

Table of contents

ACKNOWLEDGEMENTS.....	VI
DECLARATION OF AUTHORSHIP	IX
TABLE OF CONTENTS.....	X
LIST OF FIGURES	XIV
LIST OF TABLES	XVII
LIST OF ABBREVIATIONS.....	XVIII
LIST OF SYMBOLS	XX
ABSTRACT.....	XXII
ZUSAMMENFASSUNG	XXIV
1 INTRODUCTION	1
2 MOTIVATION AND OBJECTIVES	4
3 THEORETICAL BACKGROUND	6
3.1 ANAEROBIC DIGESTION	6
3.1.1 <i>Process stages</i>	6
3.1.1.1 Hydrolysis.....	7
3.1.1.2 Acidogenesis.....	8
3.1.1.3 Acetogenesis.....	10
3.1.1.4 Methanogenesis	11
3.1.2 <i>Microorganisms</i>	13
3.1.3 <i>Microbial growth</i>	16
3.1.4 <i>Process inhibition</i>	17
3.1.4.1 Ammonia inhibition.....	18
3.1.4.2 Organic acids	19
3.1.4.3 Oxygen	19
3.1.4.4 Other inhibition sources.....	19
3.1.5 <i>Biogas volume and mass balances</i>	20
3.1.5.1 Theoretical biogas volume.....	20
3.1.5.2 Chemical oxygen demand.....	21
3.1.5.3 Biomethane potential tests	22
3.1.6 <i>Physico-chemical equilibria</i>	22
3.1.6.1 Carbon Dioxide.....	23
3.1.6.2 Ammonium-ammonia equilibrium	25

Table of contents

3.1.6.3 FOS/TAC.....	26
3.2 SCALE-UP IN (BIO)PROCESS ENGINEERING	27
3.2.1 <i>Physical aspects</i>	27
3.2.2 <i>Chemical aspects</i>	29
3.2.3 <i>Biological aspects</i>	30
3.2.4 <i>Anaerobic digestion scale-up</i>	30
3.3 RHEOLOGY AND MIXING	31
3.3.1 <i>Rheology</i>	31
3.3.2 <i>Mixing in process engineering</i>	33
3.3.3 <i>Influence of mixing on the syntropy between bacteria and archaea</i>	35
4 MATERIALS AND METHODS	38
4.1 SETUP	38
4.1.1 <i>Laboratory setup</i>	38
4.1.2 <i>Technical plants</i>	40
4.2 ANALYTICAL METHODS	42
4.2.1 <i>Biogas analyses</i>	42
4.2.1.1 Biogas volume	42
4.2.1.2 Biogas composition	43
4.2.2 <i>Physico-chemical sludge analyses</i>	44
4.2.2.1 pH value measurement.....	44
4.2.2.2 Volatile fatty acids concentration determination	44
4.2.2.3 Total ammonium nitrogen concentration determination	44
4.2.2.4 Glucose concentration determination.....	45
4.2.2.5 FOS/TAC analyses	45
4.2.2.6 COD measurement.....	45
4.2.2.7 Total solids and total volatile solids analyses	46
4.2.2.8 Amino acids detection	46
4.2.3 <i>DNA analyses</i>	47
4.2.3.1 DNA extraction.....	47
4.2.3.2 Determination of DNA and RNA concentration.....	48
4.2.3.3 Quantitative Polymerase Chain Reaction (qPCR)	48
4.2.3.4 Gel electrophoresis	49
4.2.3.5 Next Generation Sequencing (NGS).....	49
4.2.3.6 Automated Ribosomal Intergenic Spacer Analysis (ARISA)	50
4.2.4 <i>Mixing parameters</i>	51
4.2.4.1 Viscosity as a function of shear rate	51
4.2.4.2 Stirring rate	51
4.2.4.3 Mixing time	51
4.2.4.4 Power input.....	51
4.3 EXPERIMENTS.....	52
4.3.1 <i>Reproducibility</i>	52
4.3.2 <i>Ammonia inhibition</i>	52

Table of contents

4.3.2.1	Casein digestion at elevated TAN concentrations.....	52
4.3.2.2	Starch digestion at elevated TAN concentrations	53
4.3.3	<i>Mixing</i>	55
4.3.4	<i>Process productivity and microbial growth</i>	57
5	RESULTS AND DISCUSSION	58
5.1	REPRODUCIBILITY	58
5.2	AMMONIA INHIBITION	63
5.2.1	<i>Influence of increasing TAN concentrations and pH values on casein digestion and associated microbial population structure</i>	63
5.2.2	<i>Influence of increasing TAN concentrations and lower NH₃/NH₄⁺ ratios on starch digestion and associated microbial population structure</i>	70
5.2.3	<i>Case study: Microbial response to changes in the TAN concentration in two technical-scale biogas plants</i>	82
5.3	MIXING.....	89
5.3.1	<i>Rheology and mixing parameters</i>	89
5.3.1.1	Viscosity as a function of stirring rate	89
5.3.1.2	Mixing parameters: stirring rate and mixing time.....	90
5.3.1.3	Energy inputs.....	91
5.3.2	<i>Influence of mixing on anaerobic digestion</i>	92
5.4	HYDROSTATIC PRESSURE, CO ₂ SOLUBILITY, AND pH VALUE.....	99
5.5	PROCESS PRODUCTIVITY AND MICROBIAL GROWTH.....	102
5.5.1	<i>Batch and fed-batch processes</i>	102
5.5.2	<i>Semi-continuous process</i>	105
5.5.3	<i>Continuous process</i>	107
5.5.4	<i>Factors causing productivity differences</i>	108
6	CONCLUSIONS.....	113
7	OUTLOOK	116
8	REFERENCES	117
9	APPENDICES.....	128
	LIST OF FIGURES, APPENDICES.....	128
	LIST OF TABLES, APPENDICES.....	130
	APPENDIX A – ADDITIONAL INFORMATION ON MATERIALS AND METHODS.....	131
	APPENDIX B – ADDITIONAL RESULTS ON REPRODUCIBILITY	141
	APPENDIX C – ADDITIONAL RESULTS ON AMMONIA INHIBITION, CASEIN DIGESTION	142
	APPENDIX D – ADDITIONAL RESULTS ON AMMONIA INHIBITION, STARCH DIGESTION	149
	APPENDIX E – INVESTIGATION OF THE INFLUENCE OF CHLORIDE SALTS ON THE ANAEROBIC DIGESTION OF STARCH	156
	APPENDIX F – ADDITIONAL RESULTS ON TAN REDUCTION IN TECHNICAL-SCALE BIOGAS PLANTS	158

Table of contents

APPENDIX G – ADDITIONAL RESULTS ON RHEOLOGY AND MIXING	167
APPENDIX H – ADDITIONAL RESULTS ON PROCESS PRODUCTIVITY AND MICROBIAL GROWTH	171
10 PUBLICATIONS.....	173

Stanislava Mlinar

Towards scale-down of anaerobic digestion –
aspects of scaling, process reproducibility, stability, and productivity
2023 / 200 Seiten / 29,95 € / ISBN 978-3-96831-037-4