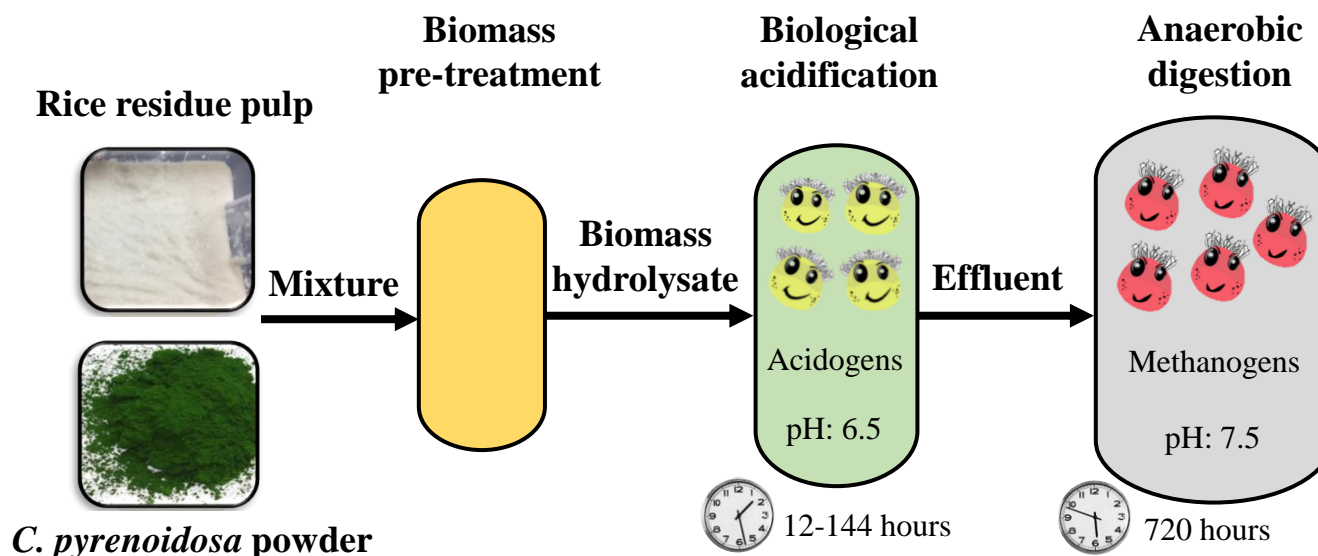


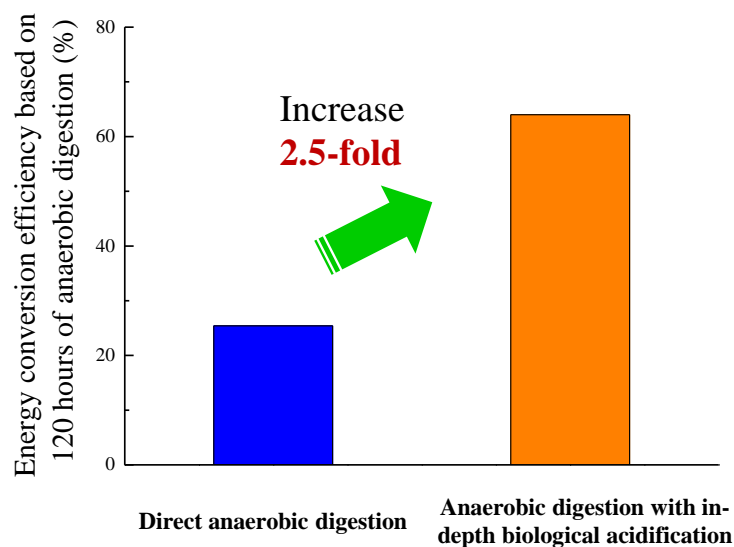
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Title	Effects of pre-treatment and biological acidification on fermentative hydrogen and methane co-production
Author(s)	Sun, Chihe; Xia, Ao; Fu, Qian; Huang, Yun; Lin, Richen; Murphy, Jerry D.
Publication date	2019-02-19
Original citation	Sun, C., Xia, A., Fu, Q., Huang, Y., Lin, R. and Murphy, J. D. (2019) 'Effects of pre-treatment and biological acidification on fermentative hydrogen and methane co-production', Energy Conversion and Management, 185, pp. 431-441. doi:10.1016/j.enconman.2019.01.118
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://www.sciencedirect.com/science/article/pii/S0196890419301943 http://dx.doi.org/10.1016/j.enconman.2019.01.118 Access to the full text of the published version may require a subscription.
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Embargo information	Access to this article is restricted until 24 months after publication by request of the publisher.
Embargo lift date	2021-02-19
Item downloaded from	http://hdl.handle.net/10468/7546

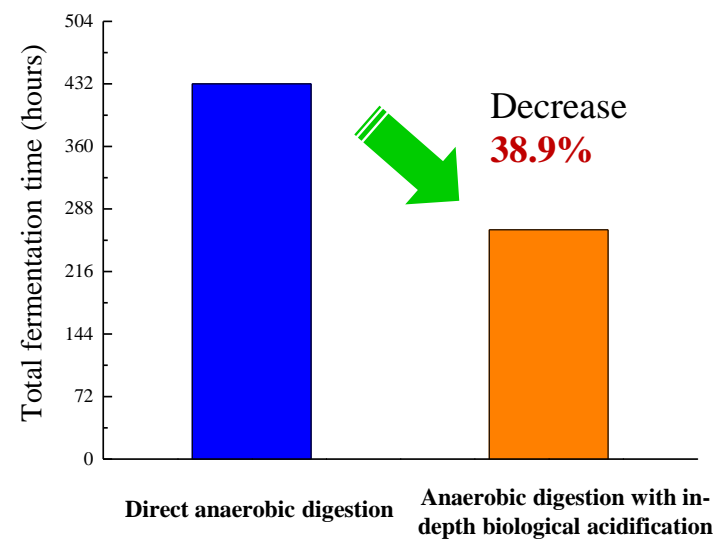
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Energy conversion efficiency based on 120 hours of anaerobic digestion



Total fermentation time



Highlights

- Synergistic effects of pre-treatment and bio-acidification were assessed.
- Hydrothermal acid pre-treatment was beneficial for biological acidification.
- Increasing bio-acidification time increased acetic acid production.
- Bio-acidification decreased lag-phase time whilst improving methane production.
- 144 hours bio-acidification achieved maximum energy conversion efficiency of 64%.

1 **Effects of pre-treatment and biological acidification on fermentative**
2 **hydrogen and methane co-production**

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1 **Abstract**

2 A sequential two-stage process comprising biological acidification followed by
3 anaerobic digestion was proposed to enhance gaseous biofuel production from the
4 mixture of rice residue and microalgae with thermo-chemical hydrolysis. The
5 maximum specific hydrogen yield of 223.1 ± 8.8 mL/g volatile solids (VS) and
6 production rate of 10.4 ± 0.4 mL/g VS/h were achieved from hydrothermal acid
7 pre-treated biomass during biological acidification. Increase in hydraulic retention
8 time of biological acidification from 12 to 144 hours significantly affected the
9 distribution of solubilised metabolic products and led to improve biological
10 acidification rates (BARs) from 15.5% to 78.5%. Compared with single stage
11 anaerobic digestion, the first stage acidification phase led to reductions in the
12 lag-phase time and peak time of anaerobic digestion in such a two-stage process. The
13 maximum specific methane production rate of 2.2 ± 0.03 mL/g VS/h was achieved
14 with a deep acidification of 144 hours yielding a BAR of 78.5%. Increasing the length
15 of time in biological acidification from 12 to 144 hours contributed to improve energy
16 conversion efficiency of 25.4%–64% after 120 hours of anaerobic digestion. These
17 results demonstrate that biological acidification is feasible to improve bioenergy
18 recovery in two-stage fermentation.

19

20 **Keyword:** Fermentation; Hydraulic retention time; Biological acidification;
21 Biomethane; Algae; Food waste.

1 **1 Introduction**

2 Biofuels, such as biogas, biodiesel and bioethanol, are alternative renewable options
3 for carbon intensive transport fossil fuels; they can significantly reduce greenhouse
4 gas emissions, improve air quality and increase the security of energy supply [1-4].
5 Compared with liquid biofuels, gaseous biofuels (such as biogas) generally have more
6 advantages [5-7], especially in the energy conversion efficiency, greenhouse gas
7 emissions, and the convenience of distribution system. Biogas can be used as an
8 energy source for various applications including heat, electricity, and vehicle fuel [8].
9 Additionally, biogas can substitute for all natural gas applications when injected to the
10 gas grid [2].

11 Anaerobic digestion is a well-established bioconversion technology, in which
12 various types of biomass and organic wastes can be converted to biogas by anaerobic
13 microorganisms at relatively low temperature (35–55 °C) and ambient pressure [9,10].
14 This technology comprises four stages (hydrolysis, acidogenesis, acetogenesis, and
15 methanogenesis) all of which require interaction between different types of
16 microorganisms [6,11]. However, the microorganisms in each stage have different
17 metabolic pathways and activities, and can be disturbed by environmental stresses and
18 undesirable process factors (such as pH, temperature, and retention time). As such, the
19 environment and the process variables need to be optimised to ensure a high
20 efficiency for biogas production in anaerobic digestion.

21 Previous studies found that the growth rate of acidogens at the acidogenesis stage
22 was far superior than that of methanogens at the methanogenesis stage, especially

1 when easily degradable feedstock (such as food waste) was used as fermentation
2 substrate [12]. Based on this, the production capacity of volatile fatty acids (VFAs) by
3 acidogens would exceed the ability of methanogens to process the VFAs [12].
4 Excessive accumulation of VFAs can cause a significant drop of pH, thereby
5 hindering the fermentative methane production [13]. A separate process of biological
6 acidification prior to anaerobic digestion is considered as one of the effective methods
7 to avoid this imbalance between VFA production and methanogenic consumption.
8 And not only that, hydrogen produced via biological acidification would become
9 another key renewable energy product. The addition of hydrogen to methane can
10 overcome several disadvantages of pure methane in engines, such as high ignition
11 temperature, slow burning speed and narrow flammability range [6].

12 Notably, the biochemical conversion efficiency and biological stability in such a
13 two-stage process are affected by the biological acidification rate (BAR) of feedstocks
14 [14,15]. This can be controlled by adapting the hydraulic retention time (HRT) of
15 biological acidification. A short HRT generally results in a low BAR with a low VFA
16 production rate, corresponding to a low hydrogen yield [6,16]. Also, the insufficient
17 substrates of VFAs for methanogens in anaerobic digestion would further lead to a
18 low methane yield. A long HRT favours the complete degradation of feedstocks and
19 produces a high concentration of VFA. Even so, the composition and concentration of
20 soluble metabolic products (SMPs), such as alcohols and VFAs, differ with different
21 HRTs [17]. The performance of the subsequent methane producing stage is influenced
22 by these SMPs. For instances, the bioactivity of methanogens is inhibited at a

1 propionic acid concentration of 900 mg/L, while the inhibitory concentrations of
2 ethanol, acetic acid, and butyric acid were higher than 1800 mg/L [18].

3 Additionally, the biological acidification process is also closely related to the
4 physicochemical properties of feedstocks and the intensities of pre-treatment [19-22].

5 For easily degradable biomass, a relatively low HRT is sufficient for acidogens to
6 achieve the high hydrolysis and acidification efficiencies, subsequently resulting in
7 significant increases in hydrogen and methane yields [6]. However, to ensure an
8 effective biological acidification of recalcitrant feedstocks, the HRT has to be
9 sufficiently high [6]. Since the release and hydrolysis of high-molecular intracellular
10 organic matters for recalcitrant feedstocks can be enhanced by the application of
11 pre-treatment, this technology is generally used to decrease the HRT of biological
12 acidification and improve the subsequent fermentation performance [19-22]. It should
13 be noted that the side reactions, such as the self-decomposition of sugars (or amino
14 acids) and Maillard reactions between sugars and amino acids, would also occur
15 during thermo-chemical pre-treatment of biomass, especially for mixtures of
16 carbohydrate-rich and protein-rich biomass [23]. Some of toxic by-products produced
17 from these adverse reactions, such as furans and phenols, may inhibit the bioactivity
18 of enzymes and damage the structures of DNA, further impeding the fermentation
19 pathway during biological acidification and subsequent anaerobic digestion [24,25].

20 Overall, the gap in the state of the art is the study of synergistic effects of
21 pre-treatment and biological acidification at various HRTs on anaerobic digestion,
22 especially for the substrates with significantly different physicochemical properties. In

1 this study, the easily degradable rice residue (RR) with high content of carbohydrates
2 and the slowly degradable microalgae *Chlorella pyrenoidosa* (CP) with high content
3 of proteins were hydrothermally pre-treated, and then the mixture was used as the
4 co-fermentation feedstock. The objectives of the present study are to:

- 5 • Analyse the impacts of various HRTs on biological acidification.
- 6 • Evaluate the synergistic effects of pre-treatment and biological acidification on
7 subsequent anaerobic digestion.
- 8 • Assess the bioenergy recovery characteristics of gaseous biofuel production from
9 co-fermentation of algae and rice residues.

10 **2 Materials and methods**

11 *2.1. Substrates and inocula*

12 RR was collected from a dining hall in Chongqing University, China. To remove the
13 attached greases, the RR was washed thoroughly using deionized water. Subsequently,
14 the treated RR was blended into pulp using a blender. RR pulp was loaded into
15 zip-lock bags and then stored at $-20\text{ }^{\circ}\text{C}$ before use. CP powder was purchased from
16 Yantai Hairong Biotechnology Co., Ltd., China. The purchased CP powder was stored
17 at room temperature in a dry environment before use. The characteristics of RR pulp
18 and CP powder are shown in Table 1.

19 The inocula for biological acidification were collected from a rural domestic
20 biogas digester in China. The raw sludge was heated at $100\text{ }^{\circ}\text{C}$ for 30 min in an
21 autoclave (Boxun YXQ-LS-SII, China). After heating treatment, the acidogens
22 survived through forming spores, while the methanogens were deactivated. To revive

1 and enrich the acidogens, the heat-treated sludge was acclimatized 3 times (72 hours
2 for each time interval) using a modified culture medium at 35 °C under an anaerobic
3 environment [26]. Total solids (TS) and volatile solids (VS) of the activated acidogens
4 were 116.9 and 73.1 g/kg fresh weight, respectively. The inocula for anaerobic
5 digestion were collected from the same biogas digester. The raw sludge was filtered
6 by a 2-mm sieve to remove large particles, and subsequently acclimatized 3 times
7 (168 hours for each time interval) using cellulose (1.5 g/L) at 35 °C under an
8 anaerobic environment. TS and VS of the activated methanogens were 58.2 and 27.1
9 g/kg fresh weight, respectively.

10 *2.2. Pre-treatment of mixed biomass*

11 The hydrothermal (140 °C, 10 min) and hydrothermal acid pre-treatment (140 °C, 10
12 min, 1% (v/v) H₂SO₄) were carried out in triplicate in a 70 mL reaction kettle
13 (Taikang QN-WCGF, China) [27]. The working volume of this reaction kettle was 50
14 mL. The mixed raw RR and CP (2.5 g TS) were pre-treated at a VS ratio of RR to CP
15 of 25 [27], corresponding to a C/N molar ratio of 31.3. After hydrothermal acid
16 pre-treatment, the pH values of biomass hydrolysates were adjusted to 7.5 ± 0.1 using
17 3 M NaOH and HCl solutions. The hydrolysates composed of solubilised matters
18 together with solid residues were loaded into 50 mL centrifuge tubes and then stored
19 at -20 °C before being used as fermentation substrates. Mixed RR and CP without
20 pre-treatment was set as the control group.

21 *2.3. Biological acidification*

22 The experimental design details of biological acidification and subsequent anaerobic

1 digestion as well as direct anaerobic digestion are shown in Fig 1. Biological
2 acidification was performed in triplicate in 500 mL glass fermenters with an effective
3 working volume of 300 mL each. The mixed RR and CP hydrolysates including
4 solubilised matters and solid residues (containing 5 g TS) were used in biological
5 acidification. A certain amount of deionized water was added to each fermenter to
6 maintain an overall volume of 270 mL, and then the fermenters were inoculated with
7 30 mL of activated acidogens. The initial pH values were adjusted to 6.5 ± 0.1 using 3
8 M NaOH and HCl solutions [28,29]. All the fermenters were sealed with rubber
9 stoppers, and nitrogen was purged for 5 min to ensure an anaerobic environment. The
10 biological acidification process was operated in a thermostatic water bath at $35.0 \pm$
11 0.5 °C under various HRTs (12–144 hours). During biological acidification, the pH
12 values were adjusted to 6.5 ± 0.1 using 3 M NaOH and HCl solutions at
13 predetermined time intervals (6 or 12 hours). The produced gases were released from
14 the headspace of fermenters, collected in graduated gas collectors [30], and then
15 recorded at each predetermined time interval [27]. A blank group only containing
16 inocula and a control group using raw mixed biomass with no pre-treatment as
17 substrate were also operated under the same experimental procedure.

18 *2.4. Anaerobic digestion*

19 Anaerobic digestion was performed in triplicate in the AMPTS II system (Bioprocess
20 Control, Sweden) [31]. The biological acidification effluents (BAEs) including
21 supernatants and solid residues were transferred to 500 mL glass fermenters and then
22 used as substrate in anaerobic digestion. Each fermenter with a working volume of

1 410 mL contained 150 mL of BAEs and 260 mL of methanogens, corresponding to a
2 substrate to inoculum VS ratio of 1:2 [32,33]. The initial pH values were adjusted to
3 7.5 ± 0.1 using 3 M NaOH and HCl solutions. All the fermenters were sealed with
4 rubber stoppers, purged with nitrogen for 5 min, and then placed in a water bath at
5 35.0 ± 0.5 °C for 720 hours. During anaerobic digestion, the pH values were without
6 control. A blank group only containing inocula and a control group (direct anaerobic
7 digestion) separately using raw, hydrothermal pre-treated, and hydrothermal acid
8 pre-treated mixed biomass, and cellulose as substrate were also operated under the
9 same experimental procedure.

10 Notably, the AMPTS II system cannot analyse the composition of the produced
11 gases. To measure the yields of hydrogen and methane produced during the initial 72
12 hours of anaerobic digestion, the produced gases contained hydrogen, methane, and
13 carbon dioxide were firstly collected in the graduated gas collectors and then recorded
14 at every 12 hours, as previously discussed. Differently, this process had no pH
15 adjustment. After the initial 72 hours of anaerobic digestion, the produced gases
16 would contain only methane and carbon dioxide. The fermentation reactors could be
17 connected to the carbon dioxide adsorption unit in the AMPTS II system and then
18 the yield of methane could be automatically recorded and measured by a build-in
19 tipping device [31].

20 2.5. Analytical methods

21 The carbohydrates, reducing sugars, proteins, lipids, TS, and VS were measured as
22 described in the previous studies [34,35]. A spectrophotometer (Hach DR3900, USA)

1 coupled with a heating digestion unit (Hach DRB200, USA) was used to analyse the
2 chemical oxygen demand (COD) and total ammonia nitrogen (TAN) [27]. An
3 elemental analyser (Elementar Vario MACRO cube, Germany) was applied to
4 measure the C, H, N, and S contents [36]; the remaining VS content was determined
5 as O [36,37]. The pH values were measured by a portable pH meter (METTLER F2,
6 Switzerland). Hydrogen, methane, and carbon dioxide were determined by a gas
7 chromatograph (GC) (Thermo Trace 1300, USA) equipped with a micro-packed
8 column (ShinCarbon ST Columns, 2 m, OD 1/16, ID 1.0 mm, Mesh 100/120) and a
9 thermal conductivity detector (TCD) [25,36]. The contents of SMPs including ethanol,
10 acetic acid, propionic acid, butyric acid, valeric acid, and caproic acid were analysed
11 using another GC (Agilent 7890B, USA) equipped with a polar capillary column
12 (Agilent DB-FFAP Column, 30 m × 0.25 mm × 0.25 μm) and a flame ionization
13 detector (FID) [36,38]. All experimental trials and measurements were conducted in
14 triplicate, and the results were expressed as the average ± standard deviation.

15 *2.6. Calculations*

16 The BAR (%) was calculated using the ratio of the total COD weight of SMPs to the
17 total COD weight of initial mixed biomass. The specific hydrogen yield (SHY) and
18 methane yield (SMY) (mL/g VS) were calculated based on the volume of total gases
19 (normalized to zero moisture content, standard temperature of 0 °C and pressure of 1
20 atm) and content of hydrogen and methane both in the gas collector and fermenter
21 headspace at each time interval [27]. Thereafter, the SHY and SMY were simulated
22 using a modified Gompertz equation [39]; the kinetic parameters including the

1 maximum production potential (H_m , mL/g VS), peak rate (R_m , mL/g VS/h), peak time
2 (T_m , h), and lag-phase time (λ , h) were calculated through the Origin software.

3 The higher heating values of hydrogen and methane were determined as 286 and
4 889 kJ/mol, respectively [29,36]. The higher heating values (kJ/g VS) of RR and CP
5 were calculated using the Mendeleev formula, Eq. (1). Where, C, H, O, and S
6 represent the VS percentage of each element in the initial biomass, respectively.
7 Additionally, the energy recovery characteristics were quantitatively analysed by
8 energy conversion efficiency (ECE) and energy conversion percentage (ECP₁₂₀). The
9 ECE (%) and ECP₁₂₀ (%) were calculated based on the Eqs. (2) – (3).

$$10 \text{ Heating value (kJ/g VS)} = 0.33858C + 1.254H - 0.10868(O - S) \quad (1)$$

$$11 \text{ ECE (\%)} = \frac{\text{Total energy value (kJ) of the produced hydrogen and methane}}{\text{Total energy value (kJ) of initial mixed biomass}} \times 100 \quad (2)$$

$$12 \text{ ECP}_{120} \text{ (\%)} = \frac{\text{ECE (\%)} \text{ based on 120 hours of anaerobic digestion}}{\text{Total ECE (\%)} \text{ based on the complete anaerobic digestion}} \times 100 \quad (3)$$

13 **3 Results and Discussion**

14 *3.1. Comparison of organic matter solubilisation from different pre-treatments*

15 The effects of hydrothermal and hydrothermal acid pre-treatment were analysed in
16 terms of solubilised COD, carbohydrates, proteins, and reducing sugars, as shown in
17 Fig. 2. The initial concentration of solubilised carbohydrates and proteins derived
18 from raw biomass were only 4.27 ± 0.18 and 0.43 ± 0.02 g/L, respectively,
19 corresponding to 6.63 ± 0.76 g solubilised COD/L. Meanwhile, the low reducing
20 sugar concentration of 0.86 ± 0.01 g/L indicated that most of solubilised
21 carbohydrates presented in the form of starch, which is the main polysaccharide in RR
22 and CP [40].

1 After hydrothermal pre-treatment, carbohydrates (28.77 ± 0.89 g/L) and proteins
2 (1.87 ± 0.32 g/L) in the soluble phase increased 5.7-fold and 3.3-fold, respectively.
3 This illustrated that RR and CP cells could be effectively disrupted by hydrothermal
4 pre-treatment. Nevertheless, the reducing sugar concentration (1.87 ± 0.24 g/L) only
5 constituted 6.5% of solubilised carbohydrates. The hydrolysis of starch into reducing
6 sugars such as maltose and glucose is due to the fracture of glycosidic bonds. Without
7 adding any chemicals, the glycosidic bonds of starch are more difficult to damage
8 under a relatively low reaction time (10 min) and temperature (140 °C) [27].

9 When raw biomass was subjected to hydrothermal acid pre-treatment, the
10 reducing sugar concentration (45.53 ± 3.3 g/L) significantly increased 52.2-fold and
11 23.3-fold, respectively, compared with raw and hydrothermal pre-treated biomass.
12 Unexpectedly, this concentration was more than the total concentration of solubilised
13 carbohydrates (42.06 ± 2.6 g/L). Previous studies found that monosaccharides such as
14 galactose and glucose could further break down into various by-products under severe
15 pre-treatment conditions in the presence of acids [41-43]; some of these by-products
16 may present reduction properties, which caused the high detected reducing sugar
17 concentration [27]. Additionally, monosaccharide can react with amino acids, which is
18 named as the Maillard reaction [44,45]. The Maillard products may also possess the
19 reducing groups such as free aldehyde and ketone groups [27]. Thus, excess reducing
20 sugars detected in the hydrolysates could be caused by the formation of these reducing
21 substances.

22 *3.2. Effects of different pre-treatments on biological acidification*

1 *3.2.1 Degradation of organic matters*

2 The degradation effects of solubilised organic matters before and after biological
3 acidification are shown in Table 2. When hydrothermal and hydrothermal acid
4 pre-treated biomass were separately fermented for 144 hours, the concentrations of
5 solubilised carbohydrates were significantly decreased from 9.59–14.02 g/L to
6 0.32–0.47 g/L. Whereas, the changes in the concentrations of solubilised proteins
7 (from 0.62–1.92 g/L to 0.4–0.56 g/L) were not obvious. This indicated that
8 carbohydrates were more readily utilised by acidogens than proteins. Previous studies
9 found that amino acids derived from proteolysis were not suitable substrates for
10 hydrogen production during biological acidification; the negligible SHYs were
11 generally ranged from 0.2 to 16.2 mL/g VS [46,47]. Therefore, hydrogen could be
12 mainly produced from the fermentation of carbohydrates. Additionally, the low final
13 concentration of solubilised carbohydrates from raw biomass (0.16 g/L) indicated that
14 organics in the solid substance would be also hydrolysed and utilized by acidogens.

15 *3.2.2 Biohydrogen production*

16 Fig. 3 depicts the effects of pre-treatment methods on fermentative hydrogen
17 production during biological acidification. When raw RR and CP were used as mixed
18 substrate, the maximum SHY and specific hydrogen production rate (SHPR) were
19 only 100.7 ± 6.6 mL/g VS and 2.7 ± 0.3 mL/g VS/h, respectively. Since the organic
20 matters in the raw biomass were tightly surrounded by the intact biomass cell wall, the
21 low concentrations of solubilised carbohydrates (1.42 ± 0.07 g/L) and proteins ($0.14 \pm$
22 0.00 g/L) were insufficient to maintain the bioactivity and growth of acidogens [36],

1 as shown in Table 2. Additionally, high-molecular polysaccharides were difficultly to
2 hydrolyse and utilise by acidogens [48]. A low reducing sugar concentration ($0.29 \pm$
3 0.01 g/L) before biological acidification resulted in low SHY and SHPR.

4 When hydrothermal pre-treated biomass was used as substrate, the maximum
5 SHY and SHPR increased to 169.5 ± 25.0 mL/g VS and 5.8 ± 0.4 mL/g VS/h,
6 respectively. This could be attributed to the improvements in the damage to the
7 biomass structures and the release of intracellular carbohydrates (9.59 ± 0.28 g/L) and
8 proteins (0.62 ± 0.09 g/L). However, the low hydrolysis efficiency of polysaccharides
9 during hydrothermal pre-treatment also resulted in low reducing sugar concentration
10 (0.62 ± 0.11 g/L), which still resulted in an unsatisfactory level of hydrogen
11 production during biological acidification.

12 When hydrothermal acid pre-treatment was applied to hydrolyse raw biomass,
13 the maximum SHY and SHPR significantly increased to 223.1 ± 8.8 mL/g VS and
14 10.4 ± 0.4 mL/g VS/h respectively, which shows 2.2-fold and 3.8-fold increases
15 compared with the values obtained from raw biomass. This was due to the highest
16 concentrations of solubilised organic matters especially reducing sugars (15.18 ± 0.23
17 g/L) before biological acidification. Meanwhile, the increase of available carbon and
18 nitrogen sources effectively promoted the biomass degradation by acidogens [49,50].

19 The kinetic parameters of fermentative hydrogen production derived from the
20 modified Gompertz model are presented in Table 3. The highest SHY potential of
21 223.7 mL/g VS and SHPR of 10.8 mL/g VS/h were obtained from hydrothermal acid
22 pre-treated biomass. Compared with raw biomass without/with hydrothermal

1 pre-treatment, the high amounts of easily degradable low-molecular organic matters
2 obtained from hydrothermal acid pre-treatment also effectively shortened the
3 lag-phase time (decreased from 6.7 to 4.2 hours) and peak time (decreased from 21.9
4 to 11.8 hours) of biological acidification.

5 *3.2.3 Production of soluble metabolite products*

6 As shown in Table 2, the SMPs in the effluents of biological acidification contained
7 abundant butyric acid (6.18–9.51 g COD/L) and acetic acid (2.62–3.86 g COD/L), and
8 a small quantity of propionic acid (0.27–1.54 g COD/L), caproic acid (0.99–1.11 g
9 COD/L), ethanol (0.22–0.39 g COD/L) and valeric acid (0.12–0.2 g COD/L). In this
10 case, acidogens mainly conducted acetic acid and butyric acid pathways. The total
11 SMP concentration obtained from raw, hydrothermal pre-treated, and hydrothermal
12 acid pre-treated biomass were 11.75 ± 0.35 , 13.16 ± 0.58 and 15.19 ± 0.14 g COD/L,
13 respectively, corresponding to the BARs of $60.7 \pm 1.2\%$, $68.0 \pm 2.0\%$ and $78.5 \pm 1.2\%$.
14 Compared with hydrothermal and hydrothermal acid pre-treatment, the concentration
15 of propionic acid (1.54 ± 0.01 g COD/L) from raw biomass without pre-treatment was
16 1.2-fold and 4.7-fold higher, respectively. Since the production of propionic acid is
17 considered as an unfavourable hydrogen consuming pathway [51], such a
18 phenomenon may be another explanation for the relatively lower SHY and SHPR
19 obtained from raw biomass.

20 The concentrations of TAN derived from amino acid hydrolysis increased to the
21 range of 40.3–204.8 mg/L. But such a concentration is still below the suggested
22 threshold level (4000 mg/L) that negatively affects the bioactivity of acidogens [13].

1 This further confirmed that co-fermentation of RR and CP could effectively mitigate
2 the inhibitory effects of TAN accumulation during biological acidification.

3 *3.3. Effects of hydraulic retention time on biological acidification*

4 The hydrothermal acid pre-treated biomass was used as fermentation substrate to
5 assess the effects of various HRTs on biological acidification. As shown in Fig. 3 and
6 Table 2, when the HRT was set as 12 hours, the final concentration of solubilised
7 carbohydrates and proteins were still as high as 9.5 ± 1.53 and 0.88 ± 0.09 g/L, which
8 are $67.8 \pm 3.5\%$ and $45.8 \pm 2.1\%$ of the initial concentration, respectively. Meanwhile,
9 a low BAR of $15.5 \pm 0.6\%$ and a low SHY of 87.2 ± 0.8 mL/g VS were obtained from
10 converting biomass to SMPs (3.0 ± 0.34 g COD/L). Rathbun et al. and Xia et al.
11 found that acidogens required a few hours lag-time (3–6 hours) to develop the ability
12 to degrade specific organic matters [52,53]. Such a short HRT of 12 hours in
13 biological acidification was insufficient for complete biomass degradation, as well as
14 high SMP and hydrogen production.

15 When the HRT was increased to 48 hours, the concentration of solubilised
16 carbohydrates significantly decreased from 9.5 to 1.04 g/L, thereby leading to a high
17 SHY of 222.4 ± 8.9 mL/g VS, a high SMP production of 14.47 ± 0.13 g COD/L and a
18 high BAR of $74.7 \pm 1.4\%$. However, the change in the concentration of solubilised
19 proteins was not obvious (from 0.88 to 0.62 g/L). During the adaptation period (0–12
20 hours), a certain amount of proteins (1.04 g/L) were hydrolysed and then used as the
21 nitrogen sources to sustain the growth and reproduction of acidogens. After the
22 bioactivity of acidogens was effectively improved (12–48 hours), monosaccharide

1 consumption by acidogens generally preceded amino acid consumption [46], as
2 previously discussed. The conservative increases of TAN concentration ranged from
3 13.5 ± 1.1 to 42.7 ± 3.0 mg/L confirmed such an explanation.

4 The non-obvious decrease trend for the concentration of solubilised proteins
5 (from 0.62 to 0.6 g/L) was not disappeared when the HRT was increased to 72 hours.
6 Differently, since monosaccharide was largely exhausted, the utilisation of amino
7 acids derived from proteolysis was greatly enhanced, resulting in an obvious increase
8 in TAN (120.1 ± 6.9 mg/L). Even so, due to the low-effective fermentative hydrogen
9 production of amino acids [46,47], the SHY (222.4 ± 8.9 mL/g VS), the SMP
10 production (15.03 ± 0.32 g COD/L), and the BAR ($77.6 \pm 0.8\%$) were similar to these
11 obtained after 48 hours fermentation. This also indicated that hydrogen production via
12 biological acidification had been completed during the period of 48–72 hours.

13 When a long HRT of 144 hours was applied to acidize biomass, the final TAN
14 concentration further increased to 204.8 ± 11.6 mg/L. Although a relative in-depth
15 acidification has no significant effects on improving the SHY (223.1 ± 8.8 mL/g VS),
16 the SMP production (15.19 ± 0.14 g COD/L), and the BAR ($78.5 \pm 1.2\%$), the
17 distribution of SMPs was altered. To be specific, at the end of rapid biological
18 acidification period (about 24 hours), the concentrations of propionic acid, valeric
19 acid, and caproic acid were only 0.05 ± 0.01 , 0.01 ± 0.00 , and 0.11 ± 0.01 g COD/L,
20 respectively. However, after biological acidification of 144 hours, their final
21 cumulative concentrations increased to 0.27 ± 0.01 , 0.12 ± 0.00 , and 1.08 ± 0.04 g
22 COD/L, respectively. Hydrogen could be consumed during the production of these

1 three types of VFAs [6,54]. This may be one reason for the non-obvious increases in
2 SHY. Some hydrogen and carbon dioxide could be also converted to acetic acid via
3 the homoacetogenic pathway, thereby resulting in the increase in acetic acid
4 concentration (3.86 ± 0.19 g COD/L). Additionally, the decrease in butyric acid
5 concentration (9.51 ± 0.19 g COD/L) also suggested that a long HRT of biological
6 acidification may lead to a mutual transformation of different SMPs.

7 Noblecourt et al. reported that the process of hydrogen production via biological
8 acidification would obviously decrease when the mass concentration of VFAs
9 exceeded 12.5 g/L [55]. In this study, the COD concentration of VFAs obtained from
10 12–144 hours fermentation were in the range of 2.74–14.85 g COD/L (Table 2),
11 corresponding to the mass concentration of 1.78–9.58 g/L. These values are much
12 lower than the threshold level. Besides, the pH values for biological acidification were
13 all adjusted to 6.5 ± 0.1 at each predetermined time interval (6 or 12 hours). Therefore,
14 the inhibitory effects caused by the pH drop and VFA accumulation would be fully
15 mitigated during the whole period of biological acidification.

16 *3.4. Methane production during anaerobic digestion*

17 *3.4.1 Direct anaerobic digestion*

18 When cellulose was used as substrate for direct anaerobic digestion, the maximum
19 SMY was 311.5 ± 2.2 mL/g VS. This result suggested a healthy inoculum condition,
20 and the bioactivity of methanogens for converting cellulose to methane was already
21 within the acceptable range [31]. Fig. 4a shows the SMYs obtained from raw,
22 hydrothermal pre-treated, and hydrothermal acid pre-treated biomass during direct

1 anaerobic digestion. Based on raw biomass, the maximum SMY of 220.0 ± 0.2 mL/g
2 VS was relatively low due to the presence of unbroken biomass cell structures. After
3 hydrothermal pre-treatment, the maximum SMY increased to 272.4 ± 0.8 mL/g VS,
4 indicating that the application of pre-treatment could also improve the performance of
5 anaerobic digestion [56]. Whereas, a severe pre-treatment such as the use of dilute
6 acid led to an obvious decrease in SMY (255.7 ± 1.2 mL/g), which was a totally
7 different trend to hydrogen production during biological acidification. This was
8 attributed to the combined action of anaerobic mixed microflora and special
9 fermentation substrate.

10 The anaerobic mixed microflora used in methane production contained various
11 types of microorganism such as acidogens and methanogens. Since starch could be
12 effectively hydrolysed into reducing sugars under hydrothermal acid pre-treatment,
13 the easily degradable substrates especially RR (more than 90% of starch) were rapidly
14 degraded by acidogens, resulting in the accumulation of VFAs and decrease of pH
15 (5.03 ± 0.51) at the early stage of direct anaerobic digestion (0–48 hours). Thus, the
16 growth of methanogens would be inhibited [6], thereby achieving a relatively low
17 SMY.

18 In fact, such negative effects also occurred during direct anaerobic digestion
19 from raw and hydrothermal pre-treated biomass, which was directly reflected through
20 the fluctuation of specific methane production rates (SMPRs), as shown in Fig. 4b. On
21 the first 24 hours of direct anaerobic digestion, the SMPRs were as high as 1.5–2.0
22 mL/g VS/h, suggesting efficient substrate degradation and methane production. Su et

1 al. reported that acidogens generally grew faster than methanogens [12]. As
2 previously discussed, the VFAs produced by acidogens were more than the VFAs
3 consumed by methanogens. The excessive accumulation of VFAs resulted in a
4 significant drop of pH and a rapid decrease of SMPRs (only 0.01–0.12 mL/g VS/h) in
5 the next 72 hours. After an adaptation period of 216–312 hours, the accumulated
6 VFAs were gradually consumed, and the SMPRs climbed back to 1.9–2.2 mL/g VS/h
7 with the recovery of methanogens.

8 In direct anaerobic digestion, the produced hydrogen in the acidogenesis process
9 could not be completely consumed by methanogens at the initial stage of fermentation
10 (0–72 hours). As a result, a significant amount of hydrogen was generated from raw,
11 hydrothermal pre-treated, and hydrothermal acid pre-treated mixed biomass with
12 maximum SHYs of 56.1 ± 2.3 , 106.4 ± 4.1 , and 141.1 ± 5.6 mL/g VS, respectively.

13 As shown in Table 3, the fitting coefficients from fermentative methane
14 production via direct anaerobic digestion using the modified Gompertz equation were
15 in the range of 0.9379 to 0.9797, which are lower than the values from anaerobic
16 digestion with biological acidification. The unstable methane production caused by
17 the accumulation of VFAs generated a big difference between the kinetic fitting
18 parameters and the experimental data.

19 *3.4.2 Effects of pre-treatments on anaerobic digestion after biological acidification*

20 Fig. 5 shows the effects of pre-treatments on anaerobic digestion after biological
21 acidification. The BAEs derived from 144 hours of biological acidification with
22 optimal adjusted pH values of around 7.5 were used as substrate in the subsequent

1 anaerobic digestion process. Since most of the organic matters especially
2 carbohydrates were degraded through biological acidification with sufficient duration,
3 the inhibition phenomenon disappeared and no hydrogen was produced.

4 Based on the BAEs of raw mixed biomass, the maximum SMY and SMPR were
5 206.4 ± 2.8 mL/g VS and 2.8 ± 0.1 mL/g VS/h, respectively. When the mixed biomass
6 was hydrothermally pre-treated, the maximum SMY and SMPR increased to $223.1 \pm$
7 0.8 mL/g VS and 3.2 ± 0.1 mL/g VS/h, respectively. This could be attributed to the
8 fact that the BAEs of hydrothermal pre-treated biomass contained more SMPs (13.16
9 ± 0.58 g COD/L) as compared with the BAEs of raw biomass (11.75 ± 0.35 g COD/L),
10 as shown in Table 2. Generally, the performance of anaerobic digestion was positively
11 related with the concentration of SMPs (alcohols and VFAs) in the BAEs [23]. SMPs
12 are considered as favourable substrates for fermentative methane production.

13 Notably, when raw mixed biomass was hydrothermally pre-treated by diluted
14 acid, the concentration of SMPs in the BAEs further increased to 15.19 ± 0.14 g
15 COD/L, while the maximum SMY and SMPR reduced to 183.7 ± 1.4 mL/g VS and
16 2.2 ± 0.03 mL/g VS/h, respectively. This may be explained by the toxic by-products
17 such as furan derivatives, phenols and the Maillard products typically derived from
18 thermochemical pre-treatment [23]. Overall, hydrothermal pre-treatment under acid
19 catalysis is an effective method to improve hydrogen production during biological
20 acidification, whereas the subsequent methane fermentation of their BAEs may not
21 perform as optimally as desired.

22 As shown in Table 3, anaerobic digestion from various BAEs (144 hours of

1 biological acidification) could be accurately described by the modified Gompertz
2 equation with high fitting coefficients (R^2 ranged from 0.9888 to 0.9926). The highest
3 SMY potential of 224.1 mL/g VS and SMPR of 3.3 mL/g VS/h were obtained from
4 the BAEs of hydrothermal pre-treated biomass. Compared with direct anaerobic
5 digestion, the two-stage process comprising biological acidification and anaerobic
6 digestion could effectively avoid inhibition caused by VFA accumulation, thereby
7 significantly reducing the lag-phase time (decreased from 64.9–121.3 hours to
8 21.0–23.1 hours) and peak time (decreased from 170.7–211.1 hours to 46.1–48.3
9 hours) of anaerobic digestion. On account of this, the whole fermentation period of
10 anaerobic digestion in two-stage process obviously decreased to 60–168 hours, around
11 only 1/3 of direct anaerobic digestion (Figs. 4–5).

12 *3.4.3 Effects of biological acidification time on anaerobic digestion*

13 The BAEs of hydrothermal acid pre-treated biomass were used as substrate to assess
14 the effects of biological acidification time on subsequent anaerobic digestion, as
15 shown in Fig. 6. When a short HRT of 12 hours was set for biological acidification
16 (BAR: $15.5 \pm 0.6\%$), incomplete degradation of carbohydrates (Table 2: 9.5 ± 1.53
17 g/L of residual carbohydrates) led to VFA accumulation and pH decrease at the early
18 stage of anaerobic digestion. For this reason, the maximum SMY of 132.3 ± 8.7 mL/g
19 VS and SMPR of 1.8 ± 0.1 mL/g VS/h were relatively low. Meanwhile, small
20 amounts of hydrogen of 40.0 ± 2.3 mL/g VS was observed in anaerobic digestion.

21 When the HRT of biological acidification was increased to 24 hours (BAR: 41.0
22 $\pm 1.2\%$), most of the carbohydrates were degraded (Table 2: 2.61 ± 0.58 g/L of

1 residual carbohydrates), thereby mitigating the above inhibition in anaerobic digestion.
2 Whilst, no hydrogen was produced in anaerobic digestion due to the low
3 concentration of carbohydrates in the BAEs. Nevertheless, it was still considered as
4 an unstable fermentative methane production process. The maximum SMY slightly
5 increased to 147.0 ± 6.1 mL/g VS, while the maximum SMPR decreased to 1.5 ± 0.1
6 mL/g VS/h.

7 When the HRT was increased to 48 hours (BAR: $74.7 \pm 1.4\%$), the maximum
8 SMY and SMPR significantly increased to 203.1 ± 1.0 mL/g VS and 2.0 ± 0.0 mL/g
9 VS/h, respectively. This suggested that an appropriate improvement in biomass
10 acidification degree could effectively enhance methane production from the BAEs.
11 Since biological acidification had been completed during the period of 48–72 hours,
12 further increasing the HRT of biological acidification to 72 hours (BAR: $77.6 \pm 0.8\%$)
13 resulted in slight changes in the maximum SMY (192.0 ± 1.8 mL/g VS) and SMPR
14 (1.9 ± 0.1 mL/g VS/h).

15 It should be noted that in this work a long HRT (144 hours) of biological
16 acidification with a very small increase of BAR ($78.5 \pm 1.2\%$) as compared to 72
17 hours would lead to a lower maximum SMY of 183.7 ± 1.4 mL/g VS. This
18 unfavourable phenomenon may be caused by excessive consumption of total carbon
19 sources during biological acidification. Some of the carbon sources may be converted
20 to carbon dioxide and released from the fermenters, which could not be reused in
21 subsequent anaerobic digestion. Interestingly, the maximum SMPR increased to $2.2 \pm$
22 0.03 mL/g VS/h (from 1.9 ± 0.1 mL/g VS/h). This result may be attributed to the

1 increase in acetic acid concentration (3.86 ± 0.19 g COD/L), as shown in Table 2. It is
2 known that acetic acid can be directly utilised by acetotrophic methanogens, whereas
3 other SMPs (such as ethanol, propionic acid, and butyric acid) should be firstly
4 degraded to acetic acid and then utilised to produce methane in methanogenesis [57].
5 As previously discussed, a relative in-depth acidification (144 hours) could promote
6 the further degradation of amino acids, the conversion of butyric acid to acetic acid,
7 and the process of homoacetogenesis, thereby resulting in a high concentration of
8 acetic acid and a high SMPR during anaerobic digestion.

9 As shown in Table 3, anaerobic digestion combined with biological acidification
10 (with HRTs from 12 to 144 hours) also could be accurately described by the modified
11 Gompertz equation with high fitting coefficients (R^2 ranged from 0.9811 to 0.9952).
12 The highest SMY potential of 204.1 mL/g VS was obtained after 48 hours of
13 biological acidification. A relative in-depth biomass acidification of 144 hours showed
14 the highest SMPR of 2.5 mL/g VS/h. These results were consistent with the
15 experimental data. Compared with direct anaerobic digestion, different degrees of
16 biomass acidification (15.5%–78.5%) all decreased the lag-phase time (from
17 64.9–121.3 hours to 21.0–53.6 hours) and peak time (from 170.7–211.1 hours to
18 48.3–81.4 hours) of anaerobic digestion in two-stage process. Furthermore, in terms
19 of the lag-phase time and peak time, the most significant enhancement was observed
20 after 144 hours of biological acidification with a highest BAR of $78.5 \pm 1.2\%$.

21 *3.5 Comparison of energy conversion efficiencies and energy conversion percentages*

22 The ECEs were calculated based on 120 hours of anaerobic digestion with various

1 HRT for biological acidification (0–144 hours) by using hydrothermal acid pre-treated
2 biomass as substrate. As shown in Fig. 7(a). The ECEs from hydrogen were in the
3 range of 10.3%–18.0%, which was still insufficiently high for industrial applications.
4 The maximum hydrogen ECE of $18.0 \pm 0.7\%$ was achieved after 48 hours of
5 biological acidification with a BAR of $74.7 \pm 1.4\%$ (Table 2). Further increasing the
6 HRT of biological acidification had almost no effect on improving the energy
7 conversion from hydrogen due to the non-obvious enhancement of hydrogen
8 production (Fig. 3).

9 By combining methane production, the ECEs significantly increased to
10 25.4%–64.0%. This growing trend was positively related to the acidification degree of
11 biomass. For direct anaerobic digestion without biological acidification, the methane
12 fermentation period was generally quite long (nearly 480 hours), as shown in Fig. 4.
13 In this case, when the ECEs were calculated based on 120 hours of anaerobic
14 digestion, the achievable maximum ECE was only $25.4 \pm 0.3\%$ due to the low SMY
15 of 55.6 ± 1.6 mL/g VS. However, when a relative in-depth biological acidification of
16 144 hours with a highest BAR of $78.5 \pm 1.2\%$ (Table 2) was applied prior to anaerobic
17 digestion, the methane production could be accomplished quickly. The maximum
18 SMY of 183.7 ± 1.4 mL/g VS (Fig. 6) had been achieved at the calculated period of
19 anaerobic digestion of 120 hours, thereby resulting in the maximum ECE of $64.0 \pm$
20 1.0% from hydrogen and methane.

21 Compared with the ECEs obtained from 120 hours of anaerobic digestion
22 (25.4%–64.0%), the total ECEs based on the complete fermentation process were in

1 the range of 43.5%–75.6%. Notably, the ratio of the two parameters was defined as
2 the ECP_{120} (see Equation 3), which could be used to assess the effects of biological
3 acidification on the required time to achieve the maximum total ECE. As shown in Fig.
4 7(b), the ECP_{120} from direct anaerobic digestion was only $33.5 \pm 0.4\%$, indicating that
5 raw biomass without biological acidification could not be rapidly degraded to produce
6 methane. Once raw biomass underwent biological acidification, even only 12 hours of
7 biological acidification with a low BAR of $15.5 \pm 0.6\%$ (Table 2), the corresponding
8 ECP_{120} ($84.3 \pm 0.9\%$) still increased 1.5-fold. However, by increasing the HRT of
9 biological acidification to 72 hours (BAR: $77.6 \pm 0.8\%$), the increase of ECP_{120}
10 slightly increased from $84.3 \pm 0.9\%$ to $89.6 \pm 1.2\%$.

11 Such a phenomenon was caused by the presence of high amounts of easily
12 degradable organic matters in the mixed biomass of RR and CP (i.e., starch). Since
13 these substrates could be readily used by acidogens, a short-term biological
14 acidification (12–72 hours) was sufficient to enhance subsequent methane production
15 via anaerobic digestion. Although the BAR of $78.5 \pm 1.2\%$ only slightly increased
16 during a relative in-depth biological acidification of 144 hours duration, the
17 distribution of SMPs revealed obvious differences (Table 2). As previously discussed,
18 the high concentration of acetic acid would finally realize a rapid methane production
19 with a maximum SMPR of 2.2 ± 0.03 mL/g VS/h (Fig. 6), thereby leading to a
20 maximum ECP_{120} of $99.8 \pm 0.1\%$. Overall, an in-depth biological acidification could
21 effectively accelerate the subsequent fermentative methane production, and achieve
22 the maximum potential of energy conversion over a short time frame corresponding to

1 a small volume and lower capital investment.

2 **4 Conclusion**

3 The biological acidification rates (60.7%–78.5%) would maximally increase 1.3-fold
4 with enhancing the intensity of biomass pre-treatment, thereby achieving the
5 maximum specific hydrogen yield of 223.1 ± 8.8 mL/g VS and production rate of 10.4
6 ± 0.4 mL/g VS/h. Increasing the hydraulic retention time of biological acidification
7 (12–144 hours) had significant effects on improving biological acidification rates
8 (15.5%–78.5%). Meanwhile, such a phenomenon could further affect the performance
9 of subsequent fermentative methane production. A relative in-depth biological
10 acidification of 144 hours resulted in the minimum lag-phase time and peak time of
11 anaerobic digestion. The whole anaerobic digestion period (120 hours) decreased by
12 70% with a maximum methane production rate of 2.2 ± 0.03 mL/g VS/h. Moreover,
13 the energy conversion efficiency based on 120 hours of anaerobic digestion combined
14 with an in-depth biological acidification was $64.0 \pm 1.0\%$, which shows 2.5-fold
15 increase compared with direct anaerobic digestion.

16 **Acknowledgements**

17 This work is supported by the National Science Foundation for Young Scientists of
18 China (No. 51606021), the State Key Program of National Natural Science of China
19 (No. 51836001), the Venture & Innovation Support Program for Chongqing Overseas
20 Returnees (No. cx2017019), and the Fundamental Research Funds for the Central
21 Universities (Nos. 2018CDXYDL0001, 2018CDYJSY0055). Dr Richen Lin
22 acknowledges the support from the European Commission's Marie Skłodowska-Curie

1 grant No. 797259. Prof Jerry D. Murphy is funded by Science Foundation Ireland
2 (SFI) through the Centre for Marine and Renewable Energy (MaREI) under Grant No.
3 12/RC/2302.
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Table 1 Characteristics of rice residue pulp and *Chlorella pyrenoidosa* powder.

Parameters	Rice residue pulp	<i>Chlorella pyrenoidosa</i> powder
Proximate analysis		
Moisture (wt%)	81.84 ± 0.01	6.26 ± 0.24
TS (wt%)	18.16 ± 0.01	93.74 ± 0.24
VS (wt%)	18.03 ± 0.01	78.91 ± 0.34
VS/TS (%)	99.28 ± 0.02	84.18 ± 0.37
Ultimate analysis		
C (VS%)	43.07 ± 0.21	50.62 ± 0.17
H (VS%)	5.09 ± 0.09	6.23 ± 0.31
O (VS%)	50.04 ± 0.42	33.42 ± 0.15
N (VS%)	1.31 ± 0.01	9.31 ± 0.07
S (VS%)	0.49 ± 0.03	1.28 ± 0.04
C/N molar ratio	38.4 ± 0.13	6.35 ± 0.05
Energy value (kJ/g VS)	15.58 ± 0.52	21.46 ± 0.37
tCOD (mg/g VS)	1167.91 ± 56.33	1429.44 ± 47.18
tCarbohydrates (mg/g VS)	917.21 ± 45.57	332.98 ± 26.23
tProteins (mg/g VS)	128.12 ± 17.86	504.04 ± 32.14
tLipids (mg/g VS)	12.69 ± 2.78	169.41 ± 14.69
sCOD (mg/g VS)	118.65 ± 5.64	152.65 ± 12.74
sCarbohydrates (mg/g VS)	87.53 ± 13.65	64.62 ± 11.54
sProteins (mg/g VS)	6.65 ± 1.01	40.75 ± 0.97
Reducing sugars (mg/g VS)	14.41 ± 0.76	3.68 ± 0.24
TAN (mg/g VS)	/	1.07 ± 0.04

The abbreviation referred to total (t) and solubilised (s) matters;

TS: Total solids; VS: Volatile solids; COD: Chemical oxygen demand;

TAN: Total ammonia nitrogen;

Table 2 Degradation of organic matters and production of soluble metabolic products during biological acidification.

Description	Pre-treatment methods						
	Without	Hydrothermal	Hydrothermal acid				
Acidification time (hours)	144	144	12	24	48	72	144
sCarbohydrate (g/L) ^a	1.42 ± 0.07	9.59 ± 0.28	14.02 ± 0.13	14.02 ± 0.13	14.02 ± 0.13	14.02 ± 0.13	14.02 ± 0.13
sCarbohydrate (g/L) ^b	0.16 ± 0.02	0.32 ± 0.01	9.5 ± 1.53	2.61 ± 0.58	1.04 ± 0.22	0.55 ± 0.09	0.47 ± 0.11
sProtein (g/L) ^a	0.14 ± 0.00	0.62 ± 0.09	1.92 ± 0.09	1.92 ± 0.09	1.92 ± 0.09	1.92 ± 0.09	1.92 ± 0.09
sProtein (g/L) ^b	0.12 ± 0.02	0.40 ± 0.13	0.88 ± 0.09	0.72 ± 0.24	0.62 ± 0.18	0.6 ± 0.11	0.56 ± 0.05
Reducing sugar (g/L) ^a	0.29 ± 0.01	0.62 ± 0.11	15.18 ± 0.23	15.18 ± 0.23	15.18 ± 0.23	15.18 ± 0.23	15.18 ± 0.23
Reducing sugar (g/L) ^b	0.04 ± 0.00	0.03 ± 0.01	8.68 ± 1.33	2.43 ± 0.21	1.01 ± 0.03	0.64 ± 0.01	0.04 ± 0.00
TAN (mg/L) ^b	40.32 ± 2.35	122.8 ± 8.56	13.5 ± 1.05	27.8 ± 2.31	42.7 ± 3.02	120.1 ± 6.93	204.8 ± 11.64
Total SMPs (g COD/L) ^c	11.75 ± 0.35	13.16 ± 0.58	3.0 ± 0.34	7.94 ± 0.32	14.47 ± 0.13	15.03 ± 0.32	15.19 ± 0.14
Ethanol (g COD/L)	0.22 ± 0.03	0.39 ± 0.05	0.26 ± 0.01	0.28 ± 0.03	0.3 ± 0.03	0.3 ± 0.03	0.34 ± 0.02
Acetic acid (g COD/L)	2.62 ± 0.15	3.39 ± 0.24	0.72 ± 0.08	1.6 ± 0.14	3.33 ± 0.21	3.49 ± 0.18	3.86 ± 0.19
Propionic acid (g COD/L)	1.54 ± 0.01	0.69 ± 0.14	0.03 ± 0.01	0.05 ± 0.01	0.09 ± 0.01	0.19 ± 0.01	0.27 ± 0.01
Butyric acid (g COD/L)	6.18 ± 0.4	7.38 ± 0.54	1.9 ± 0.16	5.88 ± 0.49	10.12 ± 0.28	10.38 ± 0.41	9.51 ± 0.19
Valeric acid (g COD/L)	0.2 ± 0.01	0.19 ± 0.01	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.05 ± 0.01	0.12 ± 0.00
Caproic acid (g COD/L)	0.99 ± 0.07	1.11 ± 0.14	0.08 ± 0.03	0.11 ± 0.01	0.61 ± 0.03	0.62 ± 0.02	1.08 ± 0.04
BAR (%)	60.7 ± 1.23	68.0 ± 2.03	15.47 ± 0.57	40.99 ± 1.22	74.7 ± 1.35	77.64 ± 0.77	78.46 ± 1.17

TAN: Total ammonia nitrogen; SMPs: Soluble metabolic products; BAR: Biological acidification rate; COD: Chemical oxygen demand.

^a Before fermentation; ^b After fermentation; ^c The concentrations of SMPs were based on the unit of “g COD/L” according to the references [58,59].

Table 3 Kinetic parameters of hydrogen production during biological acidification and methane production during anaerobic digestion.

Processes	Substrates	Pre-treatment methods	Acidification time (hours)	Kinetic model parameters					
				H_m (mL/g VS)	R_m (mL/g VS/h)	λ (h)	T_m (h)	R^2	
Biological acidification	Raw mixed biomass	/	144	101.61	2.50	6.67	21.62	0.9952	
		Hydrothermal	144	173.35	4.20	6.70	21.89	0.9876	
		Hydrothermal acid	144	223.68	10.78	4.17	11.80	0.9985	
Anaerobic digestion	Raw mixed biomass	/	0	229.53	0.94	121.28	211.12	0.9379	
		Hydrothermal	0	276.76	1.44	111.94	182.65	0.9797	
		Hydrothermal acid	0	267.61	0.93	64.85	170.72	0.9535	
		BAEs ^a	/	144	206.96	3.10	21.50	46.06	0.9897
		BAEs ^b	/	144	224.07	3.30	23.11	48.09	0.9888
		BAEs ^c	/	12	132.93	1.76	53.61	81.40	0.9920
			/	24	148.14	1.40	28.64	67.57	0.9811
			/	48	204.12	1.86	27.30	67.68	0.9952
		/	72	193.16	2.05	29.00	63.67	0.9897	
		/	144	184.43	2.48	20.97	48.33	0.9926	

BAEs: Biological acidification effluents. ^a BAEs of raw mixed biomass. ^b BAEs of hydrothermal pre-treated mixed biomass.

^c BAEs of hydrothermal acid pre-treated mixed biomass.

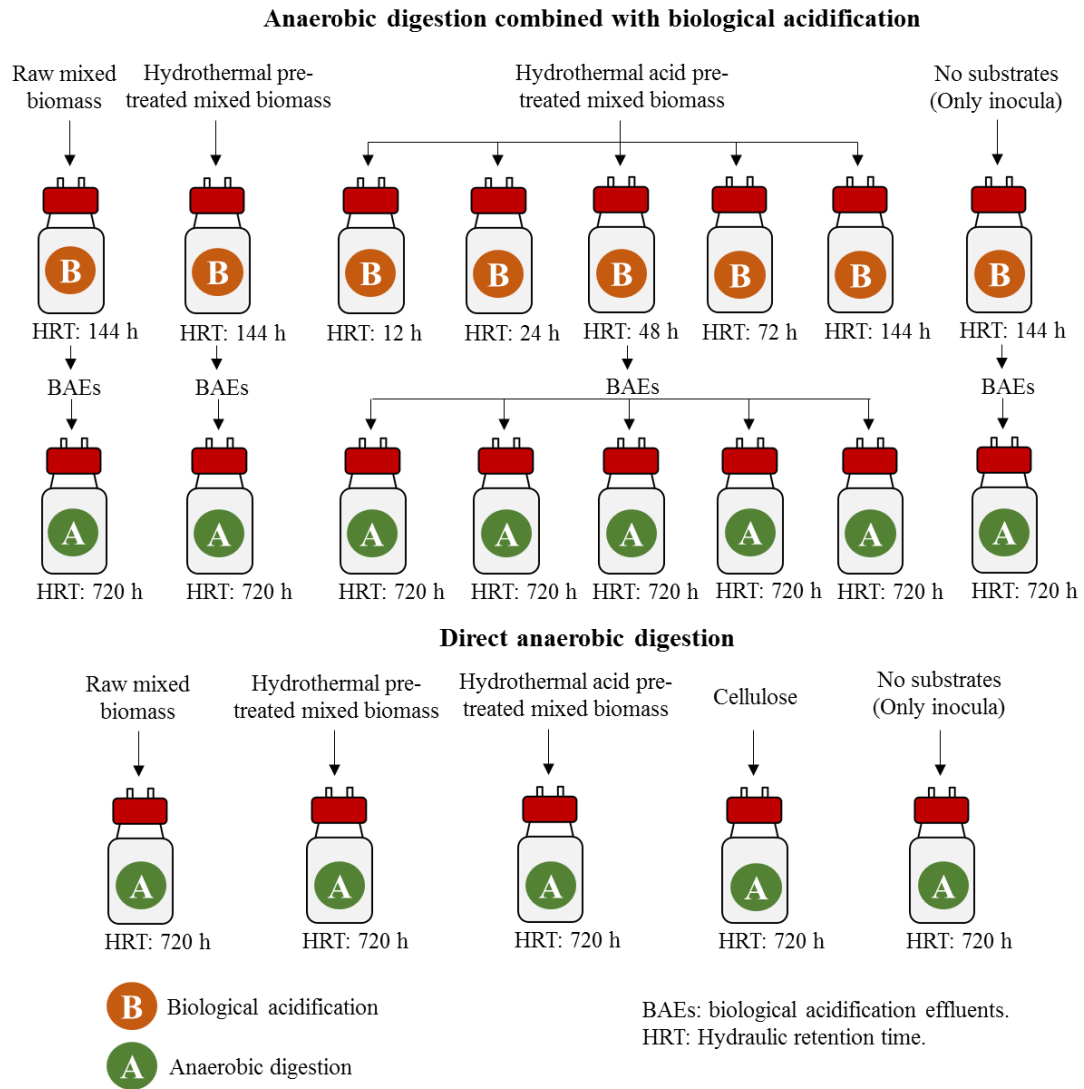


Fig 1 Design of experiment including for anaerobic digestion combined with biological acidification and direct anaerobic digestion.

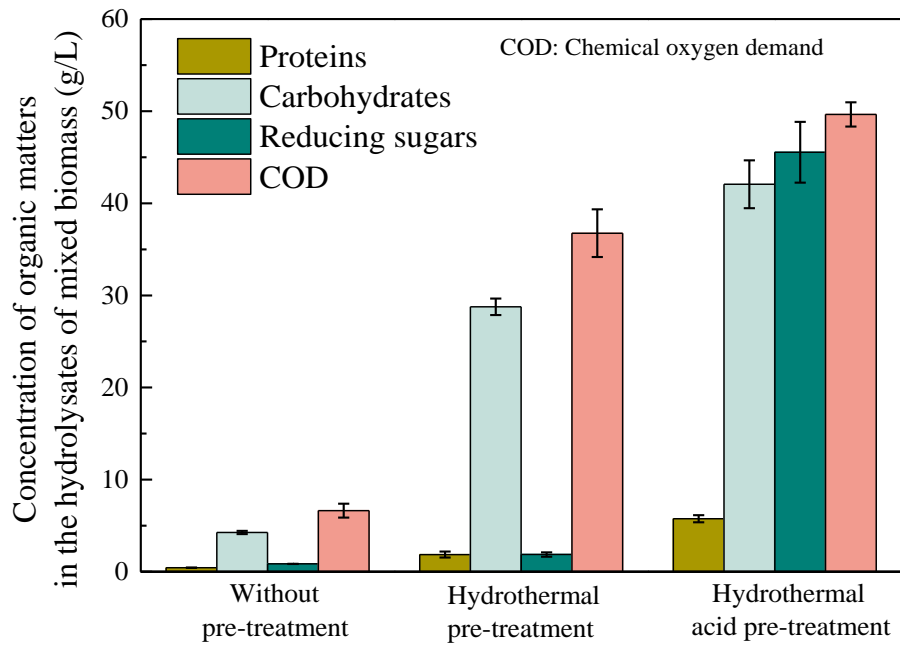


Fig. 2 Organic matter solubilisation under different pre-treatments.

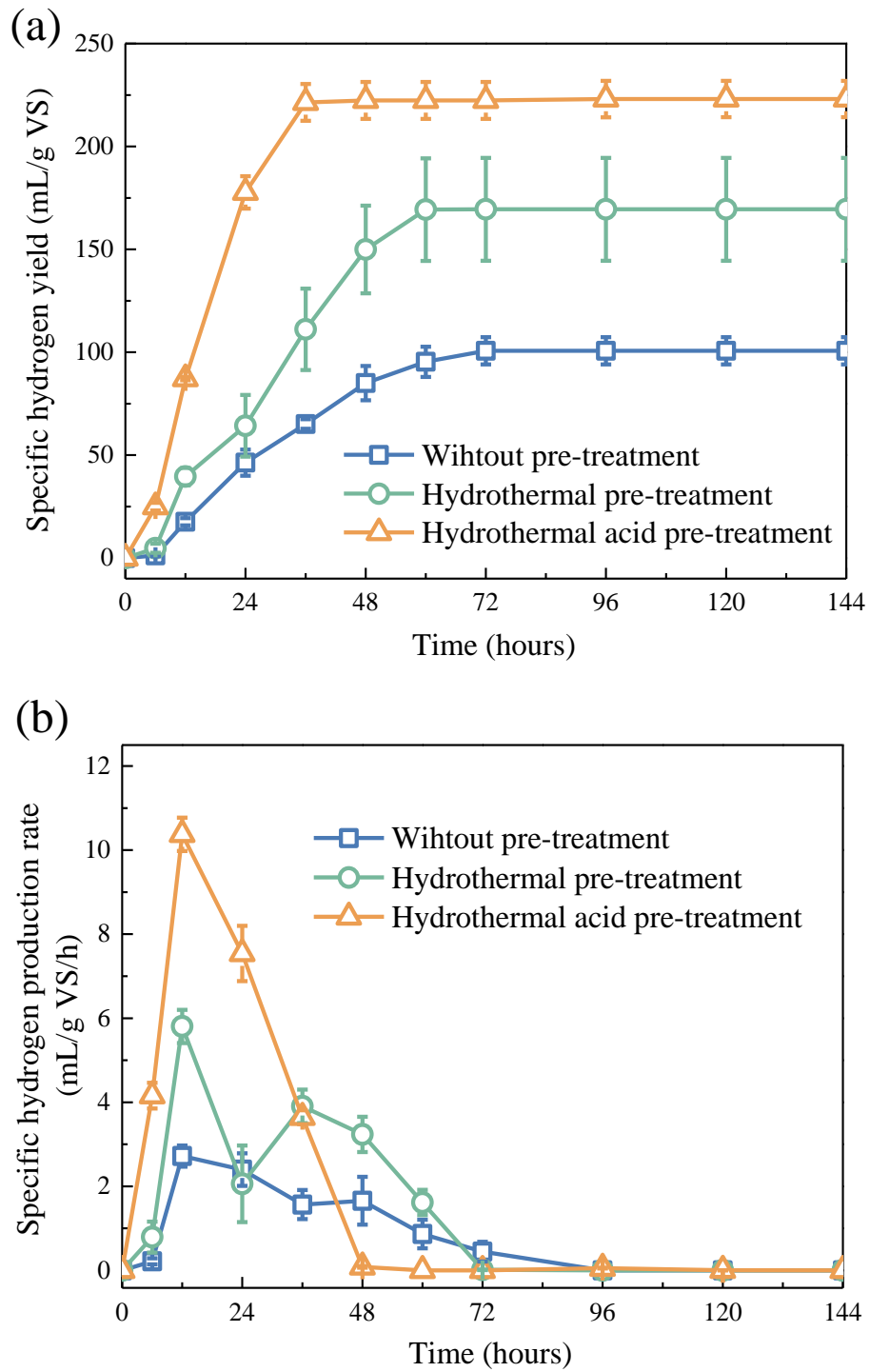


Fig. 3 Effects of different pre-treatments on hydrogen production during biological acidification: (a) Specific hydrogen yield; (b) Specific hydrogen production rate.

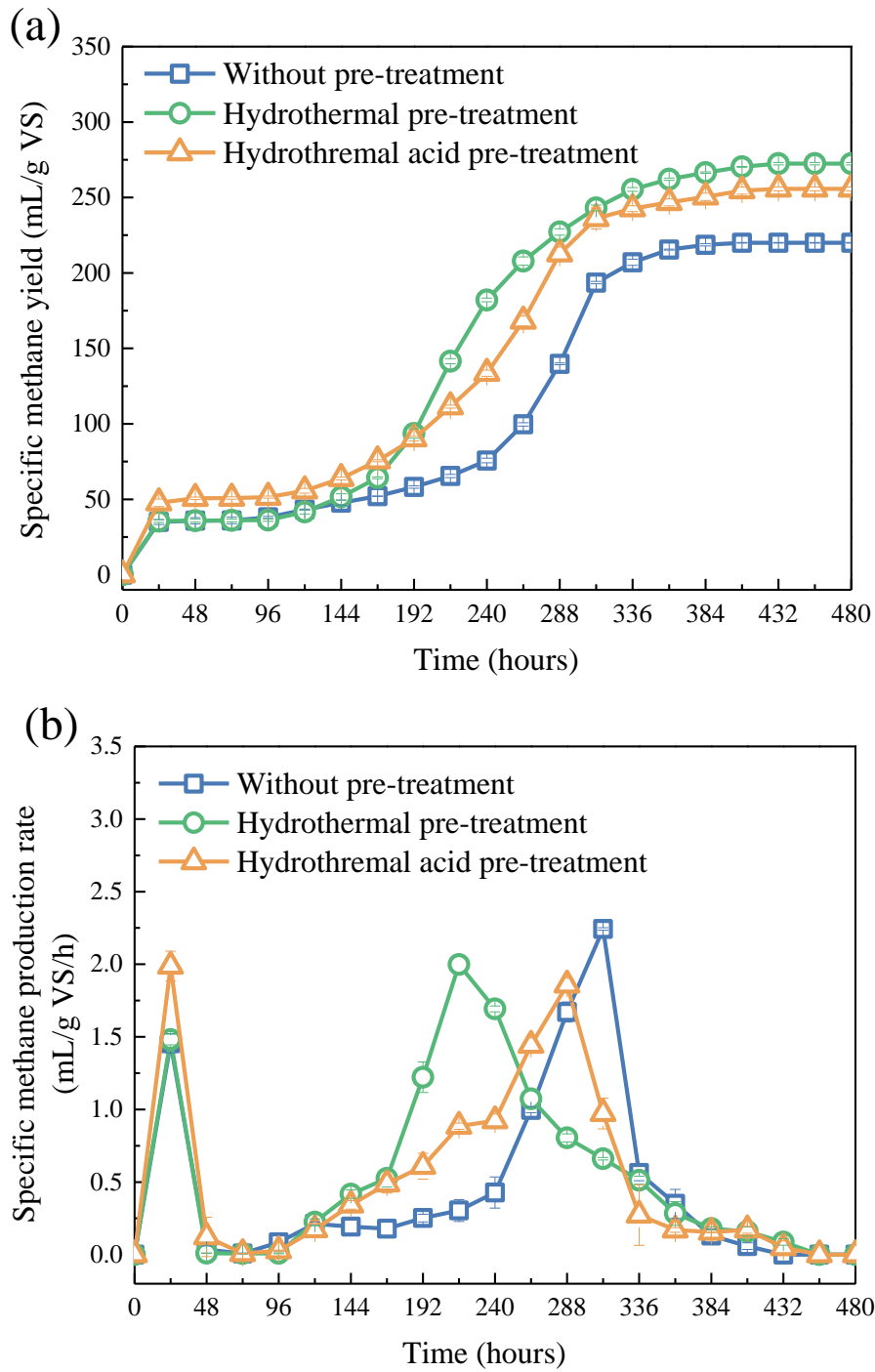


Fig. 4 Methane production during direct anaerobic digestion from raw, hydrothermal pre-treated, and hydrothermal acid pre-treated mixed biomass: (a) Specific methane yield; (b) Specific methane production rate.

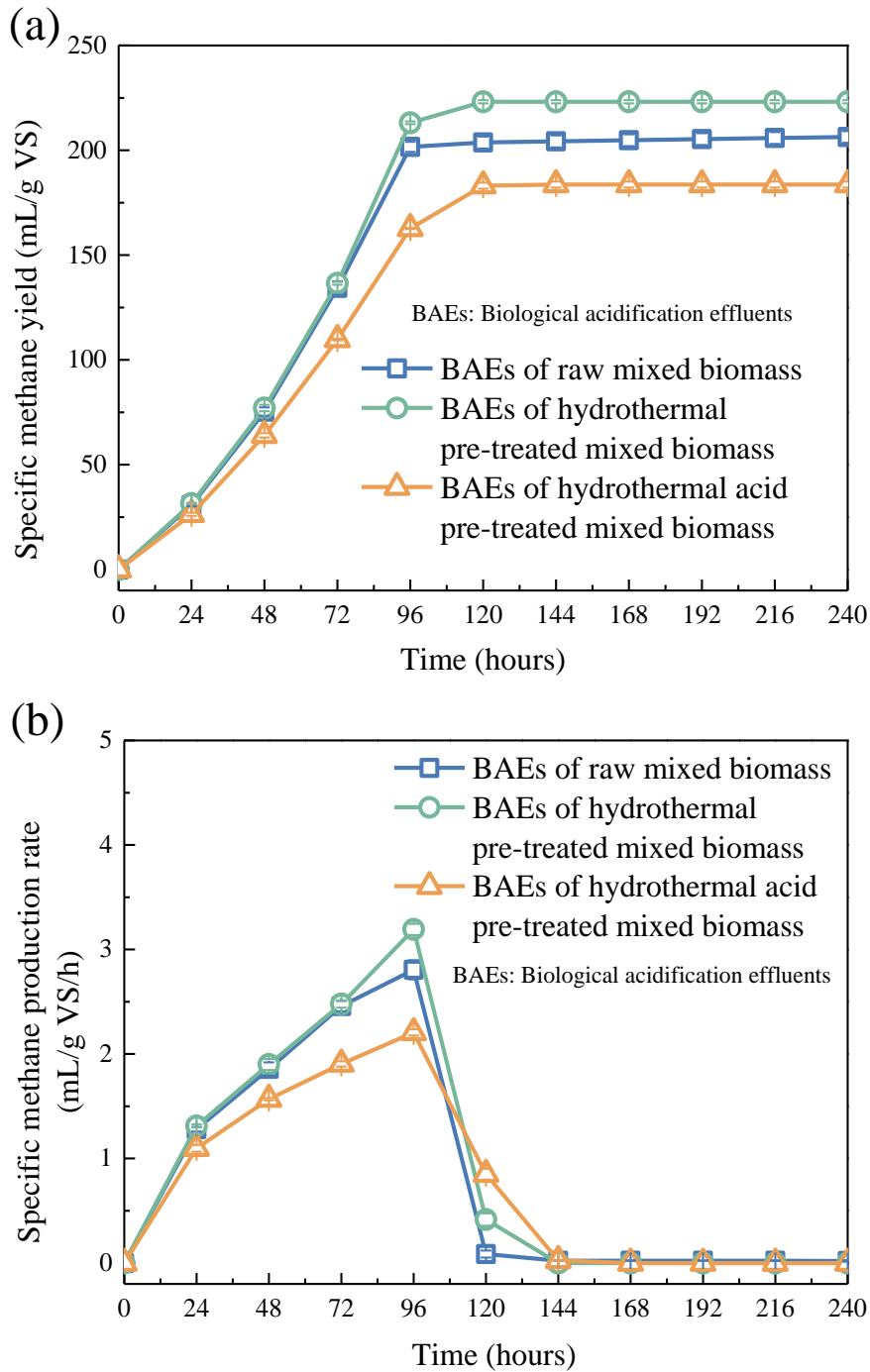


Fig. 5 Methane production during anaerobic digestion from biological acidification effluents: (a) Specific methane yield; (b) Specific methane production rate. Hydraulic retention time of biological acidification was set as 144 hours.

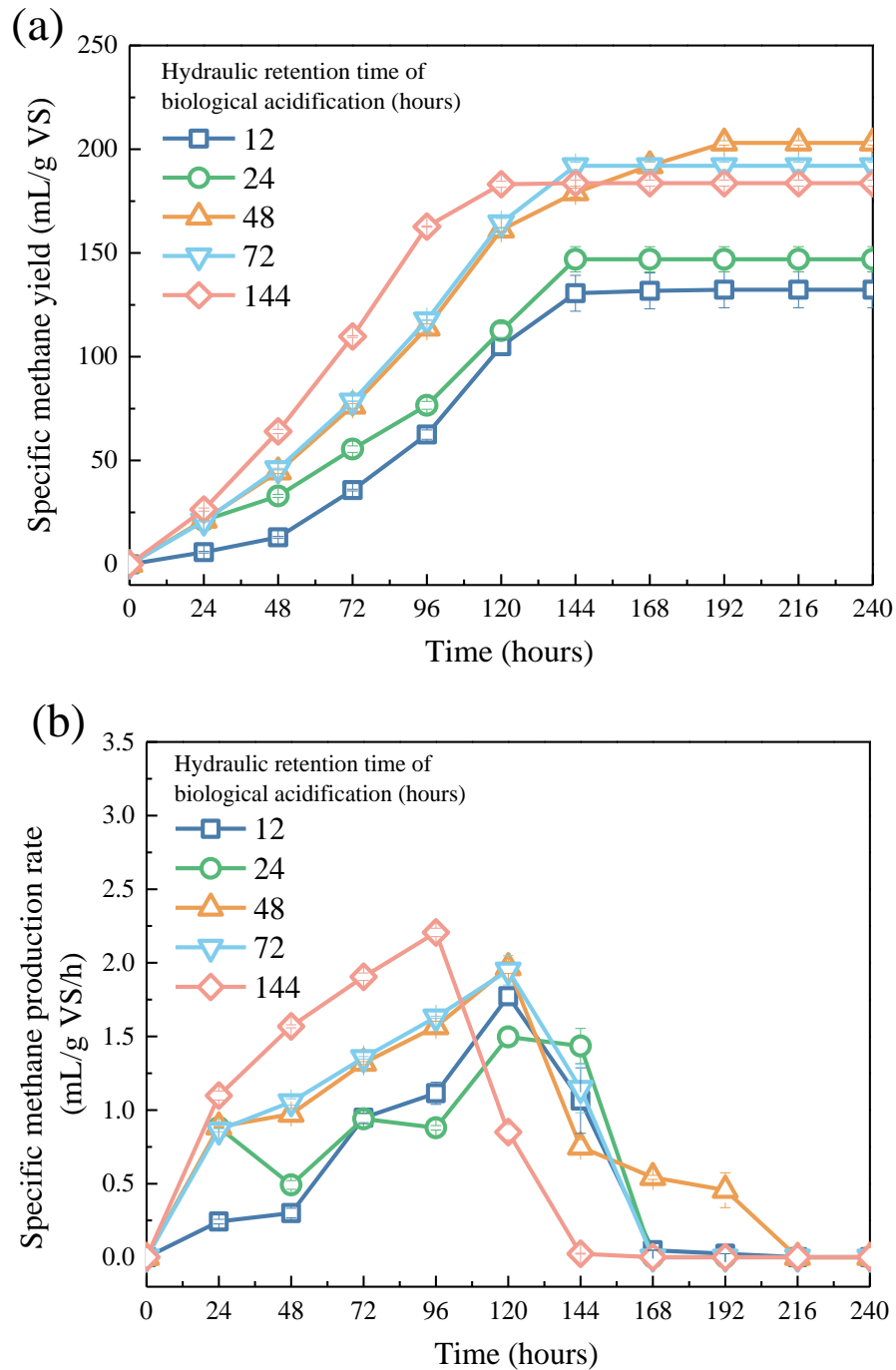


Fig. 6 Effects of biomass acidification time on anaerobic digestion: (a) Specific methane yield; (b) Specific methane production rate. Substrate used in anaerobic digestion was the biological acidification effluents of hydrothermal acid pre-treated mixed biomass.

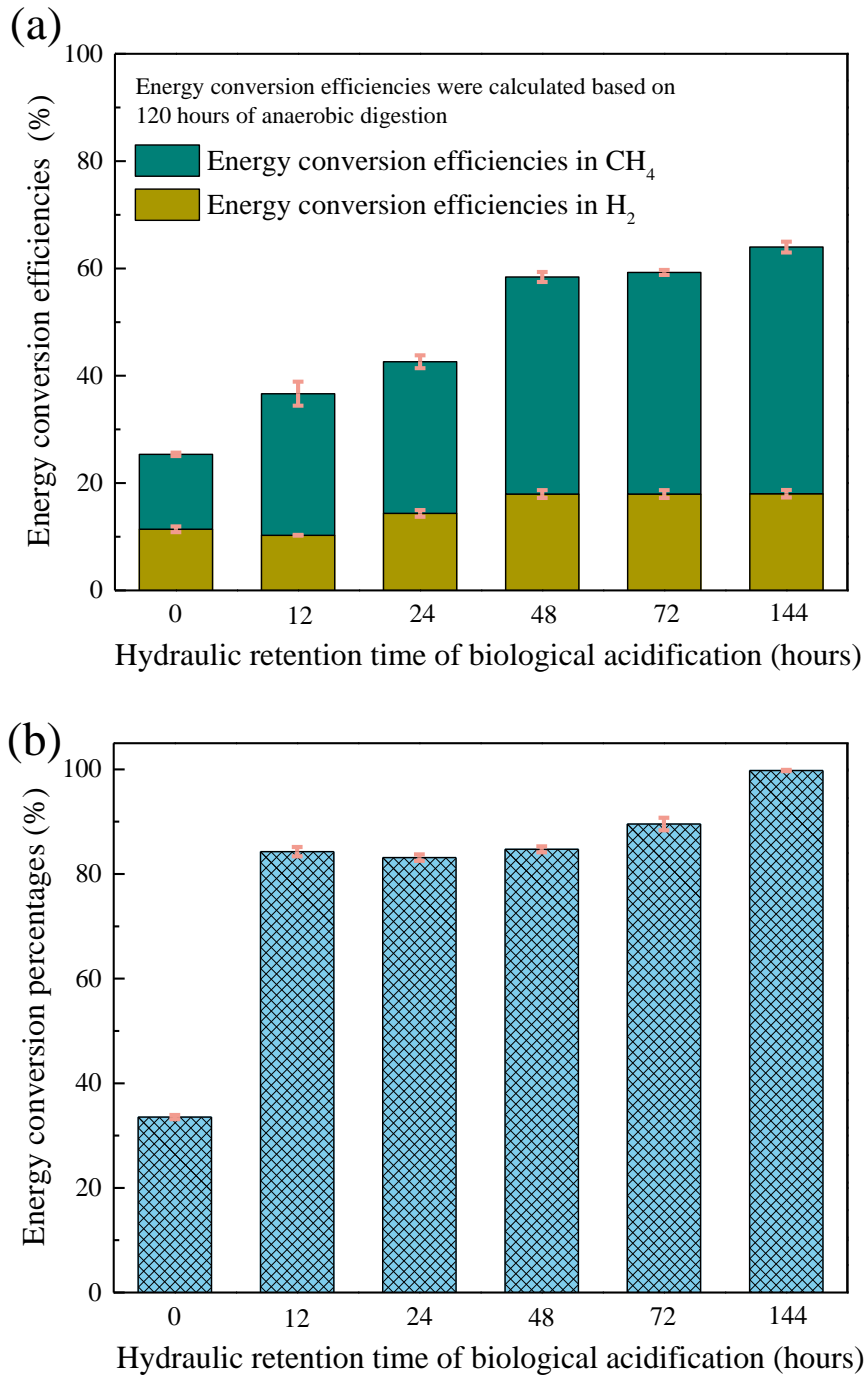


Fig. 7 Energy conversion efficiencies and energy conversion percentages during hydrogen and methane co-production: (a) Energy conversion efficiencies; (b) Energy conversion percentages. Substrate used in anaerobic digestion was the biological acidification effluents of hydrothermal acid pre-treated mixed biomass.