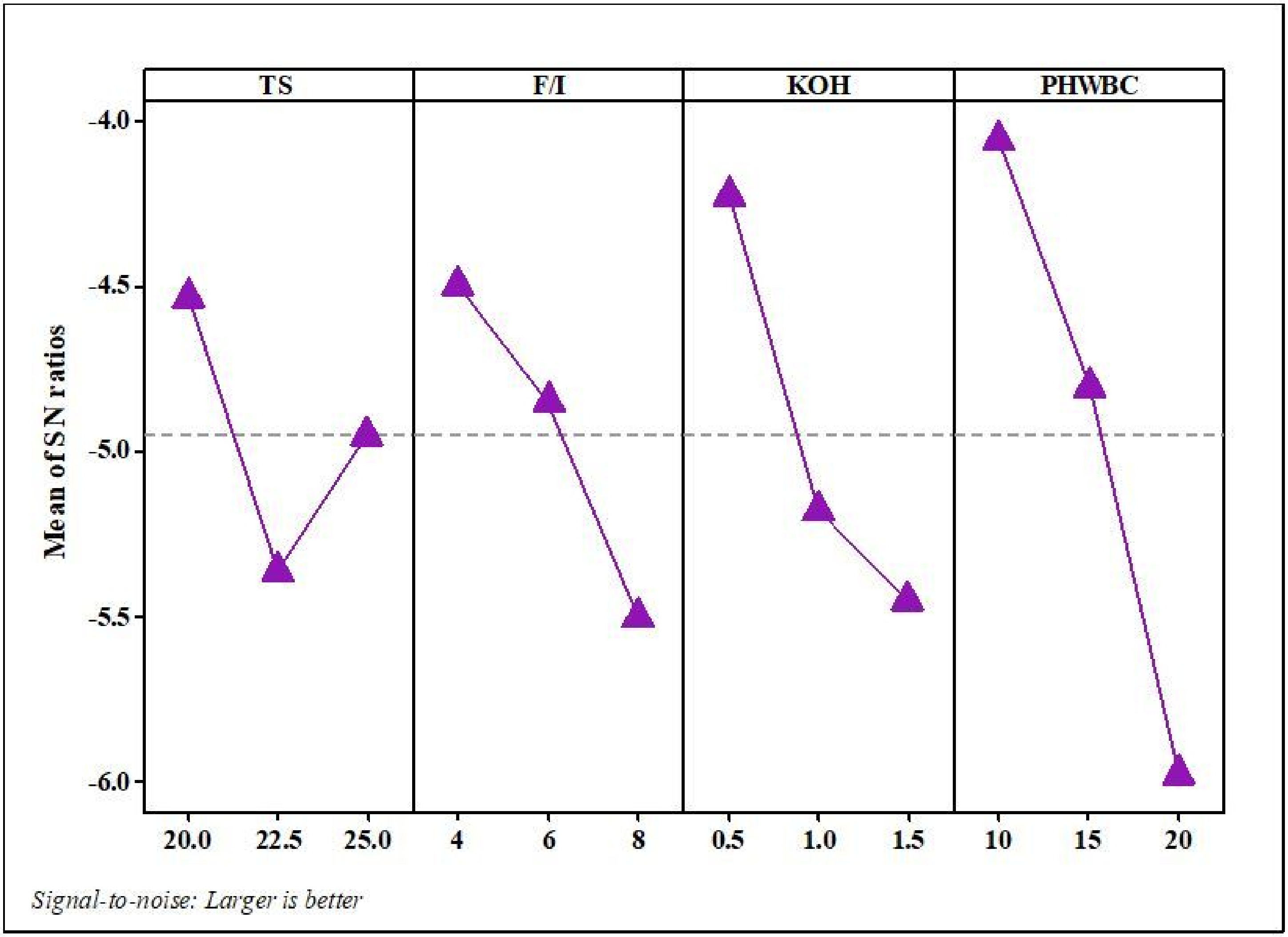


Figure 3

Main effect plot of each parameter on grey relation grade

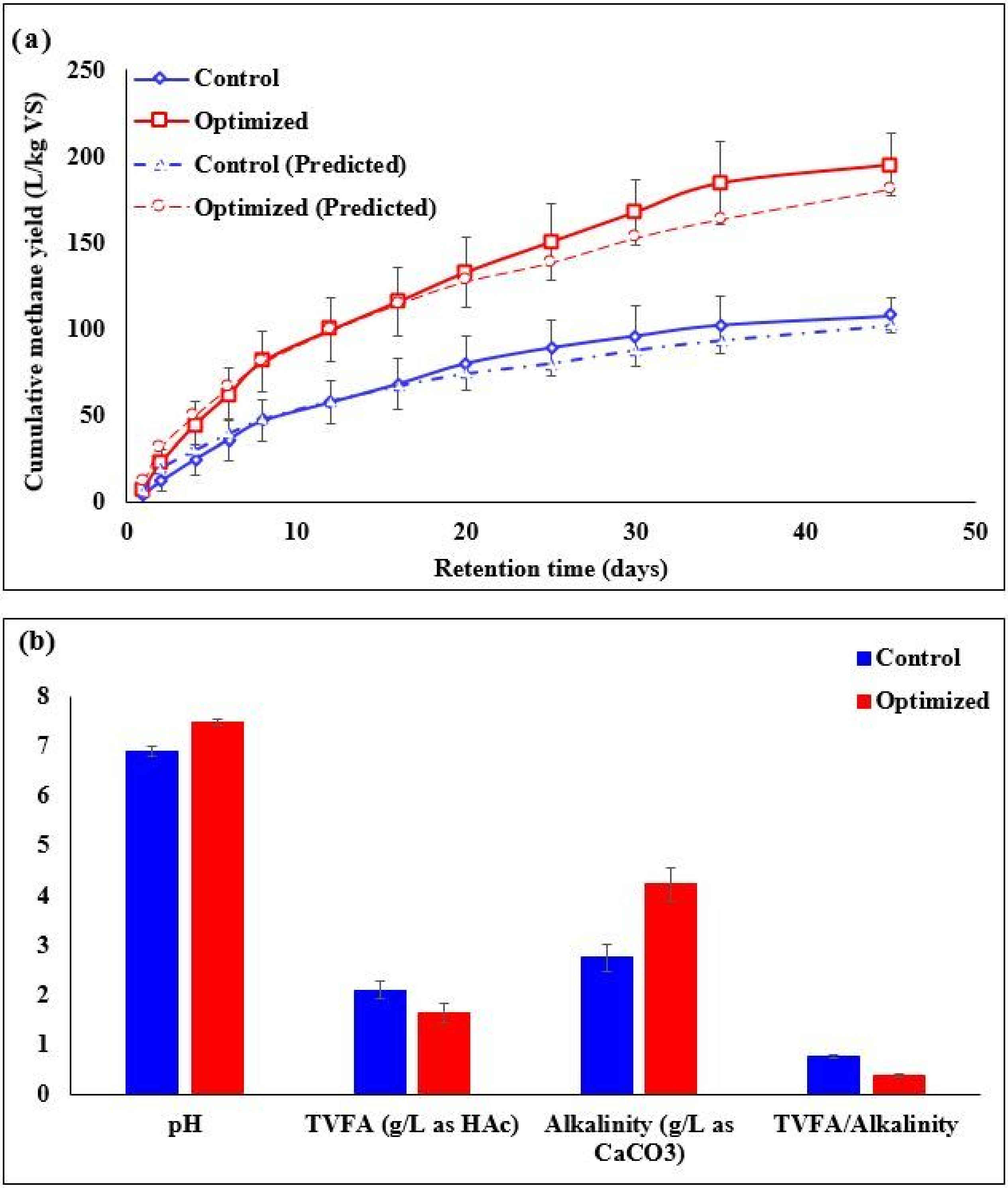


Figure 4

(a) Confirmation test showing experimental and predicted cumulative methane yield and (b) digester characteristics of control and optimized condition

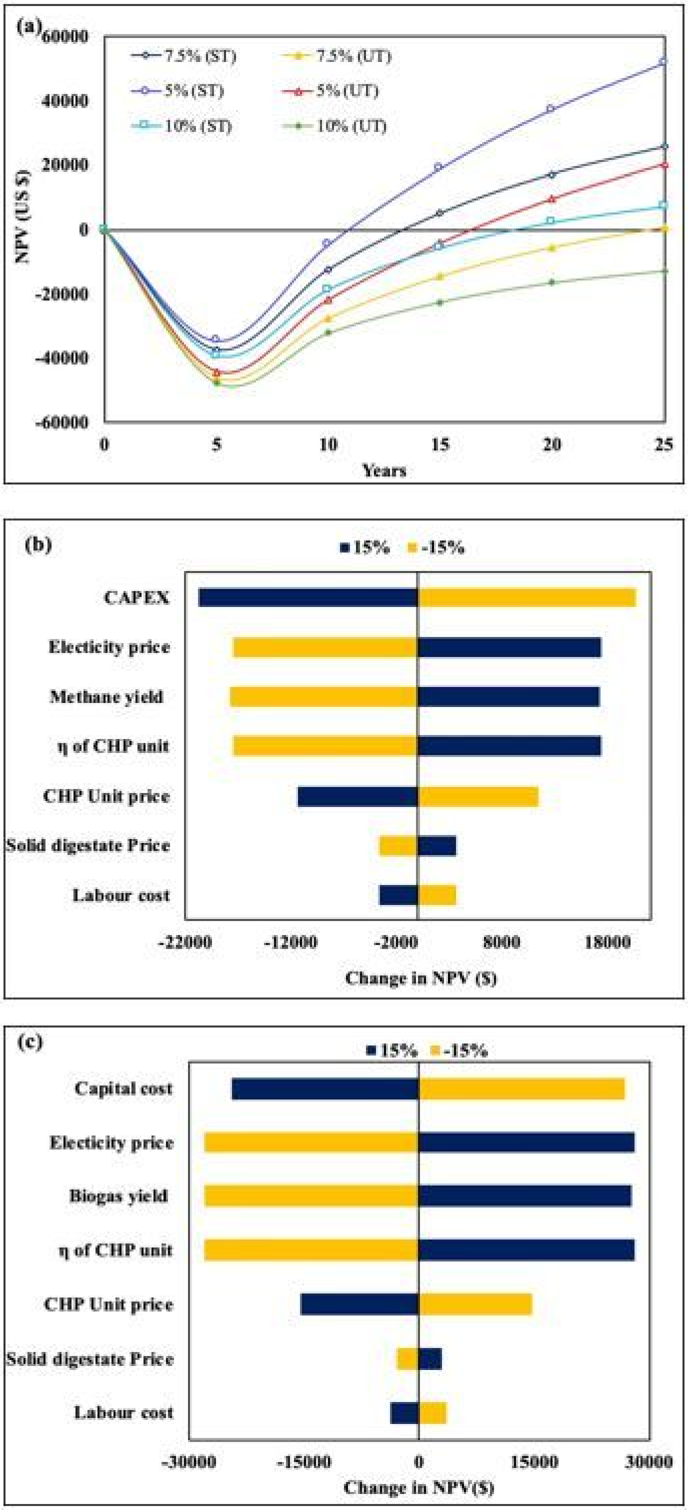


Figure 5

(a) NPV at different discount rate. (ST – simultaneously treated reactor; UT – Untreated reactor); Sensitivity analysis of (b) untreated and (c) simultaneously treated SSAD plant

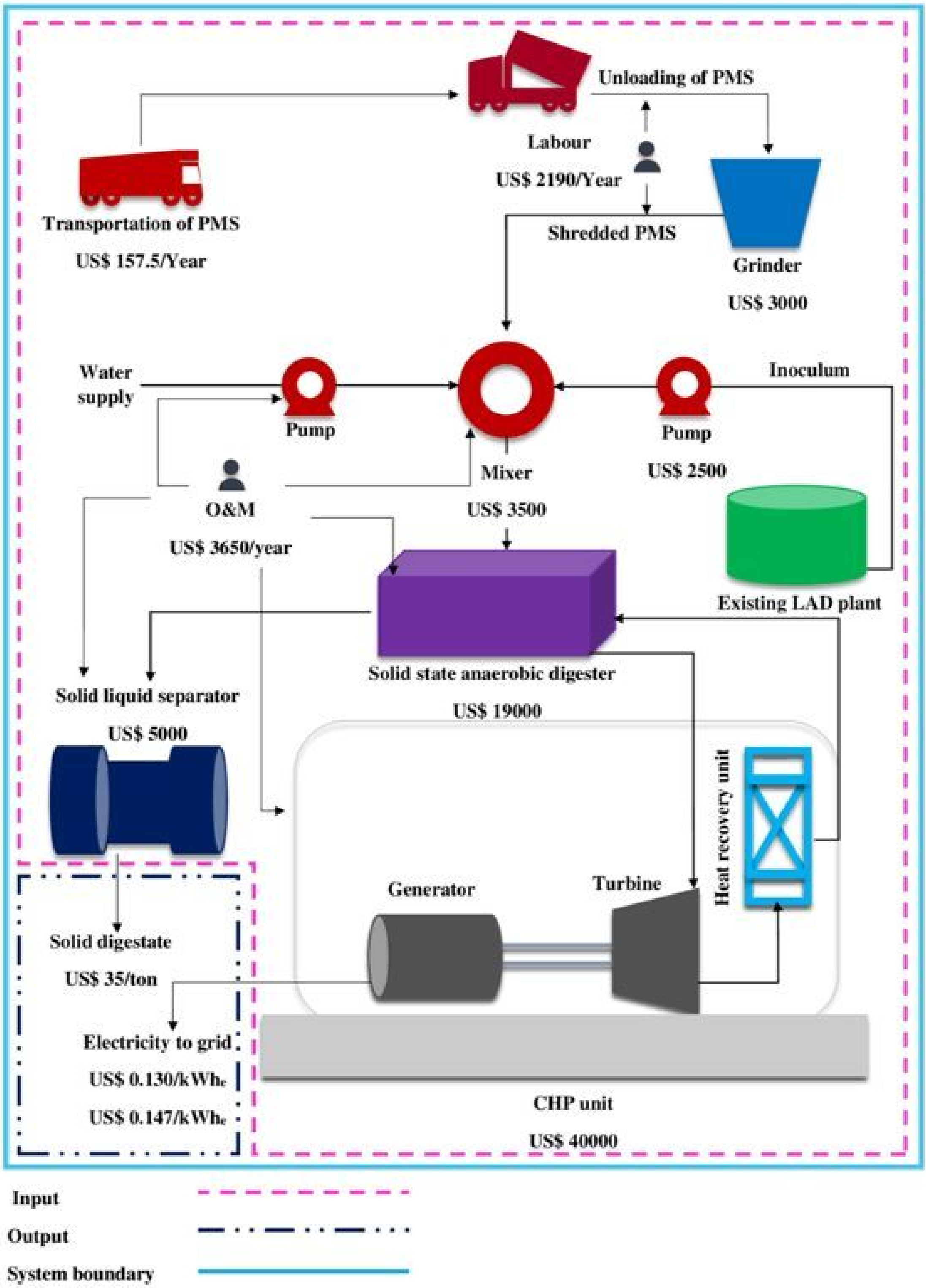


Figure 6

System boundary for techno-economic assessment

Supplementary Files

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- Table.docx