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Optimizing Heating-Cooling Performance by Retrofitting Cooling Element in Continuous Stirred Tank Pre-Treatment Bioreactor Design

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ABSTRACT

The physical processes inside stirred tank bioreactor (STBR), including mixing, reaction kinetics, and heat transfer is commonly studied in bioprocess design. STBRs have better heat transfer properties than batch reactors, which means that heat can be more easily and efficiently removed from the reaction mixture. These criteria help to prevent overheating and improve reaction efficiency. The current issue of longer heating and cooling time in pre-treatment STBR during pyrolysis of biomass products has led to this research by adding the cooling element inside the stirred tank. CFD analysis results for heating duration of the proposed retrofit design and comparison of cooling analysis between CFD simulation and site test data are to be presented and discussed in these studies. The result shows that the reactor can be retrofitted with additional internal coil with new temperature control unit (heating & cooling) to achieve heating duration by reducing time within 1 hour.

1. Introduction

Efficient biomass pretreatment is a critical step in the production of biofuels and other valuable biochemicals. One promising approach is the use of a stirred tank bioreactor (Figure 1) with continuous agitation, which can facilitate the pretreatment of lignocellulosic biomass [1-3]. This approach offers several advantages, such as improved mass transfer, enhanced reaction kinetics, and better heat and mass distribution [1]. The pretreatment of lignocellulosic biomass is necessary to convert the recalcitrant material into a form more amenable to enzymatic and microbial degradation [3]. Various pretreatment techniques have been developed, including physical, chemical, and biological methods [3]. Among these, stirred tank bioreactors with continuous agitation offer several advantages, such as efficient mixing, improved mass transfer, and the ability to control key parameters like temperature, pH, and residence time [2].

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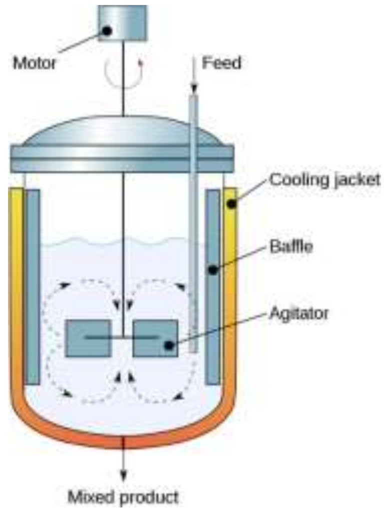

Fig. 1. A schematic of simple STBR

The stirred tank pretreatment bioreactors (STBR) also face some challenges. Researchers have explored various strategies to optimize the performance of a stirred tank pretreatment bioreactor. These include investigating the effects of key parameters such as temperature, residence time, agitation speed, and chemical loadings on the pretreatment efficiency and the subsequent enzymatic hydrolysis and fermentation steps. Furthermore, efforts have been made to develop pretreatment methods that minimize the production of inhibitory compounds, as these can negatively impact the downstream processes [2,3]. For instance, the generation of inhibitors during acid pretreatment can hinder subsequent processing steps [4]. Additionally, the high capital and operating costs associated with large- scale reaction vessels and the need for oxygen or catalysts can limit the commercial viability of this approach [5]. Despite these challenges, researchers continue to explore ways to optimize stirred tank pretreatment reactors for biomass conversion.

Recent advancements, such as the use of microwave irradiation, have shown promise in improving the efficiency and reducing the operational costs of this technology [5]. The effectiveness of the stirred tank pretreatment process is influenced by several factors, including the biomass composition, the pretreatment chemicals used, and the operating conditions [6]. For example, the choice of pretreatment chemicals, such as alkali or acid, can have a significant impact on the degree of lignin and hemicellulose removal, as well as the generation of potential inhibitors [7]. Moreover, the intensity and duration of agitation can affect the degree of biomass disruption and the accessibility of the cellulose fraction to subsequent enzymatic hydrolysis.

The use of stirred tank bioreactors with continuous agitation is a promising approach for the pretreatment of lignocellulosic biomass. By carefully optimizing the operating conditions and selecting appropriate pretreatment chemicals, this technology can enhance the accessibility of the cellulose fraction and improve the overall efficiency of the bioconversion process [6-8]. As the demand for renewable and sustainable chemical and energy sources grows, the development of efficient and cost-effective pretreatment methods, like continuous agitation in stirred tank reactors, will be crucial in establishing viable performance of a stirred tank pretreatment bioreactor.

2. Methodology

The objective of the process design study is to consider how laboratory experiments are embodied in a pilot plant and prepare the data. For that purpose, several clarifications are proposed such as continuous process scheme and modelling scheme using computational fluid dynamics (CFD). According to this consideration, equipment capacity was decided. The materials of construction were also considered. Especially hydrogenation reactor material is carefully researched because reaction condition is very severe. The natural fibres used throughout in this experiment is oil palm empty fruit bunches (EFB) fibres.

2.1 Continuous Process Scheme

The Pre-treatment STBR is preferably plug flow type because the residence time (pre- treatment time by alkali) of all EFB materials is same. To improve the plug flow property, several perforated plates are equipped and the agitator is provided to improve the contact efficiency between EFB and alkaline solution and to avoid EFB accumulation in the bottom. Agitation speed is variable so that the mixing effect and plug-flow property can be adjusted based on the pilot test result. The reactor temperature, normal 150°C is controlled with steam jacket. The pressure will be saturated pressure of NaOH solution (approx. 375 kPaG or less). After pre-treatment, the solution is cooled to about 60°C to avoid flashing.

2.2 CFD Geometrical Model

The adaptable 3D-model design of reactor fluid CFD simulation was developed using geometrical modelling method. Figure 2 below shows assembly geometry of reactor fluid with inner coil, outer coil and agitator. Fluid geometry is modelled at normal liquid level with inner coil and outer coil hollowed out in which the agitator as a solid within the fluid body for normal liquid level as shown Figure 3. The existing reactor has a single outer coil for cooling with agitator rotating about the Y-axis at 200 RPM. The fluid geometry follows the same dimensions with existing on-site reactor. Temperature monitoring point in CFD is plotted at the same location as the temperature transmitter at site.

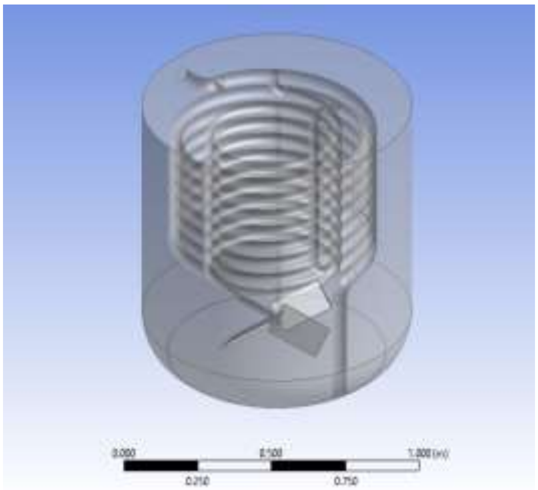

Fig. 2. Assembly geometry of the reactor fluid

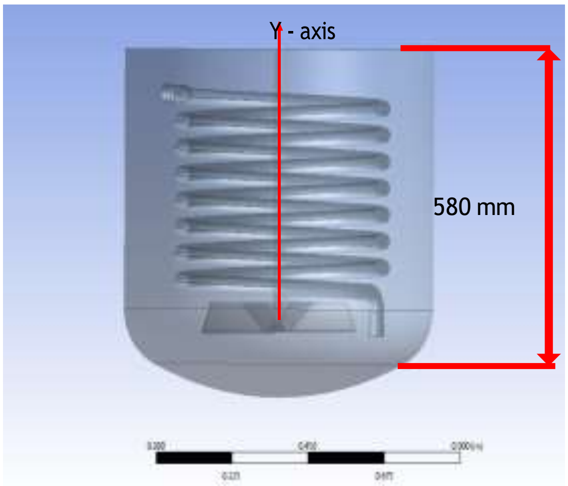

Fig. 3. Sizing of critical components for normal level liquid level

2.3 Grid Generation

The geometry of CFD model was integrated with computation domain to generate analytical solution. The equations that able to solve each significant parameter required for agitation and heating, as shown in Figures 4 and 5 below. Grid generation was regulated with tetrahedral mesh at 0.01m element size and smoothing quality set to high. Inflation layer was set between coil surface and fluid region for convection heat transfer.

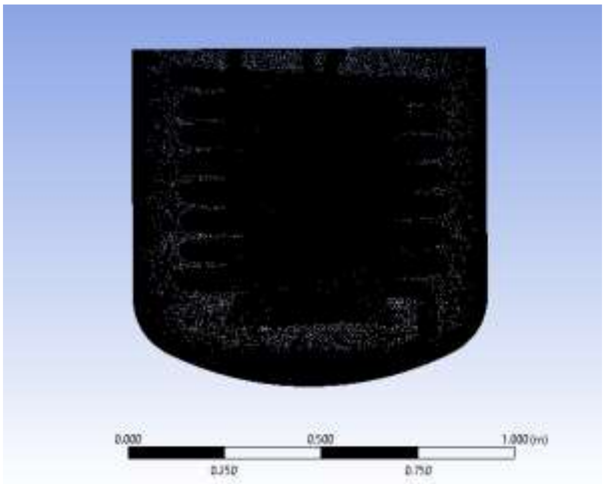

Fig. 4. Assembly geometry of the reactor fluid

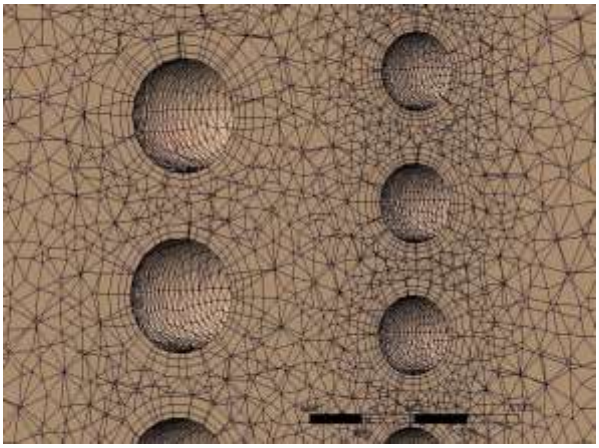

Fig. 5. Grid generation regulated with tetrahedral mesh

2.4 CFD Design Basis

The CFD EFB fluid properties are homogeneous mixture with following fluid properties as discussed with Custodian prior to CFD modelling to get behaviour of heating:

i) Density: 1200 kg/m3
ii) Viscosity: 0.0265 kg/m.s
iii) Thermal conductivity: 0.79 W/m.K
iv) Specific heat: 4170 J/kg. K

The heating source of the EFB fluid in simulation from heat flux of inner coil and outer coil. The heat flux value is constant throughout the coil and throughout the heating duration. The heat flux derived based on manual calculation which is dynamically reduced when heat transfer to EFB Slurry. The value of heat flux is shown in Table 1 below, which the 200°C is used for maintenance purposes.

Table 1
Heat flux values at specified temperature interval

Temperature interval	30°C to 60°C	60°C to 90°C	90°C to 120°C	120°C to 150°C	150°C to 180°C	180°C to 200°C	200°C
Heat Flux (W/m2)	86000	74000	62000	44000	37000	25000	12000

Heat loss define as 68 W/m2 as per calculated value based on 3E Plus software. This heat loss value was applied as an input value on the fluid region of the geometry. Agitation speed is constant at 200 RPM during heating time. The agitation derived from solid modelling of propeller submerge inside EFB Slurry. The agitator rotational velocity was applied as an input value on the geometry in the solver.

A transient analysis has been carried out using ANSYS Fluent and the agitator solid was defined as an immersed solid within the fluid region with a rotation about the Y-axis. The propeller speed is set as per agitator design. The inner and outer coil regions were defined as wall boundaries to the fluid region and thermal conditions were simulated by defining the heat flux values for the respective coils. Heat loss is defined in the fluid region. The solver solves the energy, momentum and turbulence (kinetic energy) equations to determine heat transfer and fluid movement. The transient analysis uses a time step value of 0.1s per iteration. Table 2 below tabulated the parameters set for fluid heating and agitation condition.

Table 2
Parameters for fluid heating and agitation condition

Agitator Condition	
Rotational Velocity	200 RPM
Rotational Axis	Y-Axis
Fluid Properties	
Density (kg/m3)	1200
Specific Heat (J/kg K)	4170
Thermal Conductivity (W/m K)	0.7888
Viscosity (kg/ms)	0.0265
Heating Condition	
Region	Heat Flux (W/m2)
Inner coil	Varies across time
Outer coil	Varies across time
Heat loss	68

3. Results

3.1 Temperature Profile of EFB Fluid During Heating

Manual calculation of the heating time provided with different heat flux values. The corresponding time taken has been calculated to heat up the fluid from one temperature point to another temperature point. Figure 6 EFB Fluid Condition inside STBR at target temperature 200°C. The heating duration calculated in 30-degree increments from 30°C to 180°C, and a 20-degree increment from 180 °C to 200 °C. Table 3 below shows the data comparison for manual calculated, CFD and heat flux from the simulation and graphed in Figure 7. Therefore, heat flux deployment is linear dynamic to simulate decreasing heat transfer from coils to fluid as temperature of fluid increases. The time taken for each heating interval will also increase. Calculated time is based on single formula and total duration is 57.8 minutes. Temperature distribution observe across EFB fluid volume with small temperature difference between 200 – 202 °C. Manual Calculation show 205.4°C at outer wall of internal coil which show heating behaviour from CFD as 202°C on internal coil boundary. Uniform temperature distributions are observed across EFB fluid volume with small temperature difference between 200°C – 202°C. Figure 6 shows that EFB Fluid Condition at target temperature 200°C achieved at 33.3 minutes.

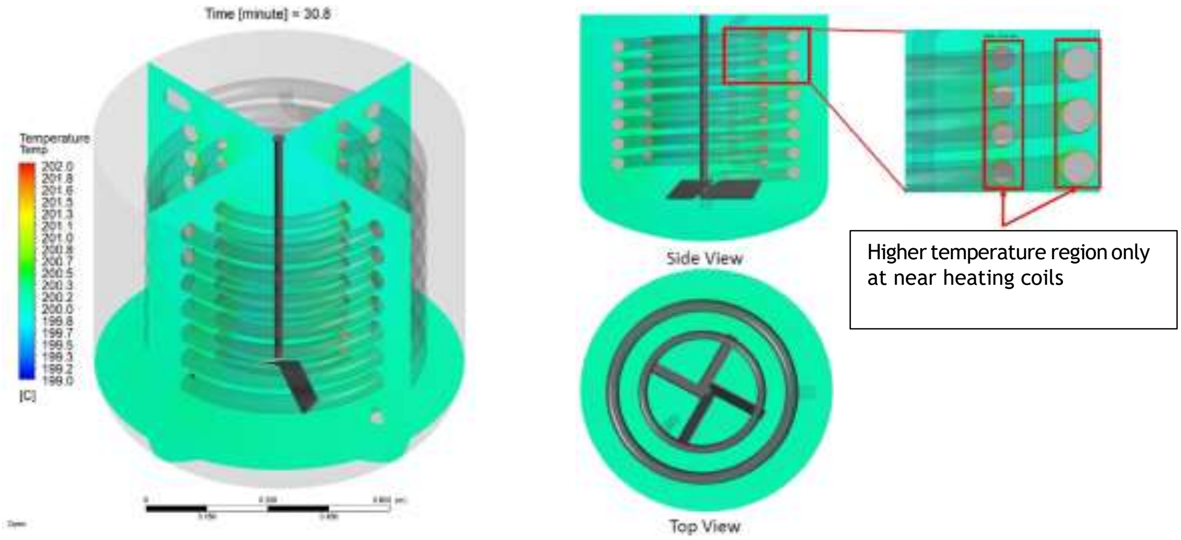

Fig. 6. EFB fluid condition inside STBR at target temperature 200°C

Table 3
Manual calculation for time taken and heat flux values

Temperature interval	30°C to 60°C	60°C to 90°C	90°C to 120°C	120°C to 150°C	150°C to 180°C	180°C to 200°C	200°C (maintenance)
Calculated time taken (min)	5.7	6.7	7.8	10.3	14.0	13.3	-
CFD time taken (min)	3.3	4.6	5.0	5.6	7.5	7.3	-
Heat flux (W/m^2)	86000	74000	62000	44000	37000	25000	12000

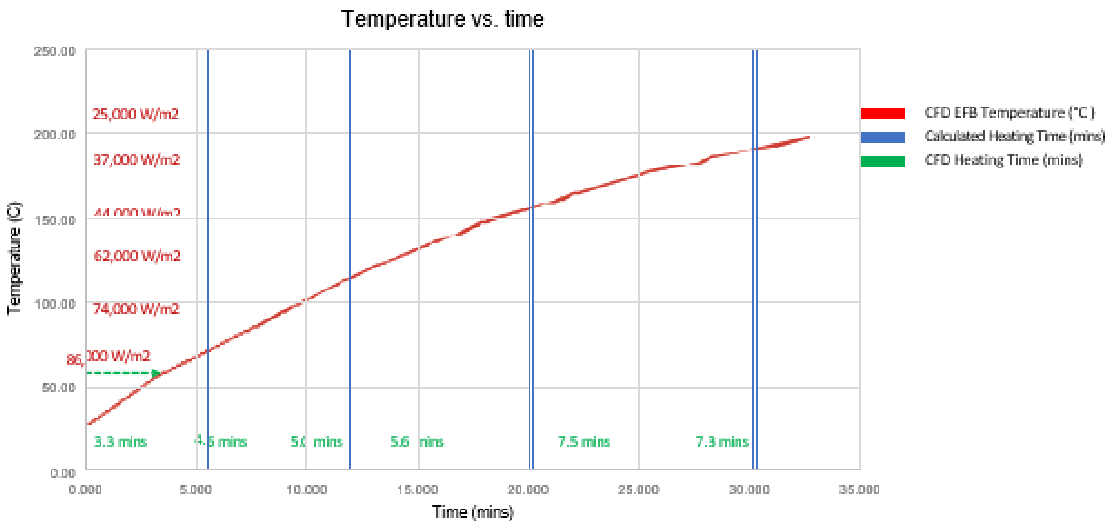

Fig. 7. EFB Fluid Condition inside STBR at target temperature 200°C

3.2 Cooling Comparative between CFD and site testing

Reactor fluid temperatures were recorded intermittently during the cooling process. The time taken for temperature increments were also recorded for each interval. Tables 4 and 5, and Figures 8 and 9 below shows the data obtained from site for fluid temperature during cooling testing and CFD result, respectively. Different heat flux values for cooling were calculated at the time intervals in the field data. Therefore, heat flux deployment is linear dynamic to simulate decreasing heat transfer from fluid to coils as temperature of fluid increases. The time taken for each cooling interval will also increase.

Table 4
Field data for fluid temperature during cooling process

Time	Temperature (C)
7:25 PM	173.43
7:45 PM	123.33
8:17 PM	89.92
8:45 PM	69.88
9:00 PM	64.63
9:10 PM	58.33
9:30 PM	52.71

Table 5
Calculated heat flux values

Temperature (C)	Heat flux (W/m2)
173.3 – 123.3	-45479.23335
123.3 – 89.92	-21431.08413
89.92 – 69.88	-14733.87034
69.88 – 64.63	-7212.384083
64.63 – 58.33	-12982.29135
58.33 – 52.71	5769.907267

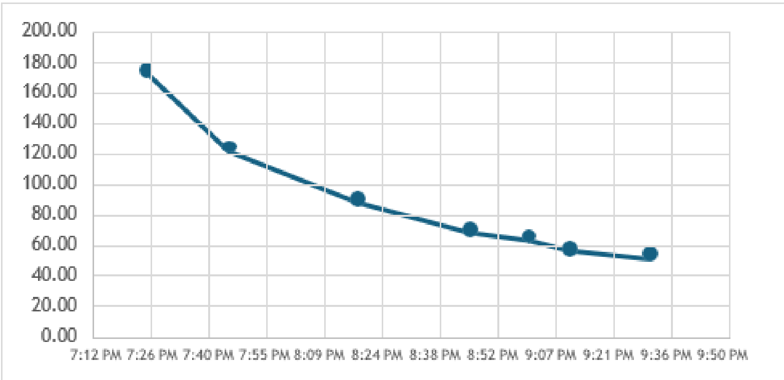

Fig. 8. TI-1004 temperature (°C) against time

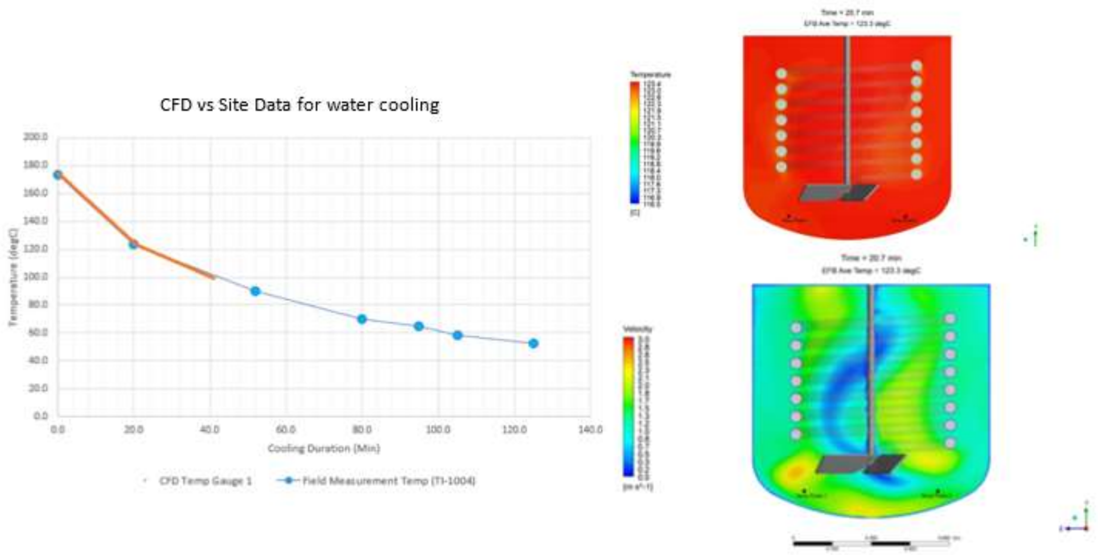

Fig. 9. Comparison of CFD result against site data for water cooling

4. Conclusions

Based on CFD analysis result and manual calculation of reactor heating process, the reactor can be retrofitted with additional internal coil and new temperature control unit (heating & cooling) to achieve heating duration within 1 hour. Current CFD analysis show same trending of cooling with site data.

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References
[1] Kim, Jun Seok, Y. Y. Lee, and Tae Hyun Kim. "A review on alkaline pretreatment technology for bioconversion of lignocellulosic biomass." Bioresource technology 199 (2016): 42-48. https://doi.org/10.1016/j.biortech.2015.08.085
[2] Guragain, Yadhu N., and Praveen V. Vadlani. "Renewable biomass utilization: A way forward to establish sustainable chemical and processing industries." Clean Technologies 3, no. 1 (2021): 243-259. https://doi.org/10.3390/cleantechnol3010014
[3] Zheng, Yi, Jian Shi, Maobing Tu, and Yu-Shen Cheng. "Principles and development of lignocellulosic biomass pretreatment for biofuels." Advances in Bioenergy 2 (2017): 1-68. https://doi.org/10.1016/bs.aibe.2017.03.001
[4] Kumar, Adepu Kiran, and Shaishav Sharma. "Recent updates on different methods of pretreatment of lignocellulosic feedstocks: a review." Bioresources and bioprocessing 4, no. 1 (2017): 7. https://doi.org/10.1186/s40643-017-0137-9
[5] Maurya, Devendra Prasad, Ankit Singla, and Sangeeta Negi. "An overview of key pretreatment processes for biological conversion of lignocellulosic biomass to bioethanol." 3 Biotech 5 (2015): 597-609. https://doi.org/10.1007/s13205-015-0279-4
[6] Kim, Jun Seok, Y. Y. Lee, and Tae Hyun Kim. "A review on alkaline pretreatment technology for bioconversion of lignocellulosic biomass." Bioresource technology 199 (2016): 42-48. https://doi.org/10.1016/j.biortech.2015.08.085
[7] Bhatia, Shashi Kant, Sujit Sadashiv Jagtap, Ashwini Ashok Bedekar, Ravi Kant Bhatia, Anil Kumar Patel, Deepak Pant, J. Rajesh Banu, Christopher V. Rao, Yun-Gon Kim, and Yung-Hun Yang. "Recent developments in pretreatment technologies on lignocellulosic biomass: Effect of key parameters, technological improvements, and challenges." Bioresource technology 300 (2020): 122724. https://doi.org/10.1016/j.biortech.2019.122724
[8] Wang, Ying, Ling Leng, Md Khairul Islam, Fanghua Liu, Carol Sze Ki Lin, and Shao-Yuan Leu. "Substrate-related

factors affecting cellulosome-induced hydrolysis for lignocellulose valorization." International journal of molecular sciences 20, no. 13 (2019): 3354. https://doi.org/10.3390/ijms20133354

[9] Jung, Young Hoon, Hyun Min Park, In Jung Kim, Yong-Cheol Park, Jin-Ho Seo, and Kyoung Heon Kim. "One-pot pretreatment, saccharification and ethanol fermentation of lignocellulose based on acid–base mixture pretreatment." RSC Advances 4, no. 98 (2014): 55318-55327. https://doi.org/10.1039/C4RA10092A

[10] Guragain, Yadhu N., and Praveen V. Vadlani. "Renewable biomass utilization: A way forward to establish sustainable chemical and processing industries." Clean Technologies 3, no. 1 (2021): 243-259. https://doi.org/10.3390/cleantechnol3010014

[11] Zheng, Yi, Jian Shi, Maobing Tu, and Yu-Shen Cheng. "Principles and development of lignocellulosic biomass pretreatment for biofuels." Advances in Bioenergy 2 (2017): 1-68. https://doi.org/10.1016/bs.aibe.2017.03.001

[12] Melis, Anastasios, Liping Zhang, Marc Forestier, Maria L. Ghirardi, and Michael Seibert. "Sustained photobiological hydrogen gas production upon reversible inactivation of oxygen evolution in the green alga Chlamydomonas reinhardtii." Plant physiology 122, no. 1 (2000): 127-136. https://doi.org/10.1104/pp.122.1.127

[13] Antal, Taras K., Galina P. Kukarskikh, Alena A. Volgusheva, Tatyana E. Krendeleva, Esa Tyystjärvi, and Andrey B. Rubin. "Hydrogen photoproduction by immobilized S-deprived Chlamydomonas reinhardtii: Effect of light intensity and spectrum, and initial medium pH." Algal Research 17 (2016): 38-45. https://doi.org/10.1016/j.algal.2016.04.009

[14] Kosourov, Sergey N., and Michael Seibert. "Hydrogen photoproduction by nutrient-deprived Chlamydomonas reinhardtii cells immobilized within thin alginate films under aerobic and anaerobic conditions." Biotechnology and Bioengineering 102, no. 1 (2009): 50-58. https://doi.org/10.1002/bit.22050

[17] Moreira, Susana M., Matilde Moreira-Santos, Lúcia Guilhermino, and Rui Ribeiro. "Immobilization of the marine microalga Phaeodactylum tricornutum in alginate for in situ experiments: bead stability and suitability." Enzyme and Microbial Technology 38, no. 1-2 (2006): 135-141. https://doi.org/10.1016/j.enzmictec.2005.05.005

[18] Akkerman, Ida, Marcel Janssen, Jorge Rocha, and René H. Wijffels. "Photobiological hydrogen production: photochemical efficiency and bioreactor design." International journal of hydrogen energy 27, no. 11-12 (2002): 1195-1208. https://doi.org/10.1016/S0360-3199(02)00071-X

[19] Younesi, Habibollah, Ghasem Najafpour, Ku Syahidah Ku Ismail, Abdul Rahman Mohamed, and Azlina Harun Kamaruddin. "Biohydrogen production in a continuous stirred tank bioreactor from synthesis gas by anaerobic photosynthetic bacterium: Rhodopirillum rubrum." Bioresource technology 99, no. 7 (2008): 2612-2619. https://doi.org/10.1016/j.biortech.2007.04.059

[20] Ding, Jie, Xu Wang, Xue-Fei Zhou, Nan-Qi Ren, and Wan-Qian Guo. "CFD optimization of continuous stirred-tank (CSTR) reactor for biohydrogen production." Bioresource technology 101, no. 18 (2010): 7005-7013. https://doi.org/10.1016/j.biortech.2010.03.146

[21] Sharma, Archita, and Shailendra Kumar Arya. "Hydrogen from algal biomass: a review of production process." Biotechnology reports 15 (2017): 63. https://doi.org/10.1016/j.btre.2017.06.001