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Pretreatment of milled and unchopped sugarcane bagasse with vortex based hydrodynamic cavitation for enhanced biogas production

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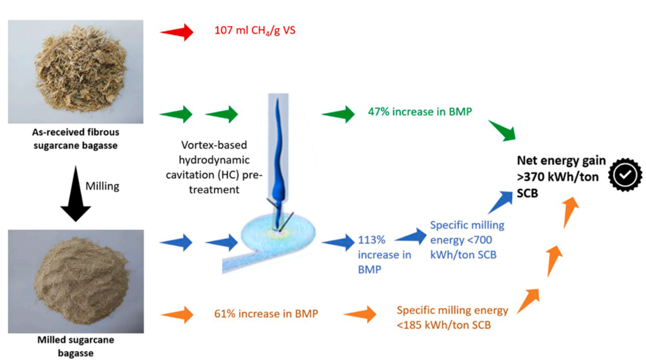
HIGHLIGHTS

- Novel vortex-based hydrodynamic cavitation (HC) pretreatment of bagasse.
- As-received fibrous biomass processed through a HC device for the first time.
- Net energy gain (373 kWh/ton) with enhanced biomethane production upon HC.
- Milling energy needs be ≤700 kWh/ton to obtain a net energy gain similar to unSCB.

GRAPHICAL ABSTRACT



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ABSTRACT

Anaerobic digestion can potentially valorise sugarcane bagasse to biogas and fertiliser. Pretreatment is however required to overcome recalcitrance and enhance the biogas yields. Literature reporting the investigation of various biomass pretreatments often use milled biomass as substrate rather than as-received fibrous biomass. This does not establish the true influence of the pretreatment type on biogas generation. Additionally, milling energy is also ignored when calculating net energy gains from enhanced biogas yields and are thus misleading. In this work, a vortex-based hydrodynamic cavitation device was used to enhance the biomethane yields from fibrous as-received biomass for the first time. Clear justification on why milled biomass must not be used as substrates for demonstrating the effect of pretreatment on biogas production is also discussed. The net energy gain from milled hydrodynamic cavitation pre-treated bagasse can be similar to as-received bagasse only when the specific milling energy is ≤700 kWh/ton.

1. Introduction

Sugarcane is a water intensive perennial grass that is mainly used for sugar production. Global sugarcane production in 2020 was ~1.9 billion tonnes with Brazil and India contributing to >60 % of its production (FAOSTAT, 2022). Sugarcane bagasse (SCB) - the predominant fibrous

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material left behind upon juice extraction constitutes ~30 wt% of the plant and pose a huge waste management challenge (Konde et al., 2021). Currently, electricity generation in cogeneration boilers is the most mature and favoured technology to deal with SCB. However, with dwindling electricity prices and issues surrounding sustainability and fly ash management, alternate SCB management means are needed (Meghana & Shastri, 2020) to generate additional revenue and sustain the sugarcane industry.

SCB is lignocellulosic in nature with a cellulose content of ~50 % (by dry weight) (Konde et al., 2021). It is therefore imperative to manage SCB sustainably by utilising it as a valuable resource. Accordingly, research has focussed on SCB based bioethanol, biogas and value-added products (Nagarajan & Ranade, 2019; Nalawade et al., 2020; Narisetty et al., 2021; Negrão et al., 2021; Valladares-Diestra et al., 2021; Zheng et al., 2021). Amongst the various avenues identified, biochemical valorisation especially via anaerobic digestion (AD) offers immense promise due to its potential to operate with net zero emissions if not net negative (He et al., 2019). There are however problems associated with digesting lignocellulosic substrates due to the recalcitrance posed by the inter/intramolecular bonding between the lignin and polysaccharide chains. Such hindrance leads to long residence times coupled with slow digestion kinetics, large reactor volumes and sub-optimal gas yields and poor substrate conversion. Therefore, substrate pretreatment is often utilised to overcome the limitations in AD (Abraham et al., 2020). Amongst the available pretreatment methodologies, physico-chemical methods are highly beneficial in improving the biogas yields from lignocellulosic biomass (Konde et al., 2021). Physico-chemical methods modify the structure and morphology of the biomass, reduces the particle size, increases the surface area and partially hydrolyses a fraction of the biomass to improve the bioavailability and thereby enhance the biogas production.

Hydrodynamic cavitation (HC) of biomass for biogas production is a physico-chemical pretreatment that is gaining increased attention (Garuti et al., 2018; Langone et al., 2018; Nagarajan & Ranade, 2021; Zieliński et al., 2019; Zubrowska-Sudol et al., 2020). HC has been reported to increase biogas yields by >2.5 folds from waste biomass (Nagarajan & Ranade, 2021). HC is the formation, growth and collapse of microbubbles (vaporous cavities) in a flowing field due to a rapid change in local pressure. The bubble implosion results in high-speed jets and shear thereby altering the structure of the biomass, whereas the cleavage of water molecules due to extreme local temperature (few 1000 K) and pressures (few 100 bars) results in the generation of highly unstable reactive radical species thereby partially hydrolysing it.

Most reported literature on biomass pretreatment utilise milled biomass as the starting material for investigating the effect of HC (Nakashima et al., 2016; Patil et al., 2016; Terán Hilares et al., 2016). While milling itself is an established physical pretreatment method (Khullar et al., 2013), using milled biomass as starting material should be justified when investigating the effect of other pretreatments on biogas generation. Although the enhancement in biogas yields were evident in these reported works, the net energy gain (if reported) excluded the milling energy requirements of the biomass. Thus, a positive net gain, as reported in literature could often be misleading. The net gains should either include milling energy or ensure that the feedstock utilised for AD is used as received. Using specific milling energies to determine the net gain is easier however, upon consideration, the net gain hardly is positive. On the other hand, when utilising the as received fibrous feedstock for AD, there are issues around mass transfer and pumpability of the biomass slurry. Especially with HC pretreatment, the conventional linear flow HC devices (orifice or venturi) have small constrictions in the flow path and are susceptible to clogging when fibrous biomass slurries are used. As an alternative, a swirl flow-based vortex-based HC device that is devoid of small constrictions has been proposed to pre-treat fibrous feedstock. Additionally, the vortex-based HC device, by design is protected from self-erosion as the cavitation bubble collapse occurs along the core of the flowing liquid (Simpson & Ranade, 2019).

Initial work with vortex-based HC device was performed with milled SCB as the feedstock (Nagarajan & Ranade, 2019). This work by (Nagarajan & Ranade, 2019) demonstrated that when milled SCB was HC treated, the enhancement in biochemical methane potential (BMP) as compared to only milled SCB was 24 %. Without considering the specific milling energy, a net positive energy gain was calculated based on the enhanced BMP observed. It was also proposed that since a vortex-based HC device was used for pretreatment, as received fibrous SCB could be utilised as the substrate.

This work, for the first time demonstrates the capability of a HC device to pre-treat as received fibrous biomass and enhance its BMP. The pretreatment performance was extensively compared with the initial work reported using milled SCB (Nagarajan & Ranade, 2019) and important conclusions around threshold specific milling energy required and potential net energy gains that could be achieved are discussed in detail. The utilisation of as received fibrous biomass as feedstock for AD pre-treated using a scalable vortex-based HC device offers immense potential for industrial AD application.

2. Experimental methods

2.1. Feedstock and inoculum collection and characterisation

SCB was received as dried fibres from Dhampur sugar mills, India and stored as received prior to experiments. These samples will be referred to as unchopped SCB (unSCB) from here on. A part of this unSCB was milled to a powder (<2000 μm) using a POLYMIX PX-MFC-90D grinder mill fitted with a 2000 μm sieve (termed as milled SCB, mSCB from here on). To prepare the inoculum, primary digestate was collected from an active digester (operated by Agri-Food and Biosciences Institute, Hillsborough, UK), digesting grass silage and cattle manure and filtered through a 1 cm mesh. The filtrate was degassed for 3 days prior to use for biochemical methane potential (BMP) tests.

To determine the total solids (TS) and volatile solids (VS) content of unSCB, 0.5 g of the biomass was firstly taken in a pre-weighed crucible and placed in an oven at 85℃ for 2 days. The samples were then let to attain room temperature and weighed before being placed in a muffle furnace at 550℃ for 2 h. Upon ashing, the crucibles were left to cool down to room temperature and weighed. The amount of moisture lost and dry weight remaining (TS) were calculated from the oven drying step whereas the amount of VS lost and ash remaining were determined from the ashing stage. A similar procedure was used to characterise the inoculum however, the initial sample used was 10 g. The TS-VS analysis was performed in triplicates.

unSCB and mSCB were further characterised for their particle size distribution (PSD). To determine the PSD, 10 g of biomass was placed on a mesh of size 3350 μm and sealed. The successive meshes of sizes 1200 μm, 850 μm and 250 μm were then stacked in descending order. Finally, a collection tray was also placed to collect SCB of size < 250 μm. The mesh stack was shaken for 5 min and the amount of each size fraction remaining was then weighed to determine the PSD for each of the types of SCB. Furthermore, the morphology of the untreated and HC treated SCB was captured using a Hitachi FlexSEM 1000 scanning electron microscope (SEM) at 20 kV acceleration under high vacuum with the samples mounted on carbon tape and gold sputter coated before imaging.

2.2. Vortex-based hydrodynamic cavitation pretreatment

A hydrodynamic cavitation (HC) rig reported by (Nagarajan & Ranade, 2019) and (Nagarajan & Ranade, 2020) was used in this work. The rig hosted a stainless steel 316 vortex based hydrodynamic cavitation device of nominal capacity 1.2 m^3/h (procured from Vivira Process Technologies, India) and a ROTO RCML 253 progressive cavity pump. All the pipes and fittings were 1″ uPVC whereas the brass gate valves were used to divert flows as required. Extensive details of the rig configuration can be found in (Nagarajan & Ranade, 2019) and (Nagarajan & Ranade, 2020).

HC pretreatment of mSCB and its effect on biochemical methanation potential (BMP) was reported earlier by (Nagarajan & Ranade, 2019). HC pretreatment of unSCB and its effect on BMP were performed in this work and compared with mSCB on the basis of net energy gains. To perform the HC pretreatment of unSCB, 69 g of the biomass was taken in 23 L tap water (working volume) to achieve a concentration of 3 g/L. A progressive cavity pump was used to pump the fibrous unSCB slurry through the HC device. It was observed that a higher bagasse loading led to clogging which required time consuming and cumbersome cleaning steps. In order to avoid such situations, a low bagasse loading (3 g/L) was used in the present experiments. Please note that clogging occurred primarily at pump and not at the hydrodynamic cavitation device used in this work. With the better slurry pump, higher loading of bagasse can be used. The slurry was let to circulate through the bypass line for ~5 min and then all the flow was diverted through the mainline by manipulating the valve positions. At this instance, the pressure drop across the cavitation device was 3.9 barg with a flow rate of 1.54 m^3/h. The throat velocity was calculated to be 3.77 m/s. Samples of 2–3 L were collected after 10, 20 and 40 passes through the HC device. The total time required to complete 40 passes was < 20 min and the bulk temperature in the holding tank stayed < 30^{O}C. Alongside, 9 g of unSCB was added to 1 L tap water and mixed for 30 min. This sample was used as the control sample and termed as the untreated unSCB. All the slurry samples were then filtered using a muslin cloth, the filtrate was stored in the fridge and the solids were dried in an oven at 85^{O}C for 2 days.

2.3. Biochemical methanation potential tests and kinetics

Untreated and HC pre-treated unSCB were subjected to BMP tests using a standard Gas Endeavour kit (Bioprocess control, Sweden). The kit was able to perform BMP tests of up to 15 bioreactors simultaneously. Therefore, 5 sets of triplicate BMP tests were performed. The first set was the inoculum only without any SCB added to it. The second set had unSCB and inoculum, whereas the last three sets of bioreactors had 10, 20 and 40 passes HC treated unSCB and inoculum. Appropriate quantity of solids and liquids were mixed in the bioreactors to achieve the initial concentration of 3 g/L. Corresponding amount of degassed inoculum was then added to the bioreactor to make up the working volume of 0.4 L at an inoculum to substrate ratio of 2 (VS basis). All the reactors were fitted with a mixer and then placed in a water bath at 41^{O}C. The mixers operated at 50 % of the maximum speed with a 10 s ON and 10 s OFF cycle. The outlet port of the reactors were connected to individual 0.08 L 3 M NaOH bottles (containing thymolphthalein indicator) to strip CO_2. The outlet ports of these stripping bottles were connected to individual pre-calibrated flow cells to quantify the volume of methane generated. Continuous automatic data logging was enabled with the use of a dedicated PC installed with the software that communicated with the flow cells. The BMP tests were performed for a period of 30 days. A first order kinetic model reported by (Nagarajan & Ranade, 2019) was used to describe the BMP data.

2.4. Net energy gain calculations

The specific energy required to pre-treat biomass using HC (E_P) can be calculated as follows (Nagarajan & Ranade, 2019),

$$E_P = \frac{\Delta P\, Q}{3600\, q\, m_s\, \eta}\ \frac{kWh}{ton\,TS} \tag{1}$$

where ΔP is the pressure drop across the HC device, Pa; Q is the flow rate through the HC device, m^3/s; q is the flow rate of slurry to AD, m^3/s; m_s is the biomass TS concentration in feed slurry, kg/m^3 and η is the pump efficiency that is usually assumed to be 0.66. For a continuous pretreatment and AD system, the Q/q ratio gives the number of passes n_p. An enhancement in biomethane yield is expected upon pretreatment, therefore the energy gained (excess energy produced) due to pretreatment, E_G can be calculated using.

$$E_G = \Delta H_{cal}\,(G_{HC} - G_0)\ \frac{kWh}{tonTS} \tag{2}$$

where ΔH_{cal} is calorific value of methane, 9.95 kWh/m^3; G_{HC} is the enhanced biomethane produced as a result of HC pretreatment, m^3/ton TS and G_0 is the biomethane produced from the as received biomass, m^3/ton TS. E_N is the net energy gain that can be calculated using.

$$E_N = E_G - E_P - E_D - E_M \frac{kWh}{ton\,TS} \tag{3}$$

In equation (3), E_D and E_M represent the specific energies required for drying and milling the as received biomass.

3. Results and discussion

3.1. Feedstock characterisation

The characterisation of feedstock for TS-VS is important as it helps to identify the usable fraction of the SCB for biogas generation. SCB had a TS content of 98.0 ± 0.1 %, VS content of 91.1 ± 1.2 % and ash content of 6.9 ± 1.2 %. The inoculum on the other hand had a TS content of 4.6 ± 0.1 %, VS content of 3.1 ± 0.1 % and ash content of 1.5 ± 0.1 %. VS quantities obtained here were used to determine the composition of the slurry in the bioreactor for BMP tests. PSD analysis was specifically performed with untreated unSCB and mSCB (Fig. 1). This was performed to highlight the difference in composition of the size fractions available for BMP (without HC treatment) between the two samples. unSCB was composed of >60 % of particles in the combined size fraction of 1200–3350 μm and >3350 μm with only 1 % of the size fraction under 250 μm. Some particles >3350 μm were as long as ~50,000 μm. In the case of mSCB, 68 % of fraction was in the range of 250–850 μm and ~25 % <250 μm. Sub-mm range particles are known to expose a greater fraction of cellulose to microbial attack (Dai et al., 2019). With unSCB, the structural integrity of the cell wall is well preserved with the lignin acting as the binder (Sharma et al., 1988). Therefore, with milling already established as an effective physical pretreatment of biomass, it is expected that mSCB will outperform unSCB in biomethane production even without HC pretreatment. It is hence important not to use milled biomass as starting materials when reporting net energy gains unless the specific drying and milling energy requirements are used in the calculations.

With the unSCB used in this work, the slurry samples were first collected after various number of passes through the vortex-based HC device. While samples until 1000 passes were collected, samples in the range of 0–40 passes were used for BMP tests. With 0 passes (untreated unSCB), large fibres were clearly seen, whereas with increase in number of passes through the vortex-based HC device, it was evident that visible large fibres were disintegrated as early as 10 passes and a more homogeneous slurry with much finer particles were obtained after 1000 passes. Similar results of shift in particles size fraction as a result of HC pretreatment was reported by (Garuti et al., 2018) who used shredded mixed agricultural residue and animal slurry as AD substrates. The physical effects (shear impact) of HC on solids such as reduced particle size, higher bulk density and improved rheology of slurries due to lower viscosity have also been reported (Li et al., 2018; Sonawane et al., 2010). HC pretreatment is known to affect the biomass beyond just particle size. For instance, the difference in structural morphology between mSCB and HC treated mSCB was shown in (Nagarajan & Ranade, 2019). Similarly, in this study, the morphological changes caused by HC pretreatment on SCB was studied using a scanning electron microscope. The observations revealed that the untreated SCB particles had an intact and well-defined cellular structure. In the case of HC treated SCB, the surface morphology

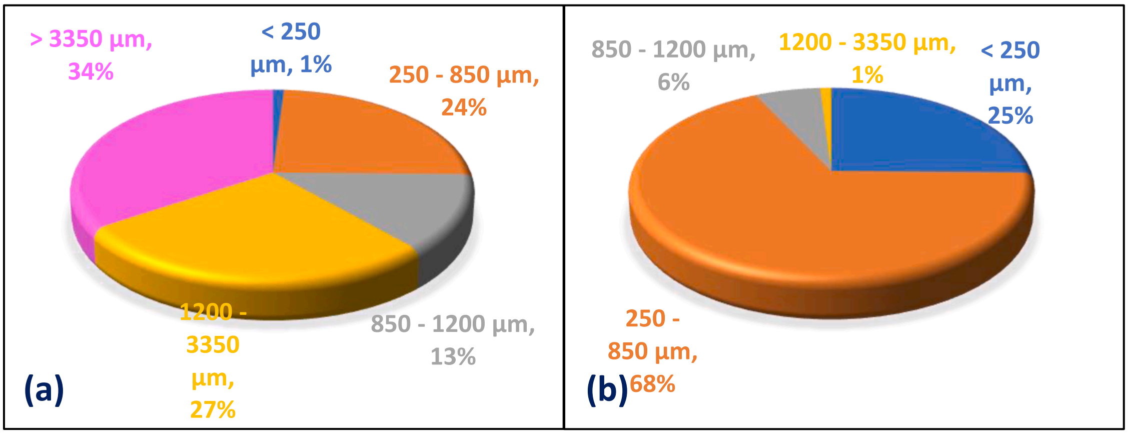

Fig. 1. Particle size distribution of (a) as received unSCB and (b) mSCB with a 2000 µm cut off sieve (both before HC pretreatment).

showed chipped boundaries and broken particles as a result of pretreatment. Such changes to SCB would lead to an increase in surface area as well as potentially improve the bioavailability of the polysaccharide fractions in the biomass thereby leading to an enhanced product yield.

3.2. Biomethane potential and kinetics

The theoretical maximum BMP of SCB as reported by (Nagarajan & Ranade, 2019) based on the empirical formula and Buswell's equation (Buswell & Mueller, 1952) is 437.9 ml CH_4/ g VS. It is however unlikely to achieve this as a fraction of the VS will be utilised towards satisfying microbial energy needs and also may include lignin that is susceptible to microbial attack. Maximising the biomethane yield is however critical and can be achieved with effective pretreatment. Untreated unSCB, at the end of 30 days generated 107 ml CH_4/g VS (Fig. 2a) which is ~25 % of the theoretical yield. Upon vortex-based HC pretreatment, the BMP increased to 130 ± 27 ml CH_4/g VS, 158 ± 13 ml CH_4/g VS and 157 ± 18 ml CH_4/g VS after 10, 20 and 40 passes respectively. These were correspondingly higher than untreated unSCB by 21 %, 47 % and 46 % and were 30 %, 36 % and 36 % of the theoretical BMP. Considering Fig. 2b, mSCB without HC pretreatment (0 passes) already enhanced the BMP by 61 % (39 % theoretical yield) thus supporting the discussion on the influence of particle size on BMP in section 3.1. This is also consistent with literature where a smaller mean biomass particle size was reported to enhance the BMP significantly compared to the untreated fibrous biomass (Dai et al., 2019; Gallegos et al., 2017; Sharma et al., 1988). Upon optimal HC treatment (9 passes) of mSCB, the BMP was enhanced by 113 % (52 % theoretical yield) compared to untreated unSCB. It could also be seen that (Table 1), the lag time required for gas generation was gradually reduced in both cases with increase in number of passes through the HC device.

Considering an average cellulose and hemicellulose content of 41 % and 27.5 % in SCB (Konde et al., 2021; Nagarajan & Ranade, 2019) the maximum theoretical BMP from SCB can be recalculated to be 284 ml CH_4/g VS (assuming that lignin cannot be converted to biomethane). With this recalculated theoretical BMP of SCB, the experimental BMP from 9 passes HC treated mSCB would be ~81 %. The kinetic parameters of both the BMP profiles shown in Fig. 2 are summarised in Table 1. It has to be however noted that since the BMP of mSCB were performed as the preliminary work and reported in (Nagarajan & Ranade, 2019), the rate of biomethane generation cannot be directly compared, whereas the BMP can be compared directly. This is because, despite collecting the inoculum from the same working digester, but at different instances, the composition of the inoculum may vary and have an influence on the gas generation rates.

SCB has been reported as an excellent feedstock for biomethane generation. However, pretreatment is often required to overcome the recalcitrance and improve the substrate conversion to biogas. The most common SCB pretreatments reported are chemical or physico-chemical methods (Kaur et al., 2020; Mustafa et al., 2018; Nagarajan & Ranade, 2019; Nosratpour et al., 2018; Sajad Hashemi et al., 2019) that are capable of enhancing the biomethane yields significantly. For instance, Kaur et al., 2020 investigated the effect of alkaline pretreatment of SCB and determined that 2 % NaOH treatment at room temperature was better than 2 % $Ca(OH)_2$ treatment in enhancing the biogas yields under both mesophilic and thermophilic conditions. With 2 % NaOH, the enhancement observed was 20 % and 2 % under mesophilic and thermophilic conditions respectively. Nosratpour et al., 2018 on the other hand investigated the hydrothermal pretreatment of bagasse in the presence of 0.5 M Na_2CO_3 at 140^OC and obtained a ~4.5-fold increase in methane yield. At a higher temperature of 180^OC and with lime as the preferred alkali, Mustafa et al., 2018 achieved 47 % increase in biogas production. In an unconventional physico-chemical pretreatment with 10 % ammonia and 50 % ethanol at 70^OC, Sajad Hashemi et al., 2019 improved the biomethane yields by up to 2.8-folds. In all of these cases, though the focus of the work was directed towards investigating the effect of non-physical pretreatment methods on BMP of SCB, the initial substrate used was always milled to a certain degree. Furthermore, (Konde et al., 2021) compiled a review on the pretreatment methods available for enhancing the biogas generation from SCB and reported that almost all of the non-physical methods use milled SCB as the starting material. While this is the case as reported in literature, the true effect of the pretreatment under consideration cannot be investigated with the use of milled SCB. Instead, as received biomass must be used to clearly demonstrate the effects. Similar reporting of data can also be seen widely in literature with other biomasses (Garuti et al., 2018; Patil et al., 2016; Zieliński et al., 2017; Zubrowska-Sudol et al., 2020) and other biofuel production methodologies (Bimestre et al., 2020; Madison et al., 2017; Nakashima et al., 2016; Terán Hilares et al., 2018) as well.

In addition, when net energy gains are reported based on the enhanced biomethane yields, it is always assumed that the as received biomass and the milled biomass would perform similarly under similar pretreatment conditions. This is however not true as demonstrated in this work, where the unSCB upon optimal 20 passes HC pretreatment showed a 47 % enhancement in BMP whereas the mSCB upon optimal 9 passes improved the BMP by 113 % when compared to as received unSCB (Fig. 3). It is therefore critical to determine the specific energy requirements for pretreatments and establish the threshold energy required for milling to obtain net positive energy gains.

3.3. Specific energy requirements and net energy gain

HC, especially vortex-based HC has been reported to enhance the BMP of various biomasses (Nagarajan & Ranade, 2021). The specific

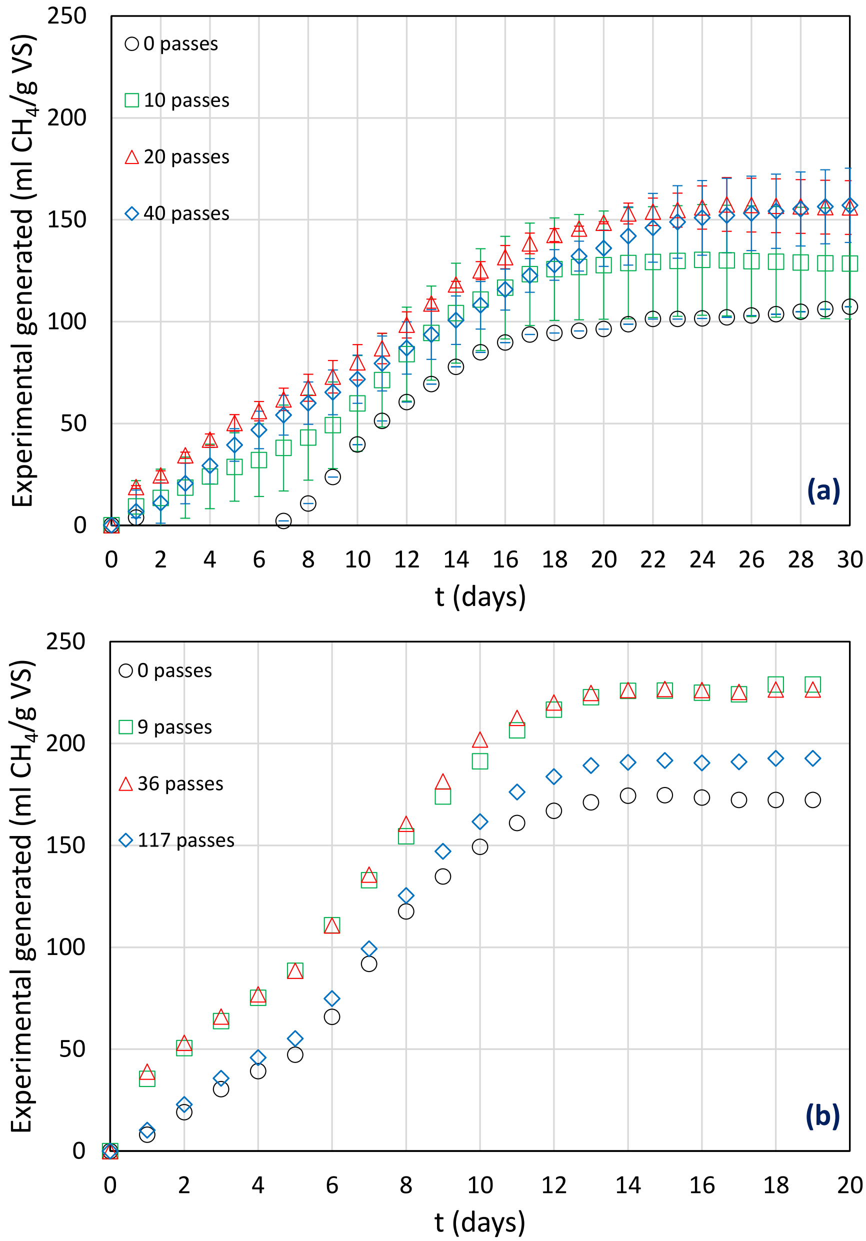

Fig. 2. BMP profiles of (a) untreated and HC treated unSCB and (b) mSCB and HC treated mSCB; 0 passes denote (a) unSCB and (b) mSCB samples before HC pretreatment; data for (b) obtained from the preliminary work by (Nagarajan & Ranade, 2019).

energy requirements for HC pretreatment are also the least amongst all the other methods. For instance, acoustic cavitation is known to be energy intensive and its specific energy requirements range between 470 and 2400 kWh/ton TS; drying and milling – a conventional physical pretreatment has specific energy requirements that ranges between 450 and 1400 kwh/ton TS; whereas HC has been reported to have a specific energy requirement in the range of 140 – 660 kwh/ton TS (Langone et al., 2018; Miao et al., 2011; Nagarajan & Ranade, 2019; Priyanto et al., 2018; Zieliński et al., 2017). With low specific energy requirements and proven scalability (Garuti et al., 2018; Nagarajan & Ranade, 2020), HC offers an immense potential as a biomass pretreatment method that could be commercially exploited.

Using equation (1), E_P could be calculated as a function of m_s and is shown in Fig. 4a (blue curve). It can be seen that E_P decreases with an increase in m_s. While the study reported here utilised a biomass loading of 3 kg/m^3 for demonstrating the capability of vortex-based HC for enhancing biomethane production, industrial loading for commercial AD are at least 10 times higher (>3% TS) with typical loading of ~10 % TS. Assuming G_{HC} stays constant across various solid loadings (typically would vary/increase with solid loading) and no E_D and E_M when using unSCB, E_N could be calculated as a function of m_s (as shown in the orange curve in Fig. 4a). It can be seen that from a solid loading of >10 kg/m^3 (1 % TS) a net positive energy gain is possible to achieve when unSCB is pre-treated using vortex-based HC for 20 passes. At 10 kg/m^3 loading, the specific energy required for HC treatment, E_P was found to be 347 kWh/ton SCB with a net positive energy gain, E_N of 60 kwh/ton SCB. At typical commercial AD loadings of 100 kg/m^3 (10 % TS), E_P was found to be 35 kWh/ton SCB with an E_N of 373 kWh/ton SCB.

In the case of mSCB, without HC pretreatment at a solid loading of 100 kg/m^3, the net energy gain, E_N of 373 kWh/ton SCB (HC treated unSCB) can only be achieved when the combined milling and drying energies are ≤ 185 kWh/ton SCB. However, as mentioned in this section earlier, this specific energy requirement for milling and drying energies are considerably lower than the reported values. Therefore, it is highly

Table 1
Kinetic parameters obtained from the first order model to describe the BMP of various SCB samples used in this work; *data from preliminary work obtained from (Nagarajan & Ranade, 2019).

Sample	Sample abbreviation	Fitted BMP (ml CH4/ g VS)	Experimental BMP (ml CH4/ g VS)	Rate of gas generation (day^{-1})	Lag time (days)	Correlation coefficient	% Increase in BMP	% Theoretical BMP achieved	% Recalculated theoretical BMP achieved
unSCB 0P	Untreated unchopped SCB	113	107	0.16	7.2	0.99	–	25 %	38 %
unSCB 10P	10 passes HC treated unchopped SCB	146	130	0.11	4.9	0.97	21 %	30 %	46 %
unSCB 20P	20 passes HC treated unchopped SCB	170	158	0.11	2.7	0.96	47 %	36 %	55 %
unSCB 40P	40 passes HC treated unchopped SCB	170	157	0.09	0.3	0.97	46 %	36 %	55 %
mSCB 0P*	Milled SCB	175	172	0.35	5.5	0.99	61 %	39 %	61 %
mSCB 9P*	9 passes HC treated milled SCB	229	229	0.38	7.5	0.99	113 %	52 %	81 %
mSCB 36P*	36 passes HC treated milled SCB	227	227	0.39	6.5	0.99	111 %	52 %	80 %
mSCB 117P*	117 passes HC treated milled SCB	193	193	0.36	6.0	0.99	80 %	44 %	68 %

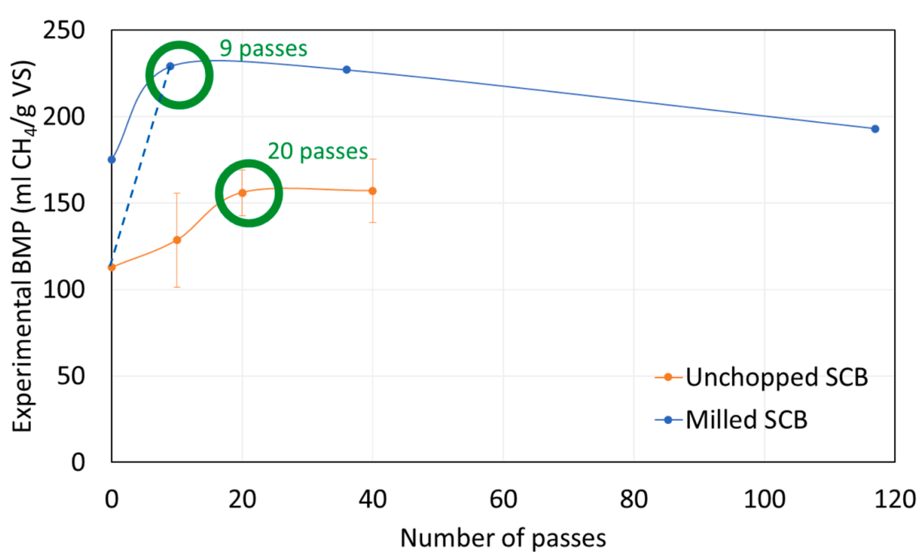

Fig. 3. Enhancement in BMP observed from unSCB and mSCB with and without HC.

unlikely that milling alone can result in a net positive energy gain despite showing an enhancement in biomethane yields when considering capital expenditure costs during the overall techno-economic assessment.

It is hence important to now establish whether HC combined with milling is truly beneficial in yielding a net positive energy gain. At optimal conditions of 9 passes through the vortex-based HC device, it was established that the enhancement in biomethane yield was 113 % when compared to as received unSCB (Table 1). It was also earlier determined that the specific energy required for HC pretreatment, E_P of mSCB was ~140 kWh/ton SCB (Nagarajan & Ranade, 2019) for 10 kg/m^3 loading. With the loading of 100 kg/m^3, E_P reduced to 15 kWh/ton SCB. Therefore, the net energy gain, E_N that can be obtained from combined milling and HC pretreatment was calculated as a function of milling energy and shown in Fig. 4b (blue curve). In the same plot, an orange circle denotes the net gain that can be obtained at 100 kg/m^3 loading from HC pre-treated unSCB at 20 passes (373 kWh/ton SCB). When the milling energy (and drying energy combined) is as high as 1000 kWh/ton SCB, a meagre net positive energy gain of 79 kWh/ton SCB can be achieved. However, if the combined milling and drying energy requirement is halved to 500 kWh/ton SCB, then the net gain achieved would be as high as 579 kWh/ton SCB thereby justifying the use of milling followed by vortex-based HC pretreatment of SCB (green circle shown in Fig. 4b). To obtain a similar net energy gain as that attained with vortex-based HC pre-treated unSCB, the combined milling and drying energy could be as high as 700 kWh/ton SCB as shown by the green square in Fig. 4b. In countries like India and Brazil, upon completing the juicing process (extracting sugarcane juice from the plant), piles of bagasse are typically stacked in the open. Therefore, due to the suitable weather conditions, natural drying is possible and if managed appropriately could be more effective. In that case, achieving a combined drying and milling energy requirement of 500–700 kWh/ton SCB may be feasible. When establishing the overall techno-economics of the process and considering the capital expenditure costs, a lower milling and drying energy combined with a significant net energy gain would mean that the return of investment time could be reduced. Detailed calculation of capital costs and operating costs may be needed to make rigorous comparison of unSCB and mSCB. The presented data will be useful for carrying out such calculations.

Moving forward, it is important to explore the aspect of integrated

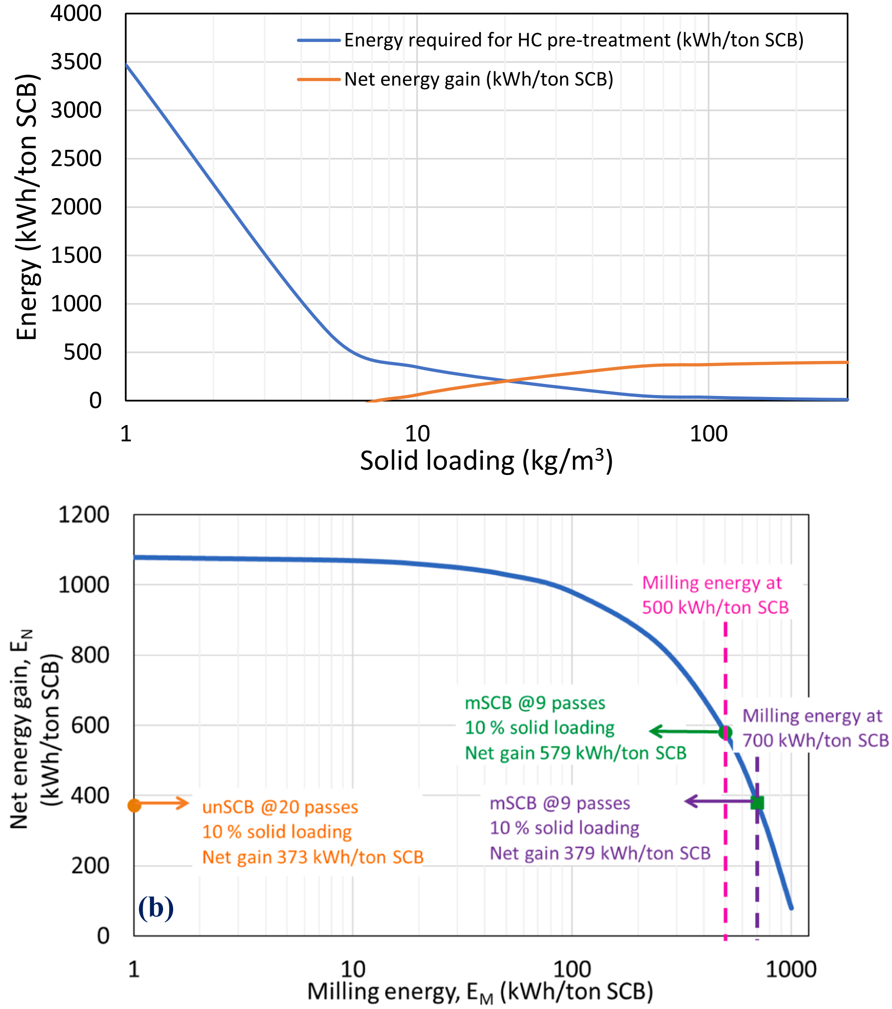

Fig. 4. (a) Specific energy required for the HC pretreatment of unSCB at 20 passes (blue curve) and corresponding net energy gain achieved due to enhanced BMP (orange curve) as function of solid loading and (b) net energy gain as a function of milling energy upon HC pretreatment of mSCB at 9 passes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

biorefineries with SCB as the feedstock (Konde et al., 2021; Nagarajan & Ranade, 2019). With as much as >80 % theoretical yield in BMP achieved from combined milling and vortex-based HC pretreatment, it is expected that the left behind fibres will be rich in crystalline cellulose bound to lignin. There is hence a possibility to utilise HC as a post treatment to further breakdown the lignin chain and obtain lignin free cellulose that could be subjected to biochemical transformations thereby realising biorefineries. While the preliminary result presented here is in favour of using combined milling and HC pretreatment to enhance the BMP from SCB, an overall techno-economic and life cycle assessment of the simulated AD plant is required. Combining this work, and previously reported work by (Nagarajan et al., 2021) on a simplified AD model, a complete assessment of the techno-economics and life cycle is currently underway and will be separately published.

4. Conclusions

Vortex-based HC pretreatment after 20 passes was successful in enhancing the BMP of unSCB by 47 % with a net positive energy gain of 373 kWh/ton (at 10 % TS). While only milling enhanced the BMP, a net positive energy gain could not be achieved. Finally, milling followed by vortex-based HC after 9 passes increased the BMP by 113 %. A net positive energy gain similar to unSCB can be achieved when the combined milling and drying energy is ≤700 kWh/ton SCB.

CRediT authorship contribution statement

Sanjay Nagarajan: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Vivek V. Ranade:** Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Professor Vivek Ranade is a co-founder and Director of Vivira Process Technologies Pvt. Ltd. which commercially offers cavitation devices used in this study.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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