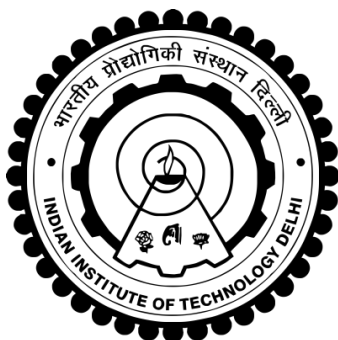


PROCESS IMPROVEMENT OF ETHANOL PRODUCTION FROM LIGNOCELLULOSIC RESIDUES

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**DEPARTMENT OF BIOCHEMICAL ENGINEERING AND
BIOTECHNOLOGY**

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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**DEPARTMENT OF BIOCHEMICAL ENGINEERING AND
BIOTECHNOLOGY**

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2019

CERTIFICATE

This is to certify that the thesis entitled “**Process improvement of ethanol production from lignocellulosic residues**” being submitted by **Ms. Siddhi S** is worthy of consideration for the award of the degree of **Doctor of Philosophy**. This thesis has been prepared under my supervision and guidance in conformity with the rules and regulations of Indian Institute of Technology Delhi and is a record of the original bonafide research work. The results presented in this thesis have not been submitted in part or full to any other universities or institutes for the award of any other degree or diploma.

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ABSTRACT

In light of the daily hike of petroleum prices, ethanol production from lignocellulosic residues such as rice straw, is gaining importance. Ethanol's massive production costs due to a complicated and energy intensive production process, is a setback to its application as a fuel alternative. In this study, an improvement of the existing ethanol production process was pursued, by replacing the energy consuming uneconomical steps with cheaper and greener alternatives. Therefore, process improvement was focused primarily on two major steps: pretreatment and fermentation.

First, the effectiveness of a novel, rapid ligninase releasing fungus coded MVI.2011, was explored as a pretreatment method for delignification of rice straw. Second, co-fermentation of hexoses and pentoses present in lignocellulose hydrolysate was performed in a modified OBR, to improve ethanol yield and productivity. In addition, mathematical models were proposed to predict the dynamics of the co-culture of the hexose and pentose fermenting yeasts (*Saccharomyces cerevisiae* (NRRL Y-132) and *Scheffersomyces stipitis* (NCIM 3507)), during co-fermentation. Also, two methods of enzyme recovery and recycle were studied and compared. Finally, energy auditing and techno-economic modelling of the improved process were performed to study its feasibility in industrial scale operation.

Optimized submerged cultivation mode of fungal pretreatment exhibited exemplary hydrolysis rate, corresponding to an increase of 1.87-fold, in comparison with untreated rice straw. The study reported for the first time, a biological pretreatment on rice straw, that took only 6 days. The mathematical models for predicting the concentration profiles of biomasses, substrates and products during co-fermentation showed good agreement between model-predicted and experimental values. The results of co-fermentation confirmed the increased efficiency of ethanol production in modified OBR with respect to yield, productivity, energy and economics. Profit analysis by various methods indicated that the designed plant is profitable and that its operation is

feasible. Therefore, implementation of the proposed process in large scale is likely to make biorefinery business more profitable.

सार

पेट्रोलियम की कीमतों में दैनिक बढ़ोतरी के मद्देनजर, चावल के भूसे जैसे लिग्नोसेल्यूलोसिक अवशेषों से इथेनॉल का उत्पादन उचित है। एक जटिल और ऊर्जा गहन उत्पादन प्रक्रिया के कारण इथेनॉल की बड़े पैमाने पर उत्पादकता, ईंधन विकल्प के रूप में इसके आवेदन के लिए एक रोक है। इस जाँच में, मौजूदा इथेनॉल उत्पादन प्रक्रिया में सुधार किया गया था, जिसमें सस्ता और हरियाली के विकल्प के साथ अनैतिक कदम उठाने वाली ऊर्जा की बदला गया। इसलिए, प्रक्रिया सुधार मुख्य रूप से दो प्रमुख चरणों पर केंद्रित था: पूर्व-उपचार और किण्वन।

सबसे पहले, एक नवीन, प्रभावशीलत तथा द्रुत लिग्निनैस रिहाई होने वाली कवक MVI.2011, चावल के भूसे के सरेखण के लिए पूर्व-उपचार विधि के रूप में पता लगाया गया था। दूसरा, लिग्नोसेल्यूलोज हाइड्रोलाइज़ेट में मौजूद हेक्सोस और पेंटोस के सह-किण्वन को एक संशोधित OBR में प्रदर्शन किया गया था, ताकि इथेनॉल की उपज और उत्पादकता में सुधार हो सके। इसके अलावा, गणितीय मॉडल को सह-किण्वन के दौरान हेक्सोज और पेंटोस फेरेंटिंग यीस्ट (सैन्क्रोमाइसेस सेरेविसिए (NRRL Y-132) और शेफर्सोमी सिपाइटिस (NCIM 3507) की सह-संस्कृति की गतिशीलता की भविष्यवाणी करने का प्रस्ताव दिया गया था। इसके अलावा, एंजाइम रिकवरी और रीसायकल के दो तरीकों का अध्ययन और तुलना की गई। अंत में, औद्योगिक प्रक्रिया के संचालन में इसकी व्यवहार्यता का अध्ययन करने के लिए सुधार प्रक्रिया की ऊर्जा ऑडिटिंग और तकनीकी-आर्थिक मॉडलिंग की गई।

अनुपचारित चावल के भूसे की तुलना में फफूंद पूर्व उपचार के अनुकूलित जलमग्न मोड ने 1.87-गुना की वृद्धि के साथ अनुकरणीय हाइड्रोलिसिस दर का प्रदर्शन किया। इस अध्ययन ने पहली बार रिपोर्ट की, एक जैविक पूर्व-चावल के भूसे पर उपचार, जिसमें केवल 6 दिन लगे। सह-किण्वन के दौरान बायोमास, सबस्ट्रेट और उत्पादों की एकाग्रता प्रोफाइल की भविष्यवाणी के लिए गणितीय मॉडल ने मॉडल-पूर्वानुमानित और

प्रयोगात्मक मूल्यों के बीच अच्छा समझौता दिखाया। सह-किण्वन के परिणामों ने उपज, उत्पादकता, ऊर्जा और अर्थशास्त्र के संबंध में संशोधित OBR में इथेनॉल उत्पादन की वृद्धि की दक्षता की पुष्टि की। विभिन्न तरीकों से लाभ विश्लेषण से संकेत मिलता है कि डिज़ाइन किया गया संयंत्र लाभदायक है और इसका संचालन संभव है। इसलिए, बड़े पैमाने पर प्रस्तावित प्रक्रिया के क्रियान्वयन से बायोफाइनरी कारोबार को अधिक लाभदायक बनाने की संभावना है।

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	iii
ABSTRACT	vii
TABLE OF CONTENTS	ix
LIST OF FIGURES.....	xiii
LIST OF TABLES.....	xv
ABBREVIATIONS	xvii
1. INTRODUCTION.....	1
1.1 Introduction	3
2. REVIEW OF LITERATURE	7
2.1 Ethanol as Fuel	9
2.2 Pretreatment.....	10
2.2.1 Comparison of pretreatment techniques	11
2.2.2 Peroxide pretreatment.....	13
2.2.3 Biological pretreatment as an alternative	14
2.2.4 MVI. 2011	15
2.2.5 Optimization techniques	17
2.3 Saccharification	17
2.3.1 Enzymatic hydrolysis	18
2.3.2 Enzyme recycling	18
2.4 Fermentation.....	19
2.4.1 Fermentation microorganisms	19
2.4.2 Co-fermentation of hexoses and pentoses	20
2.4.3 Mathematical models for co-fermentation	20
2.4.4 Operational strategies for hydrolysis and fermentation.....	21
2.4.5 Bioreactors for fermentation.....	22
2.4.6 Oscillatory Baffled Reactor (OBR)	23
2.4.7 OBR in ethanol production.....	25
2.4.8 Modified OBR	26
2.5 Purification	26
2.6 Energy and Cost of Ethanol Production process	38
2.6.1 Energy efficiency.....	38
2.6.2 Energy and Cost Evaluation of Ethanol	39
2.6.3 Techno-economic Modelling of Ethanol Production Process	41

3. RESEARCH GAPS AND OBJECTIVES.....	49
3.1 Research gap and motivations.....	51
3.2 Proposed process.....	52
3.3 Objectives	53
4. MATERIALS AND METHODS	55
4.1 Substrate.....	57
4.2 Enzymes.....	57
4.3 Microorganisms	57
4.3.1 MVI.2011.....	57
4.3.2 Yeasts for fermentation.....	58
4.4 Study of growth of MVI.2011.....	58
4.4.1 Growth of MVI.2011 on commercial lignin	58
4.4.2 Growth of MVI.2011 on agar bed.....	59
4.4.3 Dependence of MVI.2011 on alkaline pH	59
4.4.4 Growth of MVI.2011 on ethanol.....	60
4.4.5 Growth of MVI.2011 on hydrogen peroxide	60
4.5 Fungal delignification of rice straw	60
4.5.1 Solid state pretreatment.....	61
4.5.2 Submerged pretreatment	61
4.5.3 Pretreatment of rice straw in 7.5 L bioreactor.....	62
4.5.4 Evaluation of pretreatment efficiency.....	62
4.6 Optimization of submerged cultivation parameters	63
4.6.1 Design of experiments	63
4.6.2 Experimental runs	64
4.6.3 Analysis of the experiments	64
4.7 Enzymatic hydrolysis and enzyme recycle	65
4.7.1 Membrane separation.....	65
4.7.2 Substrate readsorption.....	65
4.8 Mathematical modelling of co-culture of yeasts.....	66
4.8.1 Fermenter and fermentation media	66
4.8.2 Batch fermentation for kinetic studies	67
4.8.3 Co-culture batch fermentation	67
4.8.4 Analysis of biomass, sugars and ethanol.....	68
4.8.5 Model Development.....	68
4.8.6 Validation of the model.....	69
4.9 Fermentation in OBR.....	70
4.9.1 Fermentation experiments.....	70

4.10 Distillation	71
4.11 Energy auditing and cost evaluation.....	71
4.12 Techno-economic modelling	72
4.12.1 Steps in modelling	72
4.12.3 Simulation and Techno-economic analysis	73
5. RESULTS AND DISCUSSION.....	75
5.1 Growth of MVI.2011 on commercial lignin.....	77
5.1.1 Fungal degradation of lignin	77
5.1.2 Fungal growth on agar bed and its dependence on alkaline pH	79
5.1.3 Effect of ethanol and hydrogen peroxide on fungal growth	81
5.2 Biological pretreatment of rice straw	82
5.2.1 Solid state pretreatment of rice straw	82
5.2.2 Submerged pretreatment of rice straw: Effect of glucose on pretreatment	82
5.2.3 Fungal pretreatment of rice straw: Solid state or submerged	89
5.3 Optimization of fungal delignification of rice straw	91
5.3.1 Taguchi experimental design and analysis	91
5.3.2 Analysis of lignin peroxidase activity and other sugars of Taguchi experiments	95
5.3.3 Validation of Taguchi optimized model	97
5.3.4 Scale up of Taguchi optimized delignification of rice straw	98
5.4 Recycle of cellulase enzyme	99
5.4.1 Enzyme recovery by membrane separation.....	99
5.4.2 Enzyme recovery by cellulase readsorption	101
5.5 Co-culture mathematical modelling	102
5.5.1 Model equations	102
5.5.2 Solving the model.....	104
5.5.3 Kinetic parameters from batch fermentation of pure culture.....	105
5.5.4 Concentration profiles of co-culture ethanol fermentation.....	108
5.5.5 Simulation and model validation.....	108
5.6 Co-fermentation in modified OBR	113
5.6.1 Modified OBR.....	113
5.6.2 Co-fermentation in synthetic and lignocellulosic hydrolysates.....	114
5.6.3 Fermentation inhibitors	117
5.6.4 Distillation of ethanol	117
5.6.5 Energy auditing and cost evaluation.....	117
5.6.6 Comparison between shake flask and modified OBR co-fermentations	120
5.7 Techno-economic modelling of the process	122
5.7.1 Process Overview	122

5.7.2 Modelling and Simulation.....	126
5.7.3 Analysis of Techno-economic models	130
5.7.4 Profit analysis.....	131
6. SUMMARY AND CONCLUSION.....	135
BIBLIOGRAPHY	141
APPENDIXES	169
1. ANALYTICAL METHODS AND ASSAYS.....	171
2. CHEMICAL PRETREATMENTS.....	183
3. MEDIA COMPOSITIONS AND CULTURE CONDITIONS.....	185
CURRICULUM VITAE.....	187

LIST OF FIGURES

Figure 2.1	Steps in ethanol production from lignocelluloses.....	10
Figure 2.2	Growth of MVI.2011 on MMM containing 0.1% lignin.....	16
Figure 2.3	Schematic of OBR.....	23
Figure 3.1	Diagrammatic representation of the proposed ethanol production process.....	53
Figure 4.1	Simulation window of Aspen Plus v8.6.....	72
Figure 5.1	Growth of MVI.2011 on lignin.....	77
Figure 5.2	COD measurement during the growth of MVI.2011 in lignin.....	78
Figure 5.3	Growth of the fungus in MMM containing media.....	78
Figure 5.4	Growth of MVI.2011 on agar beds.....	79
Figure 5.5	Dependence of MVI.2011 on alkaline pH.....	80
Figure 5.6	Effect of ethanol on MVI.2011's growth.....	81
Figure 5.7	Pretreatment of rice straw under submerged conditions.....	83
Figure 5.8	% Saccharification of rice straw after submerged pretreatment in the presence of glucose.....	84
Figure 5.9	Absorption values of MMM during submerged pretreatment at different wavelengths.....	84
Figure 5.10	Delignification of rice straw by submerged treatment in glucose deficient media for 4 weeks.....	86
Figure 5.11	Rice straw collected at the end of 4 weeks of submerged treatment with MVI.2011.....	86
Figure 5.12	MVI.2011 grows on the surface of liquid.....	90
Figure 5.13	Main effects plot for S/N ratios of Taguchi experimental runs.....	94
Figure 5.14	Lignin peroxidase activity of Taguchi delignification optimization experiment...96	96
Figure 5.15	Yield of reducing sugars after 8 h hydrolysis of delignified rice from Taguchi experiments.....	96
Figure 5.16	Enzyme recovery by membrane filtration.....	100
Figure 5.17	Enzyme readsorption to fresh substrate.....	101
Figure 5.18	MATLAB code for solving differential equation.....	105
Figure 5.19	Concentration profiles of pure culture fermentation.....	106
Figure 5.20	Concentration profiles of co-culture fermentation.....	107
Figure 5.21	Parity plots considering 25% error margin for concentrations.....	109

Figure 5.22	Concentration profile obtained from model prediction.....	110
Figure 5.23	Comparison between experimental and model predicted results.....	111
Figure 5.24	Modified oscillatory baffled reactor.....	114
Figure 5.25	Concentration profiles in modified OBR.....	115
Figure 5.26	Concentration profiles of other sugars in OBR.....	116
Figure 5.27	Raw material cost of the ethanol production process following three modes of pretreatment.....	118
Figure 5.28	Energy requirement of the ethanol production process following three modes of pretreatment.....	119
Figure 5.29	Operating cost of the ethanol production process following three modes of pretreatment.....	119
Figure 5.30	Flowchart of ethanol production process from rice straw.....	123
Figure 5.31	Comparison of results of 4 case scenarios.....	130

LIST OF TABLES

Table 2.1	Classification of pretreatment methods.....	11
Table 2.2	Summary of literature on biological pretreatment of rice straw.....	15
Table 2.3	Summary of literature reports on ethanol production from biological sources.....	27
Table 2.4	Summary of literature reports on energy involved in ethanol production plants...	44
Table 2.5	Summary of literature reports on production costs of ethanol plants.....	46
Table 4.1	Assumptions in cash flow analysis.....	74
Table 5.1	Effect of H ₂ O ₂ on MVI.2011's growth.....	81
Table 5.2	Saccharification after pretreatment of rice straw in solid state conditions.....	82
Table 5.3	Yield of sugars from enzymatic hydrolysis of fungal treated rice straw in submerged conditions.....	88
Table 5.4	Yield of sugars from enzymatic hydrolysis of rice straw delignified in 7.5 L reactor by submerged treatment.....	88
Table 5.5	Matrix Layout of L27 Taguchi orthogonal array design.....	92
Table 5.6	Mean response values and S/N ration of Taguchi optimization experiments.....	93
Table 5.7	Response table for signal to noise ratios: larger is better.....	94
Table 5.8	Analysis of variance (ANOVA) for the means of the factors in the experiment....	95
Table 5.9	Summary of results of optimized dlignification of rice straw using MVI.2011....	97
Table 5.10	Nomenclature used in modelling.....	103
Table 5.11	Kinetic parameters obtained or range tested in this study.....	107
Table 5.12	Kinetic parameter values that gave the best parity and comparison with literature.....	108
Table 5.13	Summary of statistical validation of the co-culture models.....	112
Table 5.14	Results of the statistical validation of co-culture mathematical models.....	113
Table 5.15	Yield and productivity of ethanol of co-fermentation in shake flask and OBR....	116
Table 5.16	Price details of raw materials.....	118
Table 5.17	Equipments cost and energy rating.....	120
Table 5.18	Equipment used in each process.....	121
Table 5.19	Summary of cost and energy of the ethanol production process across various pretreatment methods.....	122
Table 5.20	Flowchart labels.....	124

Table 5.21	Reaction components considered in the process simulation.....	127
Table 5.22	Stoichiometric reactions and fractional conversions.....	127
Table 5.23	Mass balance of components in the process.....	128
Table 5.24	Stream price details.....	129
Table 5.25	Equipment mapped and sized for economic evaluation.....	129
Table 5.26	Profit analysis of scenario 4.....	131

ABBREVIATIONS

Units

°C	degree Celsius
Btu	British thermal unit
c	centi
CFU	colony forming unit
FPU	filter paper unit
G	giga
g	gram
gal	gallon
h	hour
IU	international unit
J	joule
k	kilo
K	Thousand
L	litre
m	milli/metre
μ	micro
M	mega/molar/million
min	minute
mol	mole
n	nano
N	normal
psi	pounds per square inch
rpm	radians per minute
s	second
ton	tonne
v	volume
vvm	volume per volume per minute

V	volts
w	weight
W	watt

Nomenclature

α alpha

β beta

γ gamma

δ delta

5-HMF 5-Hydroxymethyl furfural

ANOVA Analysis of variance

AFEX Ammonia fibre explosion

CB Cellobiase

CBP Consolidated bioprocessing

CMC Carboxymethyl cellulose

COD Chemical oxygen demand

DIST Distillation

DMC Direct microbial conversion

EH Enzymatic hydrolysis

EROI Energy return on investment

EtOH Ethanol

FER Fermentation

FTIR Fourier transform infrared

HCW Hot compressed water

HPLC High performance liquid chromatography

IRR Internal rate of return

IUPAC International union of pure and applied chemistry

MMM Minimal mineral media

NMR Nuclear magnetic resonance

NPV Net present value

NREL	National renewable energy laboratory
NSSF	Non-isothermal simultaneous saccharification and fermentation
OA	Orthogonal array
OBR	Oscillatory baffled reactor
OD	Optical density
OFAT	One factor at a time
PFR	Plug flow reactor
PT	Pretreatment
SD	Standard deviation
SDA	Sabouraud dextrose agar
SDB	Sabouraud dextrose broth
SHF	Separate hydrolysis and fermentation
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification and fermentation/solid state fermentation
STR	Stirred tank reactor
TMP	Trans membrane pressure
USD	US Dollars
UV	Ultraviolet