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METHANE AND ENERGY RECOVERY POTENTIAL FROM SWINE WASTEWATER DIGESTION BY ANAEROBIC AND MICROAEROBIC PROCESSES

FORTALEZA – CE
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Dissertation presented to the Graduate Program in Civil Engineering (Water Resources), Department of Hydraulic and Environmental Engineering, Federal University of Ceará, as a requirement to obtain a degree of Master in Civil Engineering.
Concentration Area: Environmental Sanitation.

Advisor: Prof. Dr. André Bezerra dos Santos
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I dedicate this work to my advisor Erlon Lopes *(in memoriam)*.

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To God, the Author and Finisher of our faith, and Creator of all things.

To my parents.

To my advisor Erlon Lopes *(in memoriam)*, who is no longer with us but left a great legacy for our lives. And to my advisor, André Bezerra, for all knowledge and experience shared and for trusting in the dedication and engaged work.

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"The fear of the LORD is the beginning of knowledge: but fools despise wisdom and instruction." Pv 1:7

RESUMO

A pesquisa teve como objetivo avaliar a utilização e potencial de produção de biogás como fonte de energia renovável a partir do tratamento da água residuária da suinocultura (ARS) em reator anaeróbio de manta de lodo e fluxo ascendente (UASB) e em reator microaeróbio de manta de lodo e fluxo ascendente (UMSB). A ARS foi vista como um potencial substrato para recuperação energética devido a sua alta complexidade e alto teor de matéria orgânica e o grande crescimento da suinocultura no Brasil. O foco foi prioritariamente na produção de energia elétrica, entendendo o potencial dos subprodutos gerados na digestão da ARS e identificando a autossuficiência do sistema e a aplicação da energia gerada em outros setores. Um modelo matemático foi desenvolvido para estimar com mais acurácia o potencial de recuperação de energia em reatores UASB tratando águas residuárias de uma granja de suínos com até 10.000 suínos. O modelo foi desenvolvido com base na simulação de Monte Carlo para estimar o potencial energético do biogás em três categorias de granjas de suínos (pequena, média e grande), que correspondiam a diferentes escalas (250, 500 e 1.000 suínos). Para determinar o potencial energético da ARS analisou-se cargas orgânicas volumétricas (COV) de 9,3 a 21,1kgDQO $m^{-3}d^{-1}$. Para cada escala de suinicultura, o potencial de recuperação de energia elétrica foi de 1,6 a 2,1 kWh $kgDQO_{rem}^{-1}$ e 6.0 a 8.2 kWh m_{ARS}^{-1}. O potencial energético da ARS foi calculado com base nos parâmetros operacionais do reator UASB, no poder calorífico do metano no biogás e na produção diária de ARS. A regressão linear entre as variáveis ARS (L d^{-1}) (eixo x) e potencial energético do biogás (kWh d^{-1}) (eixo y) foi y=-241,60+33,55x (r^2=0,82), enquanto que para DQO removida (kg d^{-1}) (eixo x) e o potencial energético do biogás (kWh d^{-1}) (eixo y) foi y=-80,10+2,24x (r^2=0,93). O modelo demonstrou uma boa acurácia e houve um ajuste adequado aos dados monitorados, indicando poder ser aplicado na estimativa do potencial energético do biogás gerado em reatores UASB. Também foram investigados os efeitos da microaeração *in-situ* no desempenho da digestão da ARS para recuperação de metano e energia elétrica. A esse respeito, os desempenhos do reator UASB e do reator UMSB foram comparados. Duas doses de oxigênio (0,17 e 0,25 LO_2 $L_{alimentação}^{-1}d^{-1}$) foram avaliadas na recuperação de metano e energia elétrica com os reatores operados no tempo de detenção hidráulica (TDH) de 12h. A dose ar de 0,25 LO_2 $L_{alimentação}^{-1}d^{-1}$ foi posteriormente avaliada em TDHs de 10, 8 e 6h. O maior rendimento de metano obtido no reator UMSB foi de 228,6 NL $kgDQO^{-1}$ d^{-1}, durante uma COV de 12,2 kgDQO $m^{-3}d^{-1}$ (TDH de 10h). O aumento da COV e da dose no ar gerou diluição do metano no biogás, o que reduziu a possibilidade de recuperação de energia elétrica. Apesar disso, os resultados mostraram que o reator UMSB foi autossuficiente e teve eficiência energética no TDH de 12h nas doses de 0,17 e 0,25 LO_2 $L_{alimentação}^{-1}d^{-1}$ e no TDH de 10h na dose de 0,25 LO_2 $L_{alimentação}^{-1}d^{-1}$. O reator UMSB obteve um retorno de energia sobre o investimento (EROI) de 11,6 a 18,7, mostrando ser uma alternativa potencial para geração de energia.

Palavras-chave: Água residuária de suinocultura. Biogás. Balanço e recuperação energética. Processo microaeróbio.

ABSTRACT

The research aimed to evaluate the use and potential of biogas production as a source of renewable energy from swine wastewater (SWW) treatment in upflow anaerobic sludge blanket reactor (UASB) and upflow microaerobic sludge blanket reactor (UMSB) reactors. The SWW was seen as a potential substrate for energy recovery due to its high complexity and high organic matter content and the large growth of pig farming in Brazil. The focus was primarily on electricity production, understanding the potential of the by-products generated in SWW digestion, and identifying the system self-sufficiency and the application of the energy generated in other sectors. A mathematical model has been developed to more accurately estimate the potential for energy recovery in UASB reactors treating wastewater from a pig farm with up to 10,000 pigs. The model was developed based on Monte Carlo simulation to estimate the energy potential of biogas in three categories of pig farms (small, medium, and large), which corresponded to different scales (250, 500, and 1,000 pigs). In order to determine the SWW energy potential, various organic loading rates (OLR) from 9.3 to 21.1 kgCOD $m^{-3}d^{-1}$ were analyzed. For each piggery scale, the potential for electrical energy recovery was 1.6 to 2.1 kWh $kgCOD_{rem}^{-1}$ and 6.0 o 8.2 kWh m_{SWW}^{-1}. The SWW energetic potential was calculated based on the UASB reactor operational parameters, the calorific value of methane in biogas, and the daily SWW production. The linear regression between the variables SWW (L d^{-1}) (axis x) and biogas energy potential (kWh d^{-1}) (axis y) was y=-241.60+33.55x (r^2=0.82), while for COD removed (kg d^{-1}) (axis x) and biogas energy potential (kWh d^{-1}) (axis y) was y=-80.10+2.24x (r^2=0.93). The model showed good accuracy, and there was an adequate fit to the monitored data, indicating that can be applied to estimate the energy potential of biogas generated in UASB reactors. It was also investigated the effects of the in-situ microaeration on the digestion performance of SWW for methane and electrical energy recovery. In this regard, the performances of the UASB reactor and UMSB reactor were compared. Two oxygen doses (0.17 and 0.25 LO_2 $L_{feed}^{-1}d^{-1}$) were evaluated on methane and electrical energy recovery with the reactors operated at the Hydraulic Retention Time (HRT) of 12h. The air dose of 0.25 LO_2 $L_{feed}^{-1}d^{-1}$ was subsequently evaluated at HRT of 10, 8, and 6h. The highest methane yield achieved in the UMSB reactor was 228.6 NL $kgCOD^{-1}$ d^{-1}, during an OLR of 12.2 kgCOD $m^{-3}d^{-1}$ (HRT of 10h). OLR and air dose increase generated methane dilution in the biogas, which reduced the possibility of electrical energy recovery. Nevertheless, the results showed that the UMSB reactor was self-sufficient and had energy efficiency in the 12h HRT at doses of 0.17

and 0.25 LO_2 $L_{feed}^{-1}d^{-1}$ and in the 10h HRT at a dose of 0.25 LO_2 $L_{feed}^{-1}d^{-1}$. The UMSB reactor achieved an energy return on investment (EROI) of 11.6 to 18.7, showing a potentially viable alternative for power generation.

Keywords: Swine wastewater. Biogas. Energy balance and recovery. Microaerobic process.

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LIST OF ABBREVIATIONS

ABPA	Associação Brasileira de Proteína Animal
AD	Anaerobic Digestion
AEP	Available Electrical Power
AnMBR	Anaerobic Membrane Bioreactors
ANOVA	Analysis of Variance
APHA	American Public Health Association
AR	Aeration Rate
BMIW	Beet Molasses Based Industrial Wastewater
$BOD_5^{20°C}$	Biochemical Oxygen Demand
BOR	Biological Organic Rate
CAFOs	Confined Animal Feeding Operations
CEPEA	Centro de Estudos Avançados em Economia Aplicada
CETESB	Environmental Company of the State of São Paulo
CF	Capacity Factor
CFU	Correction Factor for Uncertainty
CHP	Combined Heat and Power
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
COD_{CH4}	Chemical Oxygen Demand methane
COD_{eff}	Chemical Oxygen Demand effluent
COD_{inf}	Chemical Oxygen Demand influent
COD_{rem}	Chemical Oxygen Demand removed
COD_{Sludge}	Chemical Oxygen Demand sludge
COD_{SO4}	Chemical Oxygen Demand for sulfate reduction
COD^T	Total Chemical Oxygen Demand
CS	Sewage Contribution
CW	Condensate Water
DCW	Diluted Cheese Whey
DEC	Equivalent Duration of Interruption per Consumer Unit
DOM	Dissolved Organic Matters
DZO	Zootechny Department

EIA	Energy Information Administration
EPA	United States Environmental Protection Agency
EROI	Energy Return on Investment
ET	Equalization Tank
FAO	Food and Agriculture Organization of the United Nations
FEC	Equivalent Frequency of Interruption Per Consumer Unit
FS	Fixed Solids
GHG	Greenhouse Gas
GPD	Gross Domestic Product
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
HSD	Honestly Significant Difference
IBGE	Instituto Brasileiro de Geografia e Estatística
IPCC	Inter-governmental Panel on Climate Change
LCV_A	Lower Calorific Value Available
LCV_{CH4}	Lower Calorific Value of CH_4
L-OFMSW	Organic Fraction of Municipal Solid Waste Leachate
MCF	Methane Conversion Factor
OLR	Organic Loading Rate
P_{ea}	Available Energy Potential
pH	Potential of Hydrogen
PN	Proteins
PS	Polysaccharides
PVC	Polyvinyl Chloride
RES	Renewable Energy Systems
SVC	Sugar Cane Vinasse
SW_{CH4}	Specific weight of CH_4
SWW	Swine Wastewater
TA	Total Alkalinity
TFS	Total Fixed Solids
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon

TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids
TV	Tequila Vinasses
TVS	Total Volatile Solids
UASB	Upflow Anaerobic Sludge Blanket
UFC	Federal University of Ceará
UMSB	Upflow Microaerobic Sludge Blanket
USA	United States of America
USW	Urban Solids Waste
VFA	Volatile Fatty Acids
VHL	Volumetric Hydraulic Load
VS	Volatile Solids
VSS	Volatile Suspended Solids
WTP	Wastewater Treatment Plants

LIST OF ACRONYMS

B_O	Maximum Methane Production Capacity
GJ	Gigajoules
$N\text{-}NH_4^+$,	Ammonium
O_{CH4}	Amount of Oxygen Required to Oxidize 1 Mole of Methane
P	Atmospheric Pressure
P_{ea}	Available Energy Potential
CO_2	Carbon Dioxide
K_{COD}	COD of one mole of CH_4
P_{CO}	Compressor Operating Power
Ef	Conversion Efficiency
$Y_{SVT\text{-}DQO}$	Conversion Factor
K	Conversion of Units kcal-Joules-kWh
m^3	Cubic Meter
r^2	Determination Coefficient
US$	Dollar
E_C	Energy Consumption
E_P	Energy Demand for Pumps (Feed)
K_{ef}	Energy Efficiency
E_R	Energy Recovery
€	Euro
Q	Flow
Q_p	Flow Rate
R	Gas Constant
E	Hydraulic Pressure Head
H_2	Hydrogen Gas
H_2S	Hydrogen Sulfide
kg	Kilogram
kWh	Kilowatt-Hour
MJ	Megajoules
MWh	Megawatt Hours

CH_4	Methane
$CH_{4equivalent}$	Methane Equivalent of Converted COD
F_{CH4}	Methane Flow
mg	Milligram
mL	Milliliter
Kn	Net energy available
N_2	Nitrogen Dioxide
NL	Normal Liter
$F_{N-CH4-real}$	Normalized available flow
Fn_{CH4}	Normalized methane flow
γ	Normalized specific weight of methane
N	Number of Moles
OR	Oxygen Requirement
O_2	Oxygen
OE_C	Oxygenation Efficiency Under Real Conditions
$OE_{theoretical}$	Oxygenation Efficiency Under Theoretical Conditions
PO_4^{3-}	Phosphate
η	Rate of Change
T	Reactor Operating Temperature
Y_{COD}	Sludge yield, such as COD
Y	Sludge yield, such as TVS
SW_{CH4}	Specific Weight of CH_4
SO_4^{2-}	Sulfate
S^{2-}	Sulfide
$TonCO_{2eq}$	Tons Of Carbon Dioxide Equivalent
K	Total Energy Available
V_{CH4}	Volume of Methane

SUMMARY

1 GENERAL INTRODUCTION

Between 2000 and 2020, the expected world population growth was between 1 and 2% per year, reaching 7.75 billion in 2020 (THE WORLD BANK, 2021). Energy demand has been also increasing, causing concerns about global warming, national energy security, and the trend of continuously higher consumption of natural resources for years to come (ATELGE et al., 2020), and increased demand for food. These problems inspire humanity to rethink the use of natural resources.

In response to the increased demand for food, agribusiness has grown over the last decades, with a current share in Brazil's Gross Domestic Product (GDP) of 30% (CEPEA, 2021). In agribusiness, the pig industry expanded, responsible for 32% of all animal protein consumed worldwide in 2020 (FAO, 2020). In this regard, production models have been modified to confinement systems to increase production capacity and efficiency to meet the demands (HU; CHENG; TAO, 2017).

Consequently, this industry produces a considerable amount of wastewater (JIANG et al., 2020), consisting of a mixture of urine, feces, water spillage, and undigested food waste, categorized as one of the agricultural wastewater with a high concentration of pollutants (ZHANG et al., 2021a). The swine wastewater (SWW) composition might vary according to the age of hogs, feed composition, number of hogs in the farm, hog housing methods, and other environmental factors like temperature and humidity (NAGARAJAN et al., 2019). Typical concentrations of the major pollutants in the swine wastewater could be represented as follows: 3.0 – 15.0 g L^{-1} chemical oxygen demand (COD), 2 – 7.3 gN L^{-1} total nitrogen (TN), and 0.2 – 0.5 g L^{-1} total phosphorus (TP) (CHENG et al., 2019, 2020; ZHANG et al., 2021a). Due to this high content, direct wastewater disposal can result in serious environmental problems (CHENG et al., 2018a; JIANG et al., 2020; LIU et al., 2020b; ZHENG et al., 2018).

The complexity and high load in SWW make it a suitable substrate for the anaerobic digestion (AD), also considered an economical option, to accomplish with high organic loading rates and produce biogas (AZIZ et al., 2019; MONTES et al., 2019; MOUSTAKAS; PARMAXIDOU; VAKALIS, 2020; ZHANG et al., 2021a). A variable range of reactors has made AD a competitive treatment technology for removing COD from high-strength SWW (ZHANG et al., 2021a). In addition, AD is a process that is advantageous for having low footprint demand, low sludge production, low energy and nutrients requirements compared to aerobic processes (AZIZ et al., 2019).

AD also presents advantages in relation to the physical-chemical treatment process, where there is energy savings, no consumption of chemical products for the coagulation-flocculation processes and lower amount of sludge (EUROPEAN COMMISSION, 2001; GLEBER; PALHARES, 2007; RADIS STEINMETZ et al., 2009; RAMME; KUNZ, 2009; SÁNCHEZ-MARTÍN; BELTRÁN-HEREDIA; SOLERA-HERNÁNDEZ, 2010). Anaerobic lagoons are the most applied technology in the treatment of bovine and swine manure in southern Brazil. However, large areas are required, and a suitable climate is needed for having a moderate/good efficiency (BAKER et al., 2021; LIMA et al., 2020; LOGANATH; SENOPHIYAH-MARY, 2020b; VENDRUSCOLO et al., 2020).

AD is a complex process consisting of different microorganisms dominant in various stages, i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis. (NABATEREGA et al., 2021). Hydrolysis, or the first step of the process, is characterized by the decomposition of complex and high molecular weight compounds (proteins, fats, and carbohydrates) into soluble molecules, such as amino acids, fatty acids, and short-chain sugars (CREMONEZ et al., 2021; SHOW et al., 2020; ZHANG et al., 2014). In the acidogenesis step, the low molecular weight substrates obtained from the hydrolysis phase are consumed by fermentative bacteria to form volatile organic acids (acetic, propionic, lactic, and formic acids, among others), alcohols, and gases such as carbon dioxide and molecular hydrogen (ZHANG; SHEN; NI, 2015).

In acetogenesis, the main methane precursors are formed, i.e., hydrogen and acetate. A small number of homo-acetogenic bacteria utilize CO_2/H_2 as substrates to form acetate (LI; CHEN; WU, 2019). In the final phase, methanogenesis, two groups of microorganisms are responsible for converting the intermediate compounds, so far produced, into biogas. The acetotrophic methanogens produce methane using acetate, while the hydrogenotrophic methanogens form methane using carbon dioxide and hydrogen (CREMONEZ et al., 2021).

In AD, biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2). Methane is considered the most important greenhouse gas (GHG) emitted during wastewater treatment. According to IPCC (2019) and EPA (2021), CO_2 has a Global Warming Potential (GWP) of 1 regardless of the time period used, considered as the reference gas. CO_2 remains in the climate system for a very long time: CO_2 emissions cause increases in atmospheric concentrations of CO_2 that will last thousands of years. Methane (CH_4) is estimated to have a GWP of 28–36 over 100 years. CH_4 emitted today lasts about a decade on average, much less time than CO_2. However, CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH_4 GWP also accounts for some indirect effects, such as the fact that CH_4 is a precursor to ozone, and ozone is itself a GHG (ABIOGÁS, 2021; TIAN et al., 2021; ZHANG et al., 2021b). However, methane can be used for energy recovery, causing the reduction of GHG emissions since it will be considered a clean and renewable energy source (AZIZ et al., 2019).

The search for renewable and clean energy is growing, increasing the concern with the emission of gases, reduction of water resources consumption, and adequate waste treatment/recovery (PEDROZA et al., 2021; SHEN; ZHU, 2016). In this regard, attention should be paid to the energy generation potential of the biogas/methane recovered in the AD of liquid and solid wastes and analyze the options this process can provide to the market, although some other fuels can be recovered (hydrogen) (LOBO; WANG; REN, 2017; LOVATO et al., 2015, 2021; LU et al., 2019) or the application of the carboxylic acid platform to produce organic acids of great industrial applications (SILVA et al., 2020).

Energy recovery, for instance, from biogas, is a universalization tool since it is an alternative to reduce operational expenses, namely those associated with electricity consumption. Biogas has several applications, the most common being the generation of electricity and thermal energy. Additionally, there is the possibility to be converted in biomethane, then achieving a fuel equivalent to natural gas (ABIOGÁS, 2021; CÓRDOVA et al., 2022; LOVATO et al., 2015, 2021; MACEDO; SEABRA; SILVA, 2008; NUNES FERRAZ JUNIOR et al., 2022; VOLSCHAN JUNIOR; ALMEIDA; CAMMAROTA, 2021).

Biogas represents a small share of the Brazilian electricity matrix, accounting for approximately 0.1 % of the total energy sources (MME, 2020; VOLSCHAN JUNIOR; ALMEIDA; CAMMAROTA, 2021). Brazil has 675 biogas plants distributed across most of its states. According to CIBiogás (2021), Brazil produced approximately 1.83 billion Nm^3 of biogas in 2020. With the operation of 37 new plants, an annual production of 2.2 billion Nm^3 of biogas per year was reached. Of these plants in operation, 78% are classified as small; they produce up to 1 mi Nm^3 and are mainly derived from livestock.

Among the substrates used for biogas production in Brazil, Urban Solid Waste (USW) and Wastewater Treatment Plants (WWTPs) represent 73% of all biogas produced, and 16% is from industries. Biogas produced from animal wastes (agricultural) represents 11% of biogas production. However, farming represents 79% of all substrates supplied to biogas plants. The main application of biogas plants is energy (electricity generation, thermal, mechanical and/or biomethane). The most representative application in the national scenario in 85% is electric energy, consuming 73% of the biogas generated in the plants. It is also pointed out an expansion in the chain of biogas production in the country, which is still in development (CIBIOGÁS, 2021).

According to the Brazilian Institute of Geography and Statistics (IBGE), there are 5,073.324 agricultural establishments, of which 3,526.330 units attested to have electric energy obtained from at least one modality (generated in the establishment, obtained by assignment, or bought from distributor) (FERREIRA et al., 2018; IBGE, 2017). Among the agricultural establishments, pig farming has several energy consumption related to its operation, such as mechanical ventilation, air conditioning systems (COSTANTINO et al., 2022; PIC, 2019), lighting, pumping water to supply drinking fountains, irrigating the pasture and/or plantations of the enterprise itself etc. (COSTANTINO et al., 2022; OLIVEIRA et al., 2021a). Pig farming is also facing quality energy problems, which can be evaluated using the indicators: DEC: Equivalent Duration of Interruption per Consumer Unit (in hours) and FEC: Equivalent frequency of interruption per consumer unit (in number of interruptions) (ANEEL, 2018; OLIVEIRA et al., 2021a). (COSTANTINO et al., 2022; OLIVEIRA et al., 2021a)

Brazil still has a great potential for energy recovery in the form of biogas, mainly using agricultural waste, because there are expansion areas. The total potential is 82.58 billion Nm^3 of methane per year, with only 2% of the total potential being utilized (1.83 billion Nm^3), and there is still a 98% expansion opportunity for biogas production. Unquestionably, there is still a great production potential to be explored. However, biogas has increasingly conquered its space, especially because it is a firm and non-intermittent renewable energy source that can significantly contribute to the country’s energy transition (CIBIOGÁS, 2021).

The concept of water-energy-food nexus was conceived to study and manage the global resource systems (e.g., water, energy, and food) comprehensively (RASUL, 2016; SMAJGL; WARD; PLUSCHKE, 2016; SONG et al., 2018; VALENCIA; ZHANG; CHANG, 2022; YILLIA, 2016; ZHANG et al., 2018), which is driven by rapid population increase, urbanization, and climate change (IRENA, 2015; VALENCIA; ZHANG; CHANG, 2022). The synergies and interactions among sectors in a nexus can contribute to sustainable goals that can address many resource links such as energy from waste, waste for food, water for energy, water for food etc., in a circular economy (VALENCIA; ZHANG; CHANG, 2022). All nexus approaches require a comprehensive understanding of the system analyzed to identify the resources used and their impacts on the nexus (SLORACH et al., 2020).

According to Song et al. (2018), in a paradigm shift towards the circular economy, SWW can no longer be viewed as the culprit of environmental pollution but rather a source of valuable resources, including clean water, renewable energy, and nutrients. The economic value of key resources in wastewater can help offset the SWW treatment cost (BURN, 2014). Energy can be extracted from the organic content in wastewater by anaerobic treatment to produce biogas, which is a renewable fuel. Nutrients in SWW can also be recovered to produce fertilizers for sustainable agriculture production, particularly given the finite availability of phosphorus from mining (KOPPELAAR; WEIKARD, 2013).

One alternative to improving the understanding of energy recovery from anaerobic systems and determining the energy potential of the by-product (biogas) is mathematical modeling. The models can be developed considering waste characteristics and the treatment technology, helping evaluate the system viability and decision-making process, justifying the investments, and enhancing the environmental, social, and economic benefits (ZHENG et al., 2015).

Some models are reported in the literature. However, they consider the characteristics of domestic wastewater, which are different from SWW (LOBATO et al., 2012; ROSA et al., 2016; ROSA et al., 2020). Therefore, it is necessary to develop a model that expresses the potential of SWW so that it can be used as a tool by pig farms in Brazil. However, when developing a model, which expresses the energy potential of a waste, one must consider the variations of waste characteristics that may depend on the way the pig farm operates, pig feeding, climate, and other factors, as well as the type of reactor and its operation. Developed models suitable for different scales of pig farms can provide the feasibility of the arrangement, making the system economically and energetically attractive.

Currently, high-rate anaerobic digesters receive great interest due to their high loading capacity and low sludge production. Among them, the upflow anaerobic sludge blanket (UASB) reactors have been most widely used (CHONG et al., 2012) in the treatment of domestic, agricultural, and industrial wastewater and are consolidated in some countries with a tropical climate, notably in Brazil. There are considerable WWTPs in Brazil that use the UASB technology and seek to recover biogas to generate electricity and thermal energy (ABIOGÁS, 2021).

This treatment alternative has a reduced area demand, reduced investment and operational costs, support for different scales, low energy requirements, and the ability to generate energy in the form of biogas/methane, giving greater energy independence

(ALCARAZ-IBARRA et al., 2020; KUNDU; SHARMA; SREEKRISHNAN, 2017; MAO et al., 2017). It also has high efficiency, simplicity of construction and operation, and low sludge production compared to aerobic methods due to the slow growth rate of the anaerobic microorganisms. The sludge is well stabilized for final disposal and has good dewatering characteristics. It can be preserved for long periods without significant reduction of activity, allowing its use as inoculum for the start-up of new reactors (CHONG et al., 2012).

Although widespread, UASB reactors have limitations that have not been completely solved (LIU; WEI; LENG, 2021; ROSA et al., 2018). Chernicharo et al. (2018) list five classes of problems associated with UASB reactor of interest for improvement, they are: I) Foam management (LOBATO et al., 2018); II) Sludge management (LOBATO et al., 2018); III) Corrosion and odorous emissions (BRANDT et al., 2018); IV) Biogas and fugitive methane emissions (POSSETTI et al., 2018) and V) Effluent quality (ALMEIDA et al., 2018). Numerous problems associated with UASB reactors are listed within each topic, despite their advantages and wide applications in wastewater treatment.

The most common upset of the AD process is the over-acidification/souring problem caused by the excess buildup of volatile fatty acids (VFAs) (ALAVI-BORAZJANI; CAPELA; TARELHO, 2020). This phenomenon usually leads to a drastic pH drop and breakdown of the reactor buffering capacity. Given that pH variations severely affect the microbial growth and metabolic pathways in AD, a pH decrease below the optimum levels via excessive VFAs concentration would possibly cause reduced biogas yield and ultimately financial losses (ALAVI-BORAZJANI; CAPELA; TARELHO, 2020; APPELS et al., 2011). Nevertheless, the acidification phenomenon in AD reactors not only inhibits the methanogenesis but also may lead to disruptions in the hydrolysis and acidogenesis steps (LI et al., 2009; SHEN; ZHU, 2016; XU et al., 2020), low process stability and the possible generation of biogas with reduced methane concentration.

In AD processes, ammonia is produced by degrading the nitrogenous matter in the feedstock, primarily in the form of proteins. Consequently, the operation of digesters treating high protein content substrates can be problematic as the ammonia released during the digestion of proteinaceous material can impose high ammonium concentrations (FUCHS et al., 2018; JIANG et al., 2019).

The anaerobic reactors' effluents usually require a post-treatment step to accomplish the environmental legislation and protect the receiving water bodies (HAN et al., 2021; VON SPERLING; CHERNICHARO, 2005). The removal of nutrients and pathogens is usually very low (CHONG et al., 2012; SEGHEZZO et al., 1998). However, some post-treatment options have a considerable consumption of energy that increases the treatment costs (VANOTTI et al., 2010).

Some approaches can be employed to enhance the organic matter removal and biogas production in SWW treatment under anaerobic conditions. Fortunately, recent advances in microaeration technology have shown general improvements in AD performance, stability, and biogas quality, thereby opening up a potential innovative solution in process control. Microaeration is the dosing of a small amount of air or oxygen into an anaerobic system (NGUYEN; KHANAL, 2018). Air or pure oxygen can be dosed either one time, intermittently (pulse-mode), or continuously at different stages of the AD process (pretreatment, during digestion, or post digestion) (GIROTTO et al., 2018). The microaerobic process/condition can be achieved by injecting air/oxygen into the inoculum tank, hydrolytic reactor of a two-staged reactor configuration, directly into the AD reactor, biogas or sludge recycling line, or into a digestate storage tank in order to accomplish different objectives (DOS SANTOS et al., 2021; GIROTTO et al., 2018).

Numerous advantages are discussed regarding direct microaeration in the AD, from enhancing hydrolysis to controlling VFA accumulation, which may contribute to increased methane production (KRAYZELOVA et al., 2014). Microaeration-based AD processes create a unique environment that overlaps between anaerobic and aerobic conditions by maintaining niches for anaerobes and micro-aerobes. Therefore, microaerobic condition integrating the aerobic VFAs oxidation by heterotrophs with anaerobic methanogenesis could be a promising strategy to facilitate energetic conversions of intermediates and maintain the overall stability of AD processes. To couple aerobic oxidation with anaerobic reduction reactions, an effective microaeration control strategy is needed to prevent the inhibition of obligate anaerobes (NGUYEN; KHANAL, 2018). The microaeration rate or intensity determines what effects microaeration has on AD, depending on the specific purpose.

Therefore, it is stated that AD is a potential process for energy recovery (ANTÔNIO; OLIVEIRA FILHO; SILVA, 2018; BAKRAOUI et al., 2020a) and there is an opportunity to study the biogas generated in systems that treat SWW under anaerobic and microaerobic conditions to understand its energy potential and study the approaches that can contribute to the processing of biogas (PARRA et al., 2019). This research studied the methane recovery capacity, involving the development of a mathematical model that expresses the recovery of energy and methane from SWW in a UASB reactor. It also studied the SWW treatment in an upflow microaerobic sludge blanket reactor (UMSB) to identify the advances of microaeration in process performance, stability, biogas quality, and energy production, compared to the UASB reactor.

Therefore, the framework of this research consists of:

Chapter 1 – General introduction.

Chapter 2 – Research question, hypothesis.

Chapter 3 – General objective and specific objectives.

Chapter 4 – Mathematical model for estimating methane generation potential and electric energy recovery in swine wastewater treated in UASB systems – This chapter aimed to develop a mathematical model to estimate the potential for methane and electrical energy recovery from SWW treated in UASB systems.

Chapter 5 – Bioenergy recovery of swine wastewater by an upflow microaerobic sludge blanket reactor (UMSB): methane recovery, potential, and energy balance – This chapter, different oxygen loads were first applied to investigate in-situ microaeration on the AD performance for methane recovery.

Chapter 6 – General conclusion.

Chapter 7 – References.

2 RESEARCH QUESTION AND HYPOTHESIS

2.1 Research question

Can a mathematical model express the potential for methane and electrical energy recovery from the treated SWW in UASB reactors?

Is piggery wastewater a potential substrate for biogas generation in UASB and UMSB reactors for electricity recovery?

Does a reactor under microaerobic conditions generate more energy than anaerobic conditions and remain energy self-sufficient?

2.2 Hypothesis

The present dissertation was based on the following working hypotheses:

It is possible to develop a mathematical model to estimate the potential production of methane and electric energy from the anaerobic digestion of SWW in a UASB reactor.

The microaerobic process enhances methane generation, especially due to hydrolysis improvement, resulting in higher energy recovery than the UASB reactor.

The UMSB reactor biogas can meet the system's electricity demand (such as the microaeration supply and wastewater pumping) and provide self-sufficiency.

3 GENERAL OBJECTIVE AND SPECIFIC OBJECTIVES

3.1 General objectives

To evaluate the utilization and potential of biogas production from swine wastewater (SWW) treatment in UASB and UMSB reactors as a renewable energy source.

3.2 Specific objectives

- To develop a model for estimating the energy potential of SWW treated in a UASB reactor;
- To evaluate the energetic viability of using microaeration in UMSB reactors treating SWW, with emphasis on the system self-sufficiency;
- To study the possibility of applying the biogas recovered from SWW treatment in UASB and UMSB reactors for energy generation.

4 MATHEMATICAL MODEL FOR ESTIMATING METHANE GENERATION POTENTIAL AND ELECTRIC ENERGY RECOVERY IN SWINE WASTEWATER TREATED IN UASB SYSTEMS

4.1 Introduction

Pork meat has been reported as the most widely consumed meat worldwide. In 2020, it represented 32% of the most consumed animal proteins, accounting for about $109 \cdot 10^6$ tons (CÂNDIDO et al., 2022; FAO, 2020; SPORCHIA; KEBREAB; CARO, 2021). The Confined Animal Feeding Operations (CAFOs) model has been applied to supply these increasing demands for animal protein, resulting in high swine wastewater (SWW) volume even for small geographical areas (CÂNDIDO et al., 2022; LIU et al., 2020b).

Owing to the high chemical oxygen demand (COD), nitrogen and phosphorus compounds (HAI et al., 2015a; LIU et al., 2020b; MCGLONE, 2013), antibiotics, and hormones (CHENG et al., 2018b; ZHENG et al., 2018), direct SWW discharge causes serious environmental problems and has high pollution potential, including oxygen depletion in receiving water bodies, eutrophication, global warming and toxicity-related impacts (BROOKS; ADELI; MCLAUGHLIN, 2014; MOHANA; ACHARYA; MADAMWAR, 2009; MONTES et al., 2019; ZANG et al., 2015). Therefore, efficient, economic, and environmentally friendly techniques must be developed to deal with the large amounts of SWW generated globally (LIU et al., 2020b). In this regard, some potentially feasible techniques, including composting (ARIAS et al., 2017) and anaerobic digestion (AD) (TAO et al., 2020), have been developed.

The AD can represent an important part of the biomass utilization involved in renewable energy systems (RES) (DENG et al., 2017; DING et al., 2017; KOR-BICAKCI; UBAY-COKGOR; ESKICIOGLU, 2019; LIU et al., 2020a; MA et al., 2019; MOUSTAKAS; PARMAXIDOU; VAKALIS, 2020; SUHARTINI et al., 2020; XIAO et al., 2019), bringing environmental, economic, and energy benefits (ÇELEBI; AKSOY; SANIN, 2021; JIANG et al., 2020; MEI et al., 2016; MENARDO; BALSARI, 2012; MORALES-POLO et al., 2020). In particular, the AD converts the complex organic matter present in the waste into biogas, which predominantly contains methane in addition to CO_2, H_2S, and H_2 as gaseous products, along with a COD-rich liquid digestate (NAGARAJAN et al., 2019). In dealing with agricultural wastes, these systems reduce waste loads, generate bio-energy and produce nutrient-rich fertilizers (in digester effluents). Other benefits include reducing odors, pathogen loads, and GHG emissions stemming from agricultural processes (O'CONNOR et al., 2021).

An appropriate option for the SWW anaerobic treatment is the upflow anaerobic sludge blanket reactor (UASB), due to its low investment and operational costs, low footprint, application capacity for different scales, low energy demand, and the capacity to yield energy through the produced biogas (ALCARAZ-IBARRA et al., 2020; KUNDU; SHARMA; SREEKRISHNAN, 2017; MAO et al., 2017).

However, very few studies address the energy efficiency of SWW AD processes. Energetic self-sustainability is one of the main aspects to be developed in future agro-industrial waste treatment systems. Therefore, studies must consider the by-products energy potential and the full wastewater operation energy demand (ROSA; LOBATO; CHERNICHARO, 2020; SANTOS; BARROS; TIAGO FILHO, 2016). Due to the high methane content, the biogas presents a significant caloric value that allows an effective energy recovery (ROSA; LOBATO; CHERNICHARO, 2020). One major advantage is that the energy produced in a wastewater treatment plant can be fully utilized on-site without the interference of a distribution network (TSAGARAKIS, 2007).

In this context, mathematical models can be a useful tool to estimate and assess the energy potential of UASB reactors, helping in the decision-making process (PANEPINTO et al., 2016; ROSA; LOBATO; CHERNICHARO, 2020). However, most projects and investigations conducted so far are applied to industrial wastewaters and sewage (GU et al., 2017). As a result, AD plants for SWW were hardly ever designed with energy efficiency in mind (PANEPINTO et al., 2016; ROJAS; ZHELEV, 2012; VERA et al., 2015).

The development of mathematical models to estimate biogas production and energy potential in UASB reactors treating SWW is still incipient (ROSA; LOBATO; CHERNICHARO, 2020), which was the driving force for the present research. Therefore, a model that uses simple operational parameters, such as the number of pigs and the flows of wastewater produced, is proposed, also allowing the estimation of energy recovery potential and assisting in the decision-making process.

4.2 Materials and methods

4.2.1 Substrate

The raw SWW was collected from the pig bays cleaning. Throughout the experiment, the pigs were in many development stages and were fed with corn and soybean-based food. The raw SWW was obtained from the Zootechny Department (DZO) of the Federal University of Ceará (UFC) in Fortaleza, Ceará, Brazil. It was subjected to a preliminary treatment in a 2 mm square mesh sieve for solid separation, simulating the conditions found in full-scale treatment plants (OLIVEIRA et al., 2021b). The SWW was placed in an equalization tank (ET) with mechanical agitation to prevent solids sedimentation, kept under refrigeration at 4 ºC to avoid natural biodegradation of organic matter, which impacts the reactor loading rates.

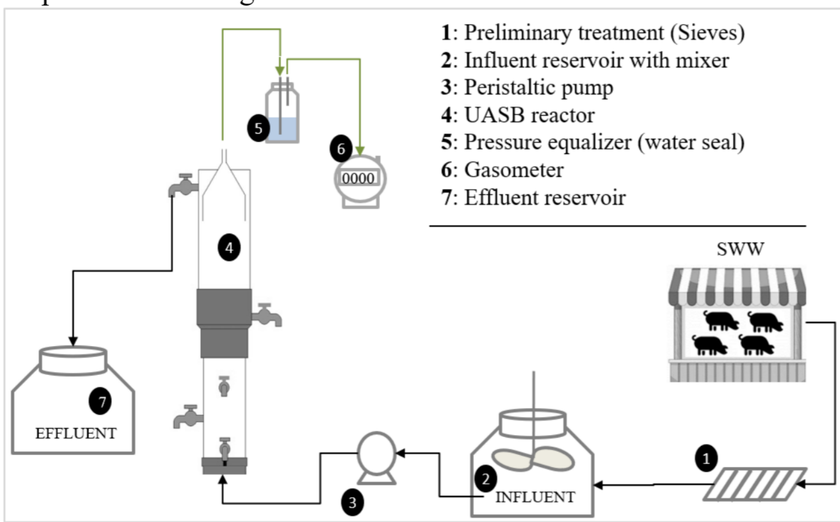
4.2.2 UASB reactor

A lab-scale UASB reactor made of PVC was used with a working volume of 3.25 L. The reactor was fed with a diaphragm pump (ColeParmer MasterFlex L/S 7522-30, USA) to keep the flow rate constant (ALCARAZ-IBARRA et al., 2020). Biogas production was quantified twice a week by using a gasometer (Ritter MolliGascounter) (DANIYAN et al., 2019; PEREIRA et al., 2019; VENDRUSCOLO et al., 2020). The UASB reactor was operated at 28 ± 6 ºC and seeded with sludge (1.6 L) from a full-scale UASB reactor used in a sewage treatment plant in Fortaleza, Brazil. The content of Total Solids (TS), Total Volatile Solids (TVS), and Total Fixed Solids (TFS) were 44.3 ± 2.5, 29.5 ± 1.4, and 14.7 ± 1.1 g L^{-1}, respectively.

4.2.3 Experimental stages

Figure 4.1 shows the experimental set-up schematic. UASB reactor started up as previously described (OLIVEIRA et al., 2021c) with an SWW average COD of 5 g L^{-1} and flow rate (Q) of 4.5 mL min^{-1}, resulting in a biological organic rate (BOR) of 0.7 kgCOD $kgVS^{-1}d^{-1}$, organic loading rate (OLR) of 10.4 ± 0.9 kgCOD m^{-3} d^{-1}, volumetric hydraulic load (VHL) of 2 m^3 $m^{-3}d^{-1}$, and hydraulic retention time (HRT) of 12 h. The influent COD, Q, OLR, VHL, and HRT values were kept constant during the 285 days of the experiment. Afterward, the flow rate was increased progressively over the operating runs, resulting in increased OLR and reduced HRT. The experimental conditions are summarized in Table 4.1.

Figure 4.1 – Experimental configuration schematic.



Note: SWW – Swine Wastewater.

Table 4.1 – Operational parameters used during the four experimental runs.

Parameter	Stages			
	I	II	III	IV
Total period (d)	225	42	38	38
Flow rate (mL min^{-1})	4.5	5.4	6.8	9.0
HRT (h)	12	10	8	6
OLR_{appl} (kgCOD $m^{-3}d^{-1}$)	10.3±0.5	12.2±0.3	14.8±0.4	20.1±0.8

4.2.4 Chemical and chromatographic analyzes

Chemical Oxygen Demand (COD) (total, particulate and soluble), Biochemical Oxygen Demand ($BOD_5^{20°C}$) (total, particulate and soluble), Total Solids (TS), Fixed Solids (FS), Total Suspended Solids (TSS), Volatile Solids (VS), Volatile Suspended Solids (VSS), Total Kjeldahl Nitrogen (TKN), $N\text{-}NH_4^+$, Total Phosphorus (TP), PO_4^{3-}, SO_4^{2-} and S^{2-}, pH were determined by APHA (APHA, 2012). Total Alkalinity (TA) and Volatile Fatty Acids (VFA) were determined using the Kapp titrimetric method (BUCHAUER; INNSBRUCK, 1998).

In addition, the quantification of CH_4 and CO_2 in the biogas was determined by gas chromatography with ionization detection by dielectric barrier discharge (GC BID-2010 Plus, Shimadzu Corporation, Japan), equipped with a GS-GASPRO column (60m×0.32 mm) (Agilent Technologies Inc., USA). Helium gas was used as the carrier gas (White Martins

LTDA, Brazil) at a flow rate of 2 mL min^{-1}, with a run time of 9 min. The oven, injector, and detector temperatures were 50ºC, 100ºC, and 250ºC, respectively.

4.2.5 Calculation of biogas potential produced from SWW

A simulation of methane production was performed by the COD removed in the anaerobic digestion process using a UASB type reactor and employing three methodologies for comparison (IPCC, 2009; LOBATO; CHERNICHARO; SOUZA, 2012; METCALF & EDDY, 2014). Methane production was estimated from the flow monitoring report, COD (influent and effluent), and normal temperature and pressure conditions. It is possible to estimate the biogas production from the final methane production and biogas composition (NADALETI, 2019). Then the chemical, electrical, and thermal energy production by methane recovery in each situation were calculated (IPCC, 2009; LOBATO; CHERNICHARO; SOUZA, 2012; METCALF & EDDY, 2014). The equations used can be found in Table 4.2.

The three methodologies used for biogas and methane productions were compared with the measured (NADALETI, 2019)data. The methodology proposed by Lobato et al. (2012) showed to be the most appropriate to model the process and therefore was selected. The Metcalf & Eddy (2014) methodology overestimated the productions.

4.2.6 Energy potential of biogas

The calculations required to generate electricity from biogas (simulated and experimentally measured) are also presented in Table 4.2. For this, a UASB reactor was operated treating SWW in which the biogas and its methane concentration were measured. Subsequently, the reactor data was used for methane estimation.

The combined heat and power (CHP) machine efficiency has been assumed to be 40% for electrical conversion (BEDOIĆ et al., 2021; CHOWDHURY, 2021; FU et al., 2018; KISELEV et al., 2019; MAVRIDIS; VOUDRIAS, 2021; NADALETI et al., 2020; PANEPINTO et al., 2016; ZHOU et al., 2015), being the most adopted value among the literature. However, it is higher than that of the generators found in Brazil. The internal combustion engine and generator group have the highest need for shutdowns due to a higher biogas content impurity. Thus, a capacity factor (CF) of 70% was used (RIBEIRO et al., 2016; SANTOS; BARROS; TIAGO FILHO, 2016). This value is less than the normally used for thermoelectric plants moved by gas, which are around 90% according to CETESB (Environmental Agency of São Paulo State) (RIBEIRO et al., 2016; THE ENVIRONMENTAL COMPANY OF SAO PAULO – CETESB, 2002).

According to EIA (2015), the technologies used to generate electricity are similar across regions of the world, but the pattern of use for those generating technologies can be significantly different. Analysis of electric generating plant utilization (measured by annual capacity factors, or the ratio of generation to capacity) over a five-year period shows a wide variability among fuel types and across world regions. Capacity factors can also be affected by partial-year generation effects, especially for technologies with recently installed capacity. By convention, the capacity factor numerator is based on actual generation, while the denominator is based on what that generator could have provided, assuming continuous operation for a full year (EIA, 2015; MUHAMMAD; CHANDRA, 2022; ZAHEDI; AHMADI; DASHTI, 2021)

The following variables were considered for the calculations: LCV is the methane lower calorific value (7,461.95 kcal kg^{-1}) for 70-81% gas content. They resulted in an available LCV of 9.98 kWh $Nm^{-3}{}_{CH4}$ for methane with a specific weight (SW_{CH4}) of 1.15 kg Nm^{-3} (FREITAS et al., 2019; MAMBELI BARROS; TIAGO FILHO; DA SILVA, 2014; ROSA et al., 2016; ROSA; LOBATO; CHERNICHARO, 2020; SANTOS; BARROS; TIAGO FILHO, 2016).

Table 4.2 – Equations for calculating the mass balance of COD in different methodologies and energy recovery potential.

(continuation)

Portion	Equation	Note
	(LOBATO; CHERNICHARO; SOUZA, 2012; VON SPERLING; CHERNICHARO, 2005)	
COD_{rem}	$COD_{rem} = COD_{inf} - COD_{eff}$	COD_{rem} = COD removed (kgCOD d^{-1}) COD_{inf} = COD influent (kgCOD d^{-1})* COD_{eff} = COD effluent (kgCOD d^{-1})*
Estimated COD mass used by sludge	$COD_{Sludge} = COD_{rem} * Y_{COD}$ $Y_{COD} = Y * K_{TVS-COD}$	COD_{Sludge} = Mass of COD converted to sludge ($kgCOD_{Sludge}$ d^{-1}) Y_{COD} = Sludge yield, such as COD ($kgCOD_{Sludge}$ $KgCOD_{rem}^{-1}$)* Y = Sludge yield, such as TVS (kgTVS $KgCOD_{rem}^{-1}$)* $Y_{TVS-COD}$ = Conversion factor (1kgTVS=1.42$kgCOD_{Sludge}$)
Estimated COD converted to methane	$COD_{CH4} = COD_{rem} - COD_{Sludge} - COD_{SO4}$ $F_{CH4} = \frac{(COD_{CH4} * R * (273 + T))}{(P * K_{COD} * 1000)}$	COD_{CH4} = Mass of COD converted to methane ($kgCOD_{CH4}$ d^{-1}) COD_{SO4} = COD used for sulfate reduction ($kgCOD_{SO4}$ d^{-1}) F_{CH4} = Methane flow (m^3 d^{-1}) R = Gas constant (0.08206 atm.L $(mol.K)^{-1}$) T = Reactor operating temperature (°C) P = Atmospheric pressure (1 atm) K_{COD} = COD of one mole of CH_4 (0.064 kgCOD $kgCH_4^{-1}$)
	(METCALF & EDDY, 2014)	
Mass balance at steady state	$Accumulation = COD_{inf} - COD_{eff} - COD_{vss-sludge} - COD_{CH4}$	
Volume occupied by 1 mole of methane	$V_{CH4} = \frac{nR(273 + T)}{P}$	n = Number of moles V_{CH4} = Volume of methane (m^3 d^{-1})
Methane equivalent to COD removed	$CH_{4\,equivalent} = \frac{V_{CH4}}{O_{CH4}}$	$CH_{4equivalent}$ = Methane equivalent of converted COD (m^3CH_4 $kgCOD^{-1}$) O_{CH4} = Amount of oxygen required to oxidize 1 mole of methane, equal to 64 gCOD mol^{-1}
Methane production	$F_{CH4} = COD_{CH4} * CH_{4\,equivalent}$	
	(IPCC, 2009)	
Amount of methane emitted (mass flow)	$m_{CH4} = COD_{rem} * B_o * MCF * CFU$	m_{CH4} = Methane flow ($kgCH_4$ d^{-1}) B_O = Maximum methane production capacity (0.25 $kgCH_4$ $KgCOD_{rem}^{-1}$) CFU = (correction factor for uncertainty) Model correction factor due to uncertainties (0.89) MCF = (methane conversion factor) Correction factor according to the treatment suffered by the effluent (for UASB 0.8 reactor)

Table 4.2 – Equations for calculating the mass balance of COD in different methodologies and energy recovery potential.

(conclusion)

Portion	Equation	Note
Standardized methane production	$Fn_{CH4} = m_{CH4} * \gamma_{CH4}$	Fn_{CH4} = Normalized methane flow ($Nm^3 d^{-1}$) γ = Normalized specific weight of methane (1.1518 kg Nm^{-3})
Recovered Electrical Power		
Estimation of available energy potential	$LCV_A = SW_{CH4} * LCV_{CH4} * K$ $P_{ea} = F_{N-CH4-real} * LCV_A * ef$	LCV_A = Lower calorific value available (9.98 kWh Nm^{-3}) - (70-81% of CH_4) SW_{CH4} = Specific weight of CH_4 (kg Nm^{-3}) LCV_{CH4} = Lower calorific value of CH_4 (kcal kg^{-1}) K = 4.19 kWh.3600^{-1} (conversion of units kcal-Joules-kWh) $F_{N-CH4-real}$ = Normalized available flow ($Nm^3 d^{-1}$) P_{ea} = Available energy potential (kWh d^{-1}) Ef = Conversion efficiency of the thermal machine

Source: Adapted from (IPCC, 2009; LOBATO; CHERNICHARO; SOUZA, 2012; METCALF & EDDY, 2014; ROSA; LOBATO; CHERNICHARO, 2020; VON SPERLING; CHERNICHARO, 2005)

Note: *Values extracted from the experiment. All methane flows were normalized to the pressure and temperature conditions of the experiment.

4.2.7 The mathematical model

A mathematical model to estimate the biogas energy potential was developed and structured in an electronic spreadsheet using Microsoft Excel 2019 and CurverExpert 1.4 under the premise of simplicity and due to the reduced number of input data. Conceptually, the model considered the SWW COD conversion routes and methane flow in the UASB reactor. The model developed was adapted from the models of biogas, methane, and energy recovery potential in UASB reactors treating domestic wastewater developed by Lobato et al. (2012)

To accurately estimate the energy potential of biogas, 500 simulations were performed for each scenario using the Monte Carlo method (uniform distribution), which is based on a high number of simulations. In each model execution, a different group of input values is selected randomly according to the uniform distribution within pre-established ranges (LOBATO; CHERNICHARO; SOUZA, 2012). According to Rosa et al. (2020), all outcomes are equally likely, i.e., each variable has the same probability that it would be the outcome. It all begins with the first simulation in which the input data are used to produce the output data until the last model run is performed.

The input data for calculating the energy potential of biogas were: Efficiency of COD removal (E_{COD}), operational temperature in the reactor (T), percentage of CH_4 in the biogas (C_{CH4}), per pig of COD contribution (0.13-0.10 $KgCOD^{T}swine^{-1}\ d^{-1}$), contribution pig population (NS – 1 to 10,000 units), per pig of sewage contribution (CS - 47.1 L $animal^{-1}\ d^{-1}$). Furthermore, this mathematical model was structured under different operational conditions. Once the input data were defined, based on these portions of COD removal from the system (experiment), the total COD converted into CH_4, and consequent volumetric production is calculated. To calculate the volume of CH_4 actually available for energy use, the model considers the losses of CH_4. Finally, deducting these losses, the potentially available energy is calculated (LOBATO; CHERNICHARO; SOUZA, 2012).

Following the simulations, model validation was based on measured biogas production and composition in small, medium, and large-scale UASB reactors, for the three pig farm size scenarios: 250, 500 and 1,000 pigs. These scales are indicated by Ministério da Agricultura, Pecuária e Abastecimento (2016) as the limit for classifying a swine farm; farms with values above 1,000 pigs are already considered large. For this purpose, COD contribution (8.4±3.7 $KgCOD^{T}\ Kg_{swine}^{-1}$) (based on a 90 kg pig) and a efficiency of COD removal (70%)

(LOBATO; CHERNICHARO; SOUZA, 2012; LOPES et al., 2020; ROSA; LOBATO; CHERNICHARO, 2020), were adopted.

4.2.8 Data analysis

Statistical significance was tested by Analysis of Variance (ANOVA), complemented with mean value comparison using Tukey's HSD tests with a threshold *p*-value of 0.05 declared significant (MONTES et al., 2019). If $p \leq 0.05$, the null hypothesis is rejected, i.e., the data groups are considered statistically different (LI et al., 2021; LOPES et al., 2018; MORALES-POLO et al., 2020; QIAN et al., 2019; ZHANG et al., 2021a). Statistical significance was analyzed for data related to the relationship and ratios of OLR and both methane production and methane content in the biogas and others throughout the experiment.

4.3 Results and discussion

4.3.1 Experimental reactor performance

4.3.1.1 Organic load removal efficiency

UASB reactor was continuously operated for 407 days, including four experimental runs at different OLR (Figure 4.3) UASB reactor started at constant OLR (10.1 kgCOD $m^{-3}d^{-1}$) for 65 days. Table 4.3 shows the total and steady-state periods of each experimental run.

Table 4.3 – Reactor performance under different experimental conditions: biogas yield and composition, OLR composition, and yield of the electric and thermal power generated.

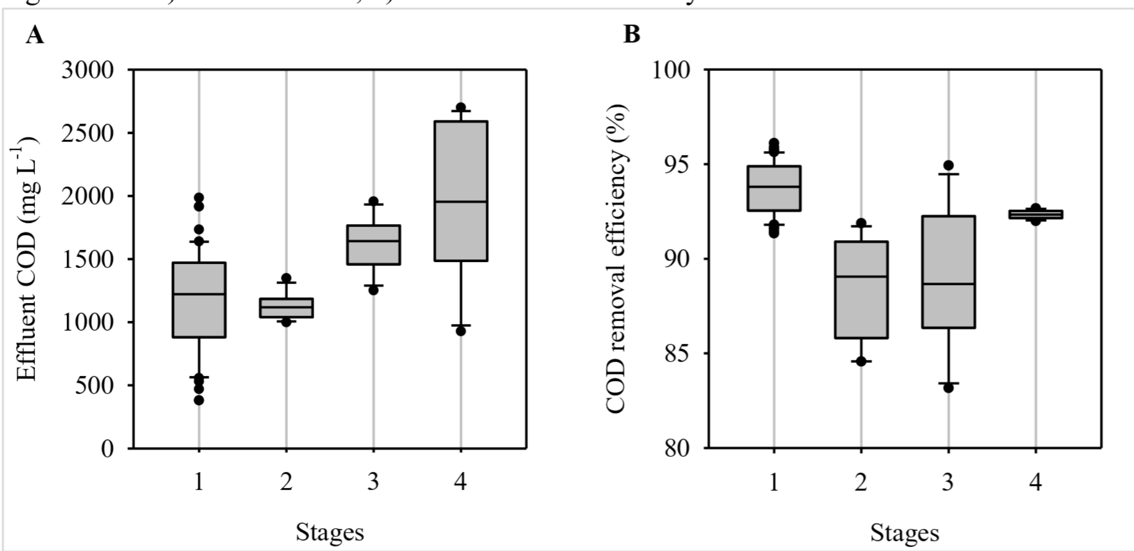
Period		**Start-up**	**I**	**II**	**III**	**IV**
HRT (h)		12	12	10	8	6
Days of operation		64	225	42	38	38
OLR						
Total applied	kgCOD m^{-3} d^{-1}	10.1±0.5	10.3±0.5	12.2±0.3	14.8±0.4	20.1±0.8
Total removed	kgCOD m^{-3} d^{-1}	9.3±0.5	9.6±0.5	10.9±0.6	13.2±0.7	18.5±0.9
COD^T influent	mgO_2 L^{-1}	5,069±238	5,124±225	5,067±118	4,939±141	5,018±201
COD^T removed	%	91.2±1.9	93.8±2.1	89.2±3.4	89.1±3.6	92.1±2.3
Biogas	NL d^{-1}	0.66±0.96	5.18±2.59	5.03±0.78	7.82±2.20	10.22±2.71
Biogas content						
CH_4	%	40.1±30.4	77.3±7.1	74.8±5.0	81.0±3.1	82.7±4.1
CO_2	%	7.2±8.2	21.7±5.1	22.2±8.9	18.4±2.6	21.3±5.1
Methane yield	NL $kgCOD^T_{rem}{}^{-1}$	26.1±46.2	195.9±98.6	169.8±28.8	247.0±68.5	260.9±63.2
Electric energy yield	kWh $kgCOD^T_{rem}{}^{-1}$	-	2.1±1.2	1.6±0.4	2.5±0.7	2.6±0.6
	kWh $m_{sww}{}^{-3}$	-	7.7±4.0	6.0±1.0	8.1±2.2	8.2±2.4
Thermal energy yield	MJ $kgCOD^T_{rem}{}^{-1}$	-	7.4±4.2	5.8±1.3	8.9±2.5	9.4±2.3
	MJ $m_{sww}{}^{-3}$	-	27.8±14.4	21.6±3.6	29.1±7.9	29.4±8.6

Note: COD^T – Total Chemical Oxygen Demand.

In Figure 4.2b, the reactor showed a good COD removal capacity, reaching the maximum of 93.8 ± 2.1 % when the HRT was 12 h. However, the highest methane production rates were obtained at HRTs of 6 and 8 h (ALCARAZ-IBARRA et al., 2020). Furthermore, in the different experiment runs, the lowest efficiency achieved was 83%, assuming that changes in HRT did not affect COD removal. In this period, the COD removals were not apparent among the four HRT, and the COD removal of each system presented an upward trend at the beginning and then kept steady (DONG et al., 2021).

Conversely, Wang et al. (2013) reported that COD removal efficiency was reduced by changing the HRT from 15 h to 10 h, although a high methane rate was still found. However, the efficiencies achieved in the current study are within the ranges reported in the literature, close to 90% (LAY et al., 2019; MONTES et al., 2019; WANG et al., 2013). These results follow the methane yielded by the reactor, showing high-efficiency performance (MONTES et al., 2019).

Figure 4.2 – a) Effluent COD; b) COD removal efficiency.



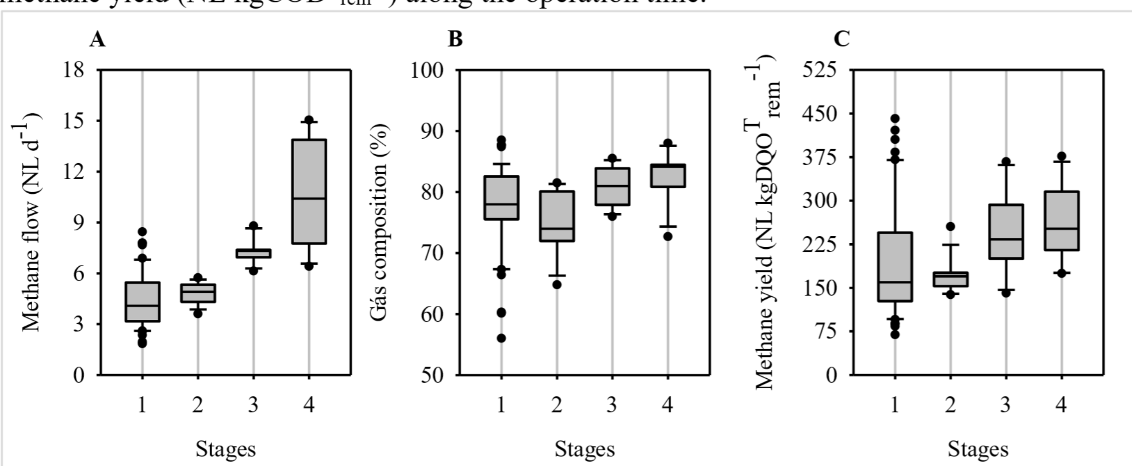
In addition, the variation in pH value in the UASB reactor was also monitored. A significant difference was found in the influent pH among the stages (*p*=4E-08), ranging from 5.3 to 8.7. However, no significant difference was found (*p*=0.136) for the effluent pH, with a minimum and maximum of 7.2 and 8.6, respectively. At 8h HRT, a low decrease in pH values was observed in the reactor effluent, 8.2 to 7.6. Regardless of the influent pH, the system showed a good buffering capacity, resulting in a low methane production variation. Some literature recommends a pH range between 6.5 to 7.5 depending on substrate and digestion technique (CHEN; CHENG; CREAMER, 2008; LEMMER et al., 2017), while Cheng et al. (2018a, 2018b) suggest a value between 7.4 to 7.0 for SWW treatment. Thus, the pH values obtained were in the recommended ranges.

4.3.1.2 Biogas and methane production

The average methane production at each experiment stage and methane content in the biogas can be observed in Figure 4.3a and 4.3b, respectively. Furthermore, Table 4.3 shows the most relevant descriptive statistics. As previously observed (MONTES et al., 2019), each time the feed conditions were modified, the daily methane yield increased due to the higher organic loading rate applied. The reactor produced a maximum daily volume of 15 LCH_4 at day 506 when the system was fed with 21.8 kgCOD $m^{-3}d^{-1}$. Montes et al. (2019) suggested a good relationship between the OLR and the methane yield during the operational periods. However, the present research did not identify such a correlation.

The reactor produced a methane flow of 1.8 to 15.0 NL d^{-1}, and the highest flow was identified in stage IV (Figure 4.3a), where the highest OLR was applied. This observation agrees with the literature, in which increasing OLR up to a certain value generates higher biogas/methane production without influencing the methane concentration (ALCARAZ-IBARRA et al., 2020; ZHAO et al., 2017). Our data showed a stable operation with OLR up to 20.1 kgCOD m^{-3} d^{-1}, allowing a stable mean methane yield of 260.9 LCH_4 $kgCOD^{T}_{rem}{}^{-1}$ (Figure 4.3c) (MONTES et al., 2019).

Figure 4.3 – Performance of the UASB reactor in terms of: a) Daily methane production along the operation time; b) Methane content in biogas at different organic loading rates; c) Specific methane yield (NL $kgCOD^{T}_{rem}{}^{-1}$) along the operation time.



The reactor produced a methane-rich biogas from the 47th day of operation onwards. At the lowest OLR applied, the biogas quality was high (77.3% CH_4). The methane content in the biogas increased linearly for the operation periods I to IV (KAMYAB; ZILOUEI; RAHMANIAN, 2019; MONTES et al., 2019). Furthermore, methane content in the biogas increased from 74.8% at an OLR of 12.2 kgCOD m^{-3} d^{-1} to 81.1% at 14.8 kgCOD m^{-3} d^{-1}.

The methane yield ranged from 68.9 to 441.0 NL $kgCOD^{T}_{rem}{}^{-1}$. There was no significant difference between the stages: methane (p=0.287) and biogas (p=0.549). The results found in this research are within the methane yield range reported in the literature for SWW and other wastewaters, as shown in Table 4.4, even though there are differences among the wastewater compositions and the operating conditions applied.

Table 4.4 – Comparison of overall performance in the system used in this study to some other studies.

Source	Reactor	Temperature (ºC)	HRT (h)	OLR^{T}_{inf} $kgCOD^{T}$ $m^{-3}d^{-1}$	Yield (NL_{CH4} $kgCOD^{T}{}_{rem}{}^{-1}$)	Duration Days	Reference
SWW	UASB	36.0	79.2	32	186	54	Montes et al. (2019)
SWW	UASB	36.0	79.2		283	54	
SWW	UASB	37.0	24	1.2	270	19	Xu et al. (2019)
			16	3.5	188	11	
			16	5.2	185	16	
			16	6.9	131	38	
			16	8.6	126	31	
			16	10.3	16	8	
SVC	UASB	22.0	20-800	0.5-32.4	299	700	Del Nery et al. (2018)
TV	UASB	35.0	168	1.3	180	-	Estrada-Arriaga et al. (2021)
			72	3.2	240		
			24	9.7	300		
DCW	UASB	35.0	40	0.81	133	-	Mainardis and Goi (2019)
CW			6	12.1	103		
L-OFMSW			6	3.0	121		
BMIW	AnMBR	37.0	12.6±8.7	3.7±2.2	380	271	Turker and Dereli (2021)
			14.8±9.2	2.6±1.0	380	289	
SWW	UASB	28.0	12	10.3	196	225	This study-observed
			10	12.2	170	42	
			8	14.8	247	38	
			6	20.1	261	38	

Note: SWW–Swine Wastewater; SCV–Sugar Cane Vinasse; TV–Tequila Vinasses; AnMBR–Anaerobic Membrane Bioreactors; BMIW–Beet Molasses Based Industrial Wastewater; DCW–Diluted cheese whey; CW–Condensate water; L-OFMSW–Organic Fraction of Municipal Solid Waste Leachate.

The experiment methane yields were lower only from UASB reactors treating SWW with an HRT of 24h (XU et al., 2019), SVC (Sugar Cane Vinasse) with an HRT of 20h (DEL NERY et al., 2018), TV (Tequila Vinasses) with an HRT of 24h (ESTRADA-ARRIAGA et al., 2021) and to an AnMBR treating BMIW (Beet Molasses Based Industrial Wastewater) with HRT of 12 and 14h (TURKER; DERELI, 2021), as shown in Table 4.4. The values achieved in stages III and IV were close to the maximums achieved in the literature. These studies, which obtained higher methane production values than in this investigation, operated the reactor under a reduced OLR. Perhaps this increase in methane production can be attributed to this reduced OLR, which did not occur in this investigation, or perhaps concerning the wastewater characteristics or adopted anaerobic technology. Among the experiment stages, stage II presented the least variability in its value (Figure 4.2b). Even though it was below the values identified in stages III and IV, no significant difference was found (p=0.6).

4.3.2 SWW energy potential assessment

The SWW energetic potential was based on the experimentally obtained methane yield values. Furthermore, the biogas conversion in generators and similar systems (e.g., reciprocating engines, boilers, and turbines) was not considered, i.e., the losses inherent to such systems were not included. Furthermore, the biogas conversion in generators and similar systems was not considered, i.e., the losses inherent to such systems were not included (FUESS et al., 2017). To check whether energy self-sufficiency can be achieved or the biogas recovered from this system can be a viable alternative to fossil fuels, the UASB reactor energy potential assessment was assessed. Energy production from the methane yield and heat recovery were identified as key factors affecting the energy balance (CHENG et al., 2021). The calculations were performed with the equations presented in Table 4.2, and the results of its potential are shown in Table 4.3. Thus, an energy analysis was performed to evaluate power generation feasibility for full-scale applications (KOR-BICAKCI; UBAY-COKGOR; ESKICIOGLU, 2019).

The overall SWW energy potential was 27.2 MJ m^{-3}_{sww} (7.6 kWh m^{-3}_{sww}), with the highest value obtained in stages III (29.1 MJ m^{-3}_{sww}) and IV (29.4 MJ m^{-3}_{sww}). The obtained values of the SWW energy potential were higher than those reported for the wastewater from the chocolate processing industry (13.6 ± 3.7 MJ m^{-3}) (ALCARAZ-IBARRA et al., 2020) and wastewater from recycled pulp and paper (6.3 MJ $kgCOD^{T}{}_{rem}{}^{-1}$) (BAKRAOUI et al., 2020b). When domestic wastewater is considered for electrical energy recovery, the following values are obtained: 2 MJ m^{-3} (ROSA et al., 2018), 1.6 to 3.5 MJ m^{-3} (ROSA; LOBATO; CHERNICHARO, 2020), and 1.5 to 2.9 MJ m^{-3} (LOBATO; CHERNICHARO; SOUZA, 2012), all of which are lower compared to the SWW potential.

The overall efficiency of a typical CHP engine is around 70 to 85%. In this regard, typical effective electric efficiencies for combustion turbine-based CHP systems range from 35% to 45%, whereas typical thermal efficiencies range from 40% to 50% (ALCARAZ-IBARRA et al., 2020; CHOWDHURY, 2021; CURLETTI et al., 2015; DUMONT et al., 2018; GIAROLA et al., 2018; KOR-BICAKCI; UBAY-COKGOR; ESKICIOGLU, 2019). The CHP system efficiency has been assumed to be 40% for electrical conversion and 45% for heat conversion (CHOWDHURY, 2021; KISELEV et al., 2019). The referred values are based on the values of engines used in the European Union (EU). Those applied in Brazil have reduced efficiencies due to the quality levels of biogas and technology.

A pig farm with about 2,500 swine has an average daily wastewater production of 3,532.5 m^3 per month. Considering the energetic potential obtained in this research, the power yield could reach up to about 29 kWh or 104 GJ per month (348 MWh per year), which represents a potential power source (ALCARAZ-IBARRA et al., 2020). Considering an average biogas-to-electricity conversion rate of 40%, the power yield of the produced biogas by the UASB reactor could reach up to 139 MWh yr^{-1}. The annual average electricity consumption per household is between 1,500 and 2,565 kWh (ALCARAZ-IBARRA et al., 2020; DAVIS; MARTINEZ; TABOADA, 2020; LUCERO-ÁLVAREZ; MARTÍN-DOMÍNGUEZ, 2019). Therefore, the power yield from biogas obtained in the anaerobic digestion of SWW in the evaluated scenario would be enough to satisfy the electricity requirements of 93 to 54 households. Considering the technologies and standards in Brazil, it was adopted 30% for electrical conversion and 35% for thermal energy conversion, which in the evaluated scenario would be enough to satisfy the electricity requirements of 70 to 41 households.

4.3.3 Simulation of the SWW energy potential

Most models that estimate methane production in UASB reactors were developed for domestic wastewater treatment. Thus, an attempt was made to develop a model that would consider certain peculiarities associated with SWW (VERONEZE et al., 2019; YENIGÜN; DEMIREL, 2013), such as high COD values and TSS content, among others (DONG et al., 2021; HUANG; LI; GU, 2010), also taking into account the actual share of methane recovered higher for SWW as per the literature (MONTES et al., 2019; SCHIEVANO; D'IMPORZANO; ADANI, 2009; XU et al., 2019).

Thus, the system capacity to produce methane was identified and used to develop the model. First, the number of swine was delimited, which defined the model application limit. Subsequently, this amount was uniformly distributed using the Monte Carlo method, and the wastewater flow was determined (ROSA et al., 2018; ROSA; LOBATO; CHERNICHARO, 2020). The methodology proposed by Lobato et al. (2012) and Rosa et al. (2020) (Table 4.2) was used to estimate the methane flow in each simulation, applying secondary data. Regressions were carried out to find models that could express and estimate the methane production of different size pig farms.

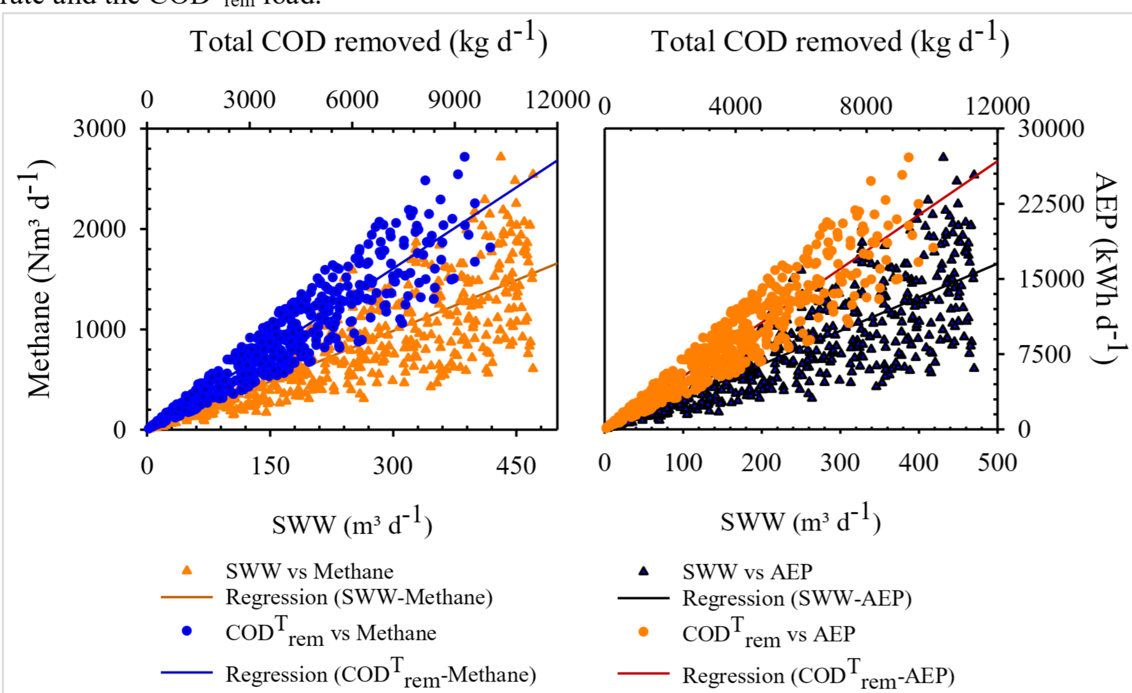
Table 4.5 summarizes the linear-regression relationships obtained for the simulated data presented in Figure 4.4. The best r^2 was observed when the input data estimated the energy potential and methane production as a function of the organic load removed. However, the r^2 coefficients as a function of the influent flow were also acceptable (0.823).

Table 4.5 – Regression equations and coefficients of determination of the adjusted data.

Unit	Yield	Variables	Equations	r²
NL_{CH4} $kgCOD^{T}_{rem}{}^{-1}$	220.6±46.4	Y – Methane (Nm^3 d^{-1}) X – COD^{T}_{rem} (kg d^{-1})	Y=-8.04+0.22X	0.934
NL_{CH4} m^3sww^{-1}	3,223.7±1,109.7	Y – Methane (Nm^3 d^{-1}) X – $Flow_{sww}$ (m^3 d^{-1})	Y=-24.24+3.37X	0.823
kWh $kgCOD^{T}_{rem}{}^{-1}$	2.2±0.5	Y – AEP (kWh d^{-1}) X – COD^{T}_{rem} (kg d^{-1})	Y=-80.10+2.24X	0.934
kWh m^3sww^{-1}	32.1±11.1	Y – AEP (kWh d^{-1}) X – $Flow_{sww}$ (L d^{-1})	Y=-241.60+33.55X	0.823

Note: Composition of regression Y=a+bX, it is understood that "a" is constant, provided when a line reaches the Y-axis, and "b" is the regression coefficient, representing the change in the mean in the variable response for a unit of change in the predictor variable (X); AEP - Available Electrical Power.

Figure 4.4 – Estimation of the SWW electric energy recovery potential, depending on the flow rate and the COD^{T}_{rem} load.



It was reported for domestic wastewater that in the worst and best scenario, the regression between methane and wastewater flow was r^2 of 0.57 and 0.78, respectively. In another perspective, it is reported that in the best scenario, a regression between electrical power and wastewater flow would be r^2 of 0.83 (ROSA; LOBATO; CHERNICHARO, 2020). This shows us that the regressions performed in this research (Table 4.5) to estimate methane were higher than the reported limits, which may represent accuracy. Regarding power, the values were close, assuming a small difference.

4.3.3.1 Validation of the mathematical model

After obtaining the models, it is necessary to validate by comparing the observed and modeled data. Errors between estimated and observed values were calculated. An r^2 of 0.86 and 0.88 were obtained for the methane flow estimate as a function of the load removed and sewage flow (data not shown), respectively. The values are the same for calculating electrical energy.

Another form of verification is comparing the yields obtained in the experiment and those estimated for real conditions. Three swine farms were used with quantities uniformly distributed by Monte Carlo simulation to analyze the estimation and potential of each scenario (Table 4.6), and the experimental (Table 4.3) and model data were compared (Table 4.6). Overall, a good adjustment was found in the proposed situations, except for small swine farming.

Table 4.6 – Ability to recover electricity and methane, and cost avoided with the application of 100% of the energy generated, GHG emissions reduction, and revenue from carbon credits sale of per swine farming scale.

Number of Swine	**250±50**	**500±50**	**1,000±50**
Potency (kWh $kgCOD^T_{rem}{}^{-1}$)	1.6±0.2	1.9±0.1	2.1±0.1
Methane (NL $kgCOD^T_{rem}{}^{-1}$)	155.5±21.4	186.0±10.6	203.5±4.9
Electric Power (kWh d^{-1})	227±89	501±170	1104±329
Methane (Nm^3 d^{-1})	22.1±8.7	49.0±16.7	108.2±32.3
Cost avoided[a] (US$ $year^{-1}$)	6,522±2,552	14,389±4,880	31,707±9,448
GHG reduction ($TonCO_{2eq}$ $year^{-1}$)	170±67	376±128	830±248
Carbon Credit (US$ $year^{-1}$)	7,315±2,885	16,209±5,517	35,786±10,681

Note: [a]Cost avoided with the application of energy; GHG – Greenhouse Gas.

Methane production achieved for large-size pig farms was close to the values obtained in stages III and IV (Table 4.4), with the productivity of 203.5 NL_{CH4} $kgCOD^T_{rem}{}^{-1}$.

The production obtained to the medium-sized swine farm came close to stages I and II, with a discrepancy of 8.5 and 8.7%, respectively. The estimation for small-size pig farms assumed a discrepancy of 40% (stage IV), which is not ideal, as reported by Alfonso-Cardero et al. (2021) and Dupnock et al. (2021), reporting a range of 10 to 30%. Thus, small and medium-sized pigs are associated with stages I and II, and large-sized pigs with stages III and IV.

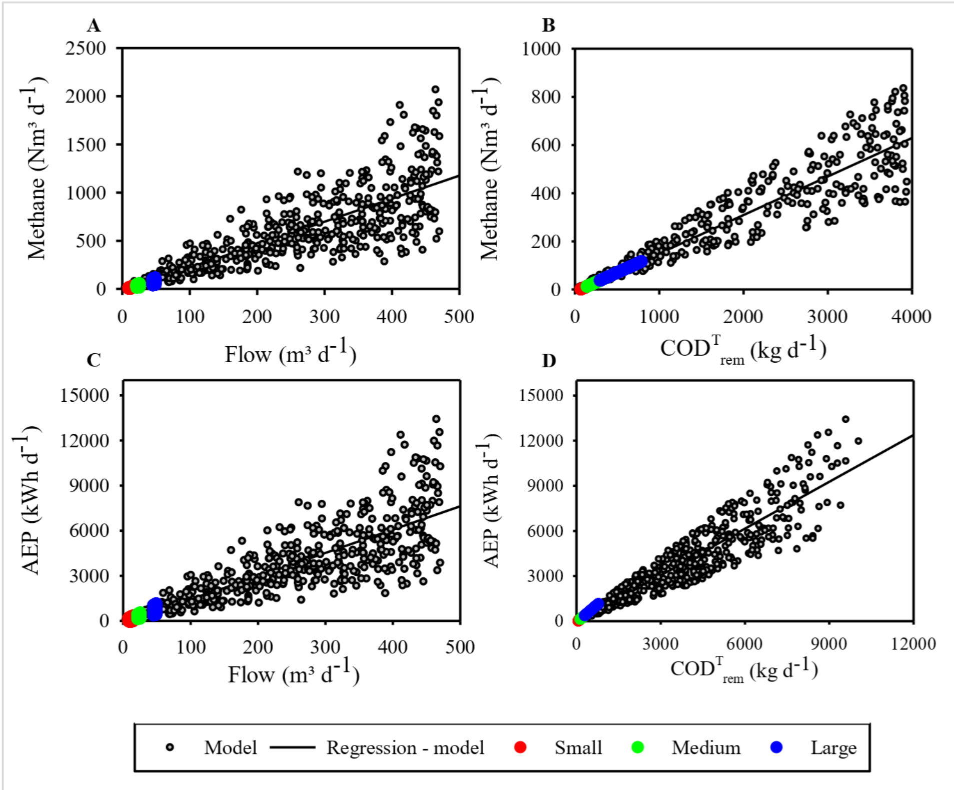
The results were obtained by a laboratory experiment operated on a bench scale under controlled conditions. Possibly at full scale, there will be losses inherent to the operation and conditions of the reactor, with the possibility of reaching values lower than those reported. The obtained yields are shown to differ due to the model constant that allows the distribution residuals to be collected from the value of -8.04 (constant) in estimating the methane flow rate as a function of the removed load.

The constant term is in part estimated by the omission of predictors from a regression analysis. In essence, it serves as a garbage bin for any bias that is not accounted for by the model terms. You can picture this by imagining that the regression line floats up and down (by adjusting the constant) to a point where the mean of the residuals is zero, which is a key assumption for residual analysis. This floating is not based on what makes sense for the constant, but rather what works mathematically to produce that zero mean. The constant guarantees that the residuals don't have an overall positive or negative bias, but also makes it harder to interpret the constant value because it absorbs the bias. This results in an increase in the yield in each situation, as shown in Table 4.6.

4.3.3.2 Adjusting the mathematical model

The simulation (Figure 4.5) considered a variation in the number of swine from 1 to 10,000. To better assess the model suitability, data from the three pig farms for methane production and electricity recovery were pooled with the model data (Table 4.5). The values are close to the trend line predicted by the model, demonstrating an acceptable adherence. The r^2 was 0.85 for estimating methane and 0.95 for energy recovery, both as a function of the removed loading rates, showing the greatest model adherence. The maximum error reached for both was 14%, close to the values reported in the literature (LOPES et al., 2018; RAJENDRAN et al., 2014).

Figure 4.5 - Model adjustment to the biogas production data measured in different types of pig farms.



4.3.3.3 System profitability

The cost of kWh consumed, obtained by the weighted average of peak and off-peak tariffs, for blue modality subgroup A2 is 0.072 US$ kWh^{-1}, the cost avoided by using 100% of the recovered energy (Table 4.6). Given the above, a small-scale pig farm, which consumed full power, would reduce its annual expenditure by approximately US$ 6,522 ± 2,552 (Table 4.6). It assumes higher values for medium and large swine farms as expected (Table 4.6). Therefore, a relevant economy can be achieved upon methane recovery, besides avoiding its release to the atmosphere. In addition, a revenue on carbon credits could be obtained, considering the commodity price of €34.76 per ton for the end of 2021 (INVESTING, 2020). The addition of carbon credits is still uncertain due to bureaucratic and economic processes for credit acquisition. Given this, it is inferred that relatively high amounts of revenue can be achieved with this activity, as a pig farm of only 250 pigs manages to raise approximately US$ 7,315 per year. The energy that can be recovered in swine farms can supply their electrical and thermal needs, and there are positive environmental effects, as the literature comments (CALISKAN; TUMEN OZDIL, 2021).

If there is a good profitability probability for biogas plants, projects that generate biogas of higher quality have the potential to reach a balance between 76.1 to 120.0 US$ kWh^{-1} (MICHAILOS et al., 2020). However, the increase in the biogas would demand a greater capital expenditure, increasing the project and investment risks. Nonetheless, the probabilities must be analyzed.

Table 4.7 – SWOT matrix for the model

Internal origin	**Strengths**	**Weaknesses**
Organization attributes	• Estimate the recoverable fraction of methane and estimate of electric energy based on SWW characteristics; • Assist in the investor's decision making; • Evaluate the potential of pig farming.	• It does not take into account solids variation, because in SWW it does; • There is an application limit.
External origin	**Opportunities**	**Threats**
Environment attributes	• Increase in pig farms with anaerobic systems; • Increase in local energy demand.	• Climate; • Energy generators; • Economy; • Dollar.

Table 4.7 shows the main model strengths and how they are susceptible to some external and internal threats. However, there is overlap by its external strengths and opportunities, as the growth of agribusiness, such as pig farming, expands the possibility of applying the model and market knowledge and exploration for potential investors. With the potential to generate electricity and thermal energy, we can overlap climatic problems that pig farms are exposed to, such as application in ventilation or heating, depending on the country region and climatic situation.

The values obtained can be affected by the internal and external economy of the country due to the products obtained. However, the avoided energy costs make it possible for the investment to flow to other sectors of pig raising. In summary, the opportunities and strengths outweigh the weaknesses and threats that may arise for the pig farming model.

4.4 Conclusions

The SWW can be treated in a UASB reactor, generating methane-rich biogas. The results show the feasibility of recovering methane with a yield of 260.9 NL $KgCOD^{T}{}_{rem}{}^{-1}$ and show the recovery capacity of electrical energy (2.6 kWh $KgCOD^{T}{}_{rem}{}^{-1}$). The developed mathematical model better represented the SWW energy potential and its theoretical capacity for methane recovery. The simulation results show that the model allowed an estimation close to reality, with reduced errors. It also showed great adherence and adjustment to the data.

Thus, the model proved to be a relevant tool for entrepreneurship, and its use can enable studies to implement energy self-sufficiency projects. It was also inferred that biogas plants have great potential for profitability in electricity generation and cost reduction in projects. However, there are limitations in full-scale design, and attention to potential losses of methane dissolved in the effluent, as gas and other forms, is necessary. Finally, there is the need for satisfactory COD removal efficiencies.

5 BIOENERGY RECOVERY OF SWINE WASTEWATER BY AN UPFLOW MICROAEROBIC SLUDGE BLANKET REACTOR (UMSB): METHANE RECOVERY, POTENTIAL, AND ENERGY BALANCE

5.1 Introduction

Anaerobic digestion (AD) is a four-step biological process known to convert organic wastes into methane effectively, a potentially valuable by-product that can be used as a fuel to produce heat and electricity (CHEN et al., 2020; LIM; WANG, 2013; ROBLES et al., 2018). Bioenergy production from AD is a promising climate change mitigation option and is considered a sustainable treatment technology (PANTALEO; GENNARO; SHAH, 2013; RAJAGOPAL; MASSÉ; SINGH, 2013).

Given the available substrates, those generated in pig farming are highlighted, an activity growing in Brazil, being the fourth-largest exporter in the world, behind only the European Union, the United States of America, and Canada (ABPA, 2020). The large quantities of solid and liquid wastes generated in this activity need treatment before their disposal into the environment (CHENG et al., 2018b; HAI et al., 2015a; ZHENG et al., 2018). However, this waste also represents a valuable source for renewable energy production in the form of biogas (JIANG et al., 2020; MAZARELI et al., 2016).

AD leads to the formation of biogas, microbial biomass (sludge), and an effluent fertilizer for application on agricultural fields for nutrient recovery (CHEN; CHENG; CREAMER, 2008; KARTHIKEYAN; VISVANATHAN, 2013; KELLEHER et al., 2002; RAJAGOPAL et al., 2011; RAJAGOPAL; MASSÉ; SINGH, 2013; WU et al., 2019). Compared with conventional aerobic processes, AD has the superiority of less energy consumption, biogas recovery, and lower sludge production (BAE et al., 2014; CHEN et al., 2020; MASSÉ et al., 2010; MCCARTY; BAE; KIM, 2011; RAJAGOPAL; MASSÉ; SINGH, 2013; STAZI; TOMEI, 2018; XIA et al., 2012). However, the main advantage is methane recovery as an energy source (JAGADABHI; KAPARAJU; RINTALA, 2010), although some other fuels can be recovered (hydrogen) or the application of the carboxylic acid platform to produce organic acids of great industrial applications (SILVA et al., 2020).

In the last few years, agricultural biogas plants, which exploit animal farming and breeding waste besides increasing energy crops, have increased (JAGADABHI; KAPARAJU; RINTALA, 2010), emerging numerous anaerobic digester projects to treat different types of organic substrates. The first two steps of the AD process – hydrolysis and acidification, involve the solubilization of complex particulate organic compounds into simple soluble compounds such as volatile fatty acids (VFAs). They are followed by the acetogenesis step, which converts the VFAs to acetate and hydrogen gas that methanogens would, in turn, consume to produce methane in the final step of the AD process (BATSTONE et al., 2002; LIM; WANG, 2013). For complex particulate organic matter, hydrolysis is usually the AD limiting step.

AD can suffer from process instability due to low hydrolysis rate, hydrogen sulfide (H_2S), ammonia, volatile fatty acids (VFAs) concentration increase, among others, and changes in operation and substrate conditions (LI et al., 2018a, 2018b; WU et al., 2019). Despite well-proven advantages, the reactor effluent does not comply with the effluent discharge standards established by many environmental agencies (CHERNICHARO, 2006; KHAN et al., 2011; SATO et al., 2006; TANDUKAR et al., 2006; TAWFIK; EL-GOHARY; TEMMINK, 2010).

Several strategies to enhance the hydrolysis of particulate organic matter and solubilization, thereby improving process stability and methane yields, have been reported in the literature (JAGADABHI; KAPARAJU; RINTALA, 2010). In this context, an alternative that may be relatively more cost-effective and easier to operate is to microaerate the anaerobic reactor, which consist of injecting small amounts of air or pure oxygen (NASCIMENTO et al., 2021b). This strategy enables both anaerobic and aerobic biological activities to occur within a single bioreactor. Although oxygen is known to induce inhibitory effects on strict anaerobic methanogens, the advantages of microaeration in AD systems have been reported (BOTHEJU, 2011; LIM; WANG, 2013). Insertion of microaeration can enhance hydrolysis by hydrolytic enzyme production increase and improving the overall process (JOHANSEN; BAKKE, 2006; KRAYZELOVA et al., 2014; MYINT; NIRMALAKHANDAN; SPEECE, 2007; PECES et al., 2016). It can also control the accumulation of VFAs in the system (KRAYZELOVA et al., 2014), contributing to a potential increase in biogas/methane production.

In this work, different oxygen loads were first applied to investigate in-situ microaeration on the AD performance for methane recovery. Methane and energy production of the microaerobic reactor was compared with an anaerobic reactor. Furthermore, an energy balance and an energy return on investment (EROI) analysis were performed for the both reactors to identify the key factors for improving the net energy balance and determine whether the bioenergy recovered can be a viable alternative to fossil fuels. Furthermore, the study evaluated if bioenergy recovery is a viable alternative to make microaeration self-sufficient.

5.2 Materials and methods

5.2.1 Substrates

The raw SWW was collected from the pig bays cleaning. Throughout the experiment, the pigs were in many development stages and were fed with corn and soybean-based food. The raw SWW was obtained from the Zootechny Department (DZO) of the Federal University of Ceará (UFC) in Fortaleza, Ceará, Brazil. Before reactors' feeding, the SWW was subjected to a preliminary treatment in a 2 mm square mesh sieve for solid separation, simulating the conditions found in full-scale treatment plants (OLIVEIRA et al., 2021b). The SWW was then stored at 4ºC.

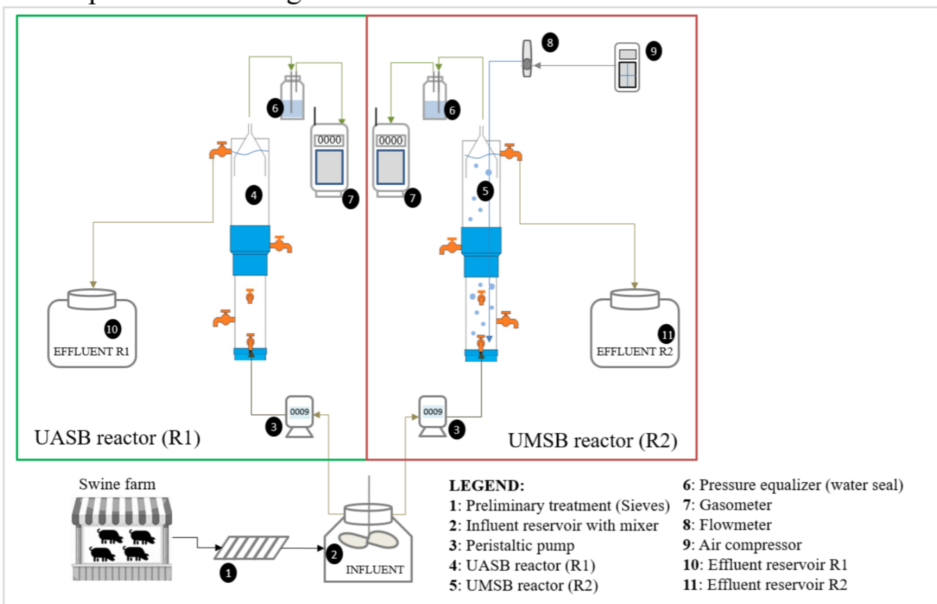
5.2.2 UMSB and UASB reactors

Two lab-scale upflow anaerobic sludge blanket (UASB) (R1) and upflow microaerobic sludge blanket (UMSB) (R2) reactors were operated, made of PVC, with an operating volume of 3.25 L. Reactors were fed with a diaphragm pump (ColeParmer MasterFlex L/S 7522-30, USA) to keep the flow rate constant (ALCARAZ-IBARRA et al., 2020), operated at (28 ± 6) ºC and seeded with a sludge (1.6L) from a full-scale UASB reactor used in a sewage treatment plant in Fortaleza, Brazil. The content of Total Solids (TS), Total Volatile Solids (TVS), and Total Fixed Solids (TFS) were (44.3 ± 2.5), (29.5 ± 1.4), and (14.7 ± 1.1) g L^{-1}, respectively. The UMSB reactor was microaerated with synthetic air (80% N_2 + 20% O_2, White Martins, Brazil) using a mass flow controller (GFC17, Cole-Parmer, USA) (OLIVEIRA et al., 2021c). The biogas production was quantified twice a week by a gasometer (Ritter MolliGascounter) (DANIYAN et al., 2019; PEREIRA et al., 2019; VENDRUSCOLO et al., 2020).

5.2.3 Mode of operation

Figure 5.1 shows the experimental set-up schematic of the process.

Figure 5.1 - Experimental configuration schematic.



Note: SWW – Swine Wastewater.

The UMSB and UASB reactors start-up were previously described (OLIVEIRA et al., 2021c) with an SWW average COD of 5 g L^{-1} and flow rate (Q) of 4.5 mL min^{-1}, resulting in biological organic rate (BOR) of 0.7 kgCOD $kgVS^{-1}d^{-1}$, organic loading rate (OLR) of (10.4 ± 0.9) kgCOD m^{-3} d^{-1}, volumetric hydraulic load (VHL) of 2 m^3 $m^{-3}d^{-1}$, and hydraulic retention time (HRT) of 12 h.

Table 5.1 – Operational conditions used throughout the experimental stages.

Item	Stages				
	I	II	III	IV	V
Total Period (d)	85	28	42	38	38
Flow rate (mL min^{-1})	4.5	4.5	5.4	6.8	9.0
HRT (h)	12	12	10	8	6
OLR_{appl} (kgCOD $m^{-3}d^{-1}$)	10.6±0.3	10.6±0.5	12.2±0.3	14.8±0.4	20.1±0.8
Dose of oxygen (LO_2 $L_{feed}^{-1}d^{-1}$)	0.17	0.25	0.25	0.25	0.25
Microaeration (mL_{air} min^{-1})	3.8	5.6	6.8	8.5	11.3

The influent COD, Q, OLR, VHL, and HRT values were kept constant during the 285 days of the experiment. Afterward, the flow rate was increased progressively over the operating runs, resulting in increased OLR and reduced HRT. The operating conditions are summarized in Table 5.1. The UMSB reactor was operated under progressive microaeration dose, based on the interval suggested by Nguyen et al. (2018), to increase particulate organic matter removal and methane production in biogas without causing remarkable biogas dilution (OLIVEIRA et al., 2021c).

The reactors' performances were analyzed in two major periods. The first was the acclimatization/non-steady-state period of 108 days, and the second was the steady-state period of 238 days, divided into five stages as shown in Table 5.1. The microaeration doses were selected based on the hydrolysis ranges reported by Nguyen and Khanal (2018).

5.2.4 Energy balance analysis

The overall energy assessment was carried out from energy recovery (E_R) from methane and energy consumption (E_C), as shown in Table 5.2. The latter parameter includes the microaeration system (P_{CO}) and the reactor feeding system (E_P).

Thus, it was evaluated whether the energy recovered with the methane generated in the UMSB supplies its microaeration demand, identifying whether there is energy self-sufficiency. The literature reports that the insertion of controlled amounts of air in the reactor can bring advantages in hydrolysis and, consequently, methane production (BOTHEJU, 2011; JOHANSEN; BAKKE, 2006; KRAYZELOVA et al., 2014; LIM; WANG, 2013; MYINT; NIRMALAKHANDAN; SPEECE, 2007; NASCIMENTO et al., 2021b; PECES et al., 2016). It was also possible to compare the methane and energy yields between the reactors and their operating conditions.

In addition, UMSB reactor scalability was evaluated, aiming to identify its energy self-sufficient on a real scale, according to the experimental data, considering different sizes of pig farms, with 500 to 10,000 swine, and adopting 4.7 kgCOD kg_{swine}^{-1}, based on a 90 kg swine (LOBATO; CHERNICHARO; SOUZA, 2012; LOPES et al., 2020; ROSA; LOBATO; CHERNICHARO, 2020). The energy balance assessment includes the input, output, and energy recovery, and the input energy was the electricity demands (XIAO et al., 2018).

Table 5.2 – Energy calculations.

	Parameter	Calculation equation	Remarks
Energy recovery (E_R)	Lower calorific value available	$LCV_A = SW_{CH4} * LCV_{CH4} * K$	LCV_A = Lower calorific value available (9.98 kWh Nm^{-3}) - (70-81% of CH_4) SW_{CH4} = Specific weight of CH_4 (kg Nm^{-3}) LCV_{CH4} = Lower calorific value of CH_4 (kcal kg^{-1}) K = 4.19 kWh.3600^{-1} (conversion of units kcal-Joules-kWh) $F_{N-CH4-real}$ = Normalized available flow (Nm^3 d^{-1}) E_0 = Available energy potential (kWh d^{-1}) Ef = Conversion efficiency of the thermal machine (ALCARAZ-IBARRA et al., 2020; CHOWDHURY, 2021; CURLETTI et al., 2015; DUMONT et al., 2018; GIAROLA et al., 2018; KOR-BICAKCI; UBAY-COKGOR; ESKICIOGLU, 2019)
	Electric power	$E_R = F_{N-CH4-real} * LCV_A * ef$	
Energy consumption (E_C)	Aerator (compressor) power	$P_{CO} = \frac{OR}{OE_c}$	P_{CO} = Compressor operating power (kWh d^{-1}) OR = Oxygen Requirement (kgO_2 d^{-1}) OE_C = Oxygenation efficiency under real conditions (kgO_2 kWh^{-1}) $OE_{theoretical}$ = Oxygenation efficiency under theoretical conditions (kgO_2 kWh^{-1}) η = Rate of change between 0.55 and 0.65
	Oxygenation efficiency	$OE_c = OE_{theoretical} * \eta$	
	Energy used to run the 1 to 10 HP peristaltic pump	$E_P = \frac{Q_p * \gamma * E}{1000}$	Ep = energy demand for pumps (feed) (kW) (CHEN et al., 2019; CHENG et al., 2021; KIM et al., 2011; MEI et al., 2016; SHIN; BAE, 2018; XIAO et al., 2018) Q_p = Flow rate (m^3 s^{-1}) γ = 9800 N m^{-3} E = hydraulic pressure head (m) (≈0.098 m)
Energy return on investment (EROI)		$EROI = \frac{Energy\ output}{Energy\ input} = \frac{E_r}{E_c}$	(CHENG et al., 2021; HALL; BALOGH; MURPHY, 2009)
Energy Efficiency of the AD process		$K_{ef} = \frac{Kn}{K}$	K_{ef} = Energy Efficiency (MORALES-POLO et al., 2020) Kn = Net energy available K = Total energy available

Source: Adapted from (CHEN et al., 2019; CHENG et al., 2021; HALL; BALOGH; MURPHY, 2009; IPCC, 2009; LIMA et al., 2020; LOBATO; CHERNICHARO; SOUZA, 2012; MEI et al., 2016; MORALES-POLO et al., 2020; ROSA; LOBATO; CHERNICHARO, 2020; SHIN; BAE, 2018; XIAO et al., 2018).

5.2.4.1 Energy recovery (E_R)

The methane flow rate was used to estimate the energy recovered, which was defined by the product between the normalized methane flow and the methane lower calorific value. To establish power to generate electricity and heat, the CHP system efficiency has been assumed to be 40% for electrical conversion and 45% for heat conversion (CHOWDHURY, 2021; KISELEV et al., 2019; SANTOS; BARROS; TIAGO FILHO, 2016), as shown in Table 5.2. Considering biogas with 70 to 80% CH_4 content, a specific weight (SW_{CH4}) of 1.15 kg Nm^{-3} and a lower calorific value available (LCV_{CH4}) of 4.831,10 kcal kg^{-1} were used, resulting in an LCV available of 6.48 kWh Nm^{-3}.

This suggested efficiency value is the most adopted among the literature. However, it is higher than that of the generators found in Brazil. The internal combustion engine and generator group have the highest need for shutdowns due to a higher biogas content impurity. Thus, a capacity factor (CF) of 70% was used (RIBEIRO et al., 2016; SANTOS; BARROS; TIAGO FILHO, 2016). This value is less than the normally used for thermoelectric plants moved by gas, which are around 90% according to CETESB (Environmental Agency of São Paulo State) (RIBEIRO et al., 2016; THE ENVIRONMENTAL COMPANY OF SAO PAULO – CETESB, 2002).

According to EIA (2015), the technologies used to generate electricity are similar across regions of the world, but the pattern of use for those generating technologies can be significantly different. Analysis of electric generating plant utilization (measured by annual capacity factors, or the ratio of generation to capacity) over a five-year period shows a wide variability among fuel types and across world regions.

Capacity factors can also be affected by partial-year generation effects, especially for technologies with recently installed capacity. By convention, the capacity factor numerator is based on actual generation, while the denominator is based on what that generator could have provided, assuming continuous operation for a full year (EIA, 2015; MUHAMMAD; CHANDRA, 2022; ZAHEDI; AHMADI; DASHTI, 2021)

5.2.4.2 Energy consumption (E_C)

Energy consumption included two parameters: Aeration (compressor) power (P_{CO}) and energy required for pumping (E_P), as shown in Table 5.2. The energy required for the microaeration system was estimated considering the oxygen density of 1.33 kg m^{-3}, obtaining the daily mass flow rate for the phases, and identifying the electrical energy (kWh d^{-1}) for the air supply system operation.

The essential energy (P_{CO}) to supply the microaeration requirements was calculated based on the oxygen requirement (OR). The parameter that converts oxygen consumption into electrical energy consumption is the oxygenation efficiency (OE), which varies between 1.2 to 2.0 kgO_2 kWh^{-1} (1.2 kgO_2 kWh^{-1} was adopted). For real operating conditions, the oxygenation efficiency is lower, and it can be calculated by the product between the theoretical efficiency and the oxygenation rate. For the calculations, the maximum values were considered to overview the critical conditions of electrical energy consumption.

5.2.5 Chemical analysis Chemical and chromatographic analyzes

Chemical Oxygen Demand (COD) (total, particulate and soluble), Biochemical Oxygen Demand ($BOD_5^{20°C}$) (total, particulate and soluble), Total Solids (TS), Fixed Solids (FS), Total Suspended Solids (TSS), Volatile Solids (VS), Volatile Suspended Solids (VSS), Total Kjeldahl Nitrogen (TKN), N-NH_4^+, Total Phosphorus (TP), PO_4^{3-}, SO_4^{2-}, S^{2-}, and pH were determined by APHA (2012). Total Alkalinity (TA) and Volatile Fatty Acids (VFA) were determined using the Kapp titrimetric method (BUCHAUER; INNSBRUCK, 1998).

In addition, the quantification of CH_4 and CO_2 in the biogas was determined by gas chromatography with ionization detection by dielectric barrier discharge (GC BID-2010 Plus, Shimadzu Corporation, Japan), equipped with a GS-GASPRO column (60m×0.32 mm) (Agilent Technologies Inc., USA). Helium gas was used as the carrier gas (White Martins LTDA, Brazil) at a flow rate of 2 mL min^{-1}, with a run time of 9 min. The oven, injector, and detector temperatures were 50ºC, 100ºC, and 250ºC, respectively.

O_2 and N_2 were quantified by gas chromatography with thermal conductivity detection (GC-TCD) (GC-17A, Shimadzu Corporation, Japan). The biogas sample (1.0 mL) was injected in splitless mode, and chromatographic separation was performed on a Mol Sieve 5A PLOT column (30 m, 0.32 mm ID) (Restek Corporation, USA). The oven, injector, and detector temperatures were 35ºC, 40ºC, and 230ºC, respectively. Helium (White Martins, Brazil) was used as the carrier gas at a flow rate of 7 mL min^{-1} with a run time of 5 min.

5.2.6 Data analysis

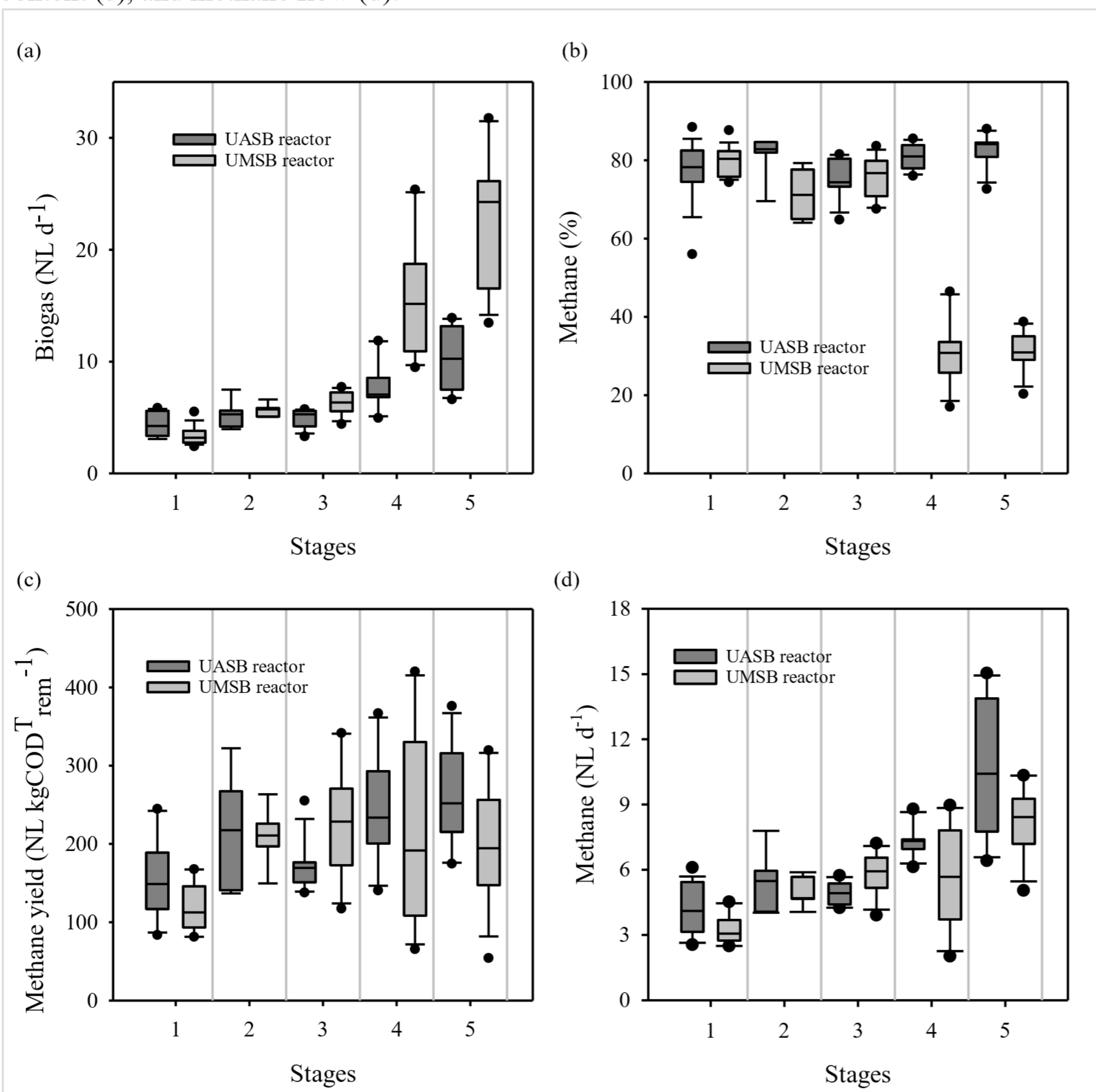
Statistical significance was tested by Analysis of Variance (ANOVA), complemented with mean value comparison using Tukey's HSD tests with a threshold *p*-value of 0.05 declared significant (MONTES et al., 2019). If $p \leq 0.05$, the null hypothesis is rejected, i.e., the data groups are considered statistically different (LI et al., 2021; LOPES et al., 2018; MORALES-POLO et al., 2020; QIAN et al., 2019; ZHANG et al., 2021a). Statistical significance was analyzed for data related to the relationship and ratios of OLR and both methane production and methane content in the biogas and others during the entire system operation.

5.3 Results and discussion

5.3.1 Biogas and methane production

Figure 5.2a shows the daily biogas production in the reactors during the stages. Peaks of biogas production occurred on the UMSB reactor during stages IV and V, Table 5.3with a large variation as shown in Table 5.3.

Figure 5.2 – Biogas and methane production: biogas flow (a), cumulative biogas (b), methane content (c), and methane flow (d).



These peaks of biogas can be attributed to high microaeration rates used when influent SWW flow was increased by HRT decrease and OLR increase, therefore increasing the oxygen demand (Table 5.1). Moreover, Figure 5.2b and 5.2d show the content and flow of methane, respectively. The methane yield as a function of the removed COD load is shown in Table 5.3.

Table 5.3 – Reactors' performance, constitution, flow, and yield of methane.

Stage	**I**	**II**	**III**	**IV**	**V**
HRT (h)	12	12	10	8	6
COD (mgO$_2$ L^{-1})					
Total influent	5,300±130	5,029±77	5,067±118	4,939±141	5,018±201
OLR (kgCOD m^{-3} d^{-1})					
Total influent	10.6±0.3	10.6±0.5	12.2±0.3	14.8±0.4	20.1±0.8
			UASB reactor (R1)		
COD^T removed (%)	93.8±2.1	92.2±4.0	89.2±3.4	89.1±3.6	92.1±2.3
Biogas (NL d^{-1})	4.4±1.1	5.3±1.2	5.0±0.8	7.8±2.2	10.2±2.7
Biogas content (%)					
CH_4	77.3±7.4	81.4±5.3	74.8±5.0	81.0±3.1	82.7±4.1
CO_2	20.1±3.8	16.9±1.0	22.2±8.9	18.4±2.6	21.3±5.1
N_2	UN	UN	UN	UN	UN
Methane yield					
(NL kgCOD$^T_{rem}$$^{-1}$)	157.9±48.9	210.1±69.9	169.8±28.8	247.0±68.5	260.9±63.2
			UMSB reactor (R2)		
COD^T removed (%)	94.2±1.2	95.0±0.5	90.3±1.9	88.5±1.7	92.2±3.6
Biogas (NL d^{-1})	3.4±0.8	5.6±0.5	6.3±1.0	15.9±5.4	22.8±5.9
Biogas content (%)					
CH_4	79.8±3.6	70.9±6.3	75.5±5.3	30.8±8.4	31.1±4.9
CO_2	20.1±3.6	16.9±1.0	12.2±7.6	7.9±2.5	7.2±1.9
O_2	UN	UN	1.5±0.5	8.0±1.8	7.9±0.9
N_2	UN	UN	9.2±2.8	53.0±12.5	51.9±3.6
Methane yield					
(NL kgCOD$^T_{rem}$$^{-1}$)	118.5±29.0	219.4±21.3	228.6±70.0	221.2±122.0	200.6±75.8

Note: UN – Unidentified

For the UASB reactor (R1), as shown in Table 5.3, there is a significant difference between the biogas (*p*=1.7E-11) and methane (*p*=2.8E-10) production between the different OLRs applied throughout the five stages. Perhaps this difference between stages in methane production is a result of COD converted to methane (CARDOSO; SAMPAIO; SALES, 2017). The highest converted values were in stages IV and V assuming 17.4 and 23.4 gCOD d^{-1}, while in the first three stages, the conversion was less than 11.8 gCOD d^{-1}. Given this, it can be assumed that higher conversions of COD methane are possible to be obtained at HRT less than 8h.

A correlation between the influent SWW and methane production was performed as reported in the literature to facilitate comprehension, and an r^2 of 0.82 was obtained (ALCARAZ-IBARRA et al., 2020; ESPARZA-SOTO et al., 2013; MONTES et al., 2019). However, no statistical difference was seen between the stages concerning the methane concentration in the biogas data reported in Figure 5.2b. Also, the values obtained were among those reported in the literature for biogas recovered in AD systems, with a limit of 50 to 80% (MENSAH et al., 2021; ROSA et al., 2016; TOLEDO-CERVANTES et al., 2017; WU et al., 2021). The specific methane yield in terms of COD for the UASB reactor varied from 68.9 to 441.0 NL $KgCOD^{T}_{rem}{}^{-1}$, with a significant difference between the stages (p=0.025), likely due to the different flow rates applied (Figure 5.2c).

More recently, several studies reported the advantages of microaeration. In light of this, this research studied the effects of different dosages of oxygen on methane and energy recovery (DÍAZ et al., 2010, 2011; DÍAZ; DONOSO-BRAVO; FDZ-POLANCO, 2011; DÍAZ; FDZ-POLANCO, 2012; FDZ.-POLANCO et al., 2009; KRAYZELOVA et al., 2015; NASCIMENTO et al., 2021b; NGUYEN; KHANAL, 2018; POKORNA-KRAYZELOVA et al., 2017; XU et al., 2019). Large variations in methane yields (p=2.1E-10) and their concentration in the biogas (p=1.0E-47) throughout the stages (Figure 5.2b and 5.2c) were verified for the UMSB reactor (R2). This difference resulted from the microaeration doses applied, increasing biogas production, and decreasing methane content (MONTES et al., 2019; NASCIMENTO et al., 2021a, 2021b). Only the methane yield values obtained in stage I were lower than those reported in the literature (ALCARAZ-IBARRA et al., 2020; CÂNDIDO et al., 2022; ESPARZA-SOTO et al., 2013; LOBATO; CHERNICHARO; SOUZA, 2012; MONTES et al., 2019; QIAN et al., 2016; ROSA et al., 2016).

Also, the high biogas flow in stages IV and V (UMSB) was due to the high SWW flow rate, which resulted in a high airflow (CHENG et al., 2020). Consequently, a methane concentration reduction in UMSB reactor biogas was observed (30.8 and 31.1%). However, this methane content reduction is only a consequence of biogas dilution with nitrogen from the synthetic air (80%) injected into the system, i.e., microaeration did not harm methanogenesis (OLIVEIRA et al., 2021c). The same behavior was observed by Nascimento et al. (2021a, 2021b). The nitrogen and oxygen concentrations detected at this stage corroborate some previous reports (CÂNDIDO et al., 2022; JENICEK et al., 2014; KRAYZELOVA et al., 2015).

Even so, the methane yield was considered high, with 221.2 and 200.6 NL $kgCOD^{T}_{rem}{}^{-1}$ for stages IV and V, respectively. This becomes an issue if biogas is used in combined heat and power plants, requiring a minimum limit of 40% (HAUBRICHS; WIDMANN, 2006; NASCIMENTO et al., 2021a, 2021b). The methane yields of the UASB reactor (R1) were within limits reported in the literature for SWW (126 to 283 NL $kgCOD^{T}_{rem}{}^{-1}$) (MONTES et al., 2019; XU et al., 2019). As there are not many studies addressing SWW AD in a UMSB reactor, the values suggested for the UASB reactor were assumed, and through this, it is found that only stages II and III agree. As shown in Figure 5.2, conditions in stages IV and V were the ones that showed the greatest variation in methane flow. The stages with the highest stability in methane production were stages I, II, and III. Among these, stages II and III obtained methane yields (219.4 and 228.6 NL $kgCOD^{T}_{rem}{}^{-1}$) higher than stages II and III of the UASB reactor. This increase was attributed to the higher biogas flow rate generated in the microaerobic reactor.

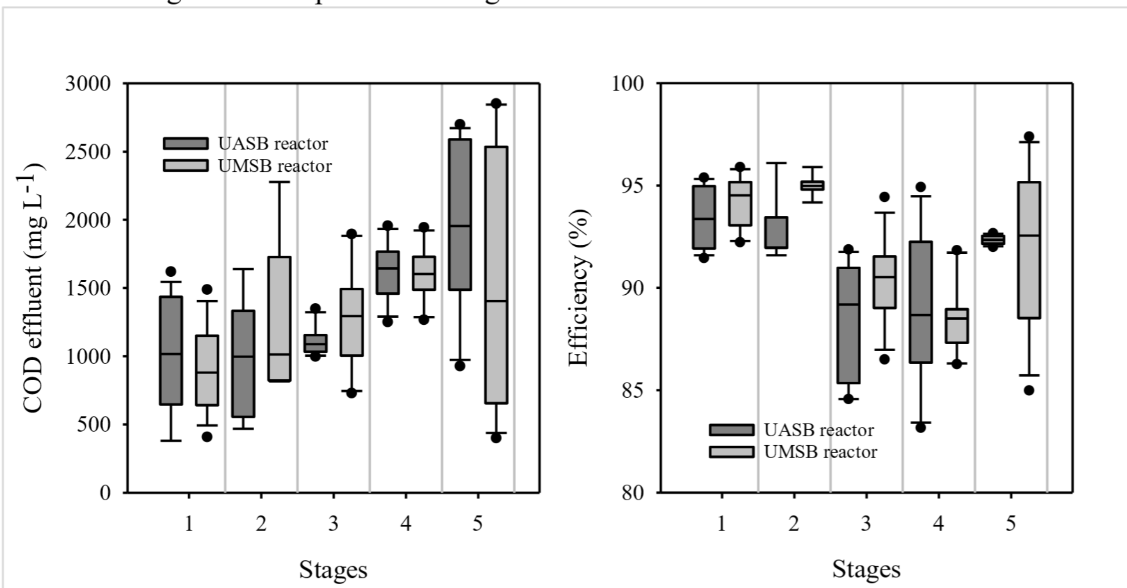
It was observed that higher air dosages such as 8.5 and 11.3 mL_{air} min^{-1} (stages IV and V) resulted in methane dilution and consequently made the system unfeasible in terms of energy recovery. According to Ruan et al. (2019) and Nguyen and Khanal (2018), waste hydrolysis is a biochemical process with a slow rate. The over microaeration beyond the oxygen consumption by facultative bacteria can cause detrimental effects on strict anaerobes due to high concentration of reactive oxygen species (ROS) that damage their phospholipid membrane and DNA (NGUYEN; KHANAL, 2018; XU; SELVAM; WONG, 2014).

However, a high methane concentration and yield were obtained when the microaeration rate of 0.25 LO_2 $L_{feed}{}^{-1}$ d^{-1} was applied in the 12 and 10h HRTs (stages II and III). On the other hand, stage I showed reduced yield compared to stages IV and V and those in the literature (ALCARAZ-IBARRA et al., 2020; ESPARZA-SOTO et al., 2013; MONTES et al., 2019). However, these stages presented biogas with acceptable methane concentrations for energy generation.

5.3.2 Reactor performance

The COD removal efficiency is shown in Figure 5.3 (WANG; YAN; XU, 2015), in which there was no significant difference between the reactors (p=0.894). Despite this, the UMSB reactor averaged higher COD removal efficiency than the UASB reactor in stages I, II, III and V. Additionally, there was also greater stability in COD removal from stages I to II, with a greater variation in stage with higher airflow (stages V), in which removal of 92.2%, was found. So, likely small air dosages could further stabilize COD removal in the reactor.

Figure 5.3 – Total COD effluent and COD removal efficiency for the UASB and UMSB reactors throughout the experimental stages.



5.3.3 Energy balance assessment of the two reactors during the steady period

5.3.3.1 Recovered energy

As the process analysis combines the energy output and input, an energy assessment and EROI (KIM et al., 2011) of the two reactors during the steady-state period were conducted (Table 5.4) (HAI et al., 2015b; JIANG et al., 2020; XIAO et al., 2018), to check whether energy self-sufficiency can be achieved or the biogas recovered from this system can be a viable alternative to fossil fuels (CHENG et al., 2021). For that purpose, reactor scale-up was performed, and the energy recovery potential and the operational energy required were calculated under the operating conditions applied in the experiment.

In stages IV and V, the methane concentration was lower than required (40%) for electric power generation (HAUBRICHS; WIDMANN, 2006; NASCIMENTO et al., 2021a, 2021b), so the energy generated in both stages was 0. Therefore, the balance of stages I, II, and III was analyzed. They were also used at different scales to identify the extent to which we found energy and economic self-sufficiency in the microaerobic reactor treating SWW (XIAO et al., 2018).

As shown in Table 5.4, the E_R in the R2 increased from 2.1 to 2.3 kWh $kgCOD^T{}_{rem}{}^{-1}$ by reducing the HRT to 10h. However, reducing HRT (in stage II) increased the air dose, increasing the system electrical energy consumption from 0.174 to 0.187 kWh $kgCOD^T{}_{rem}{}^{-1}$. Given the varying UMSB reactor operating conditions, stages I, II, and III's energy efficiency was close. However, stages II and III generate more energy surplus.

Table 5.4 – Electric power recovered and required in the experimental stages.

Stage	HRT	UASB reactor (R1)			UMSB reactor (R2)			
		E_R	E_C	K_{ef}	E_R	E_C	EROI	K_{ef}
	h	kWh $kgCOD^T{}_{rem}{}^{-1}$		-	kWh $kgCOD^T{}_{rem}{}^{-1}$		-	-
I	12	1.6±0.5	8.0E-05±1.1E-05	1	1.2±0.3	0.098±0.009	12.1±2.9	0.913±0.018
II	12	2.1±0.7	8.4E-05±8.4E-05	1	2.1±0.3	0.174±0.031	12.2±1.6	0.917±0.011
III	10	1.6±0.4	8.9E-05±1.1E-05	1	2.3±0.7	0.187±0.046	12.2±2.3	0.915±0.018
IV	8	2.5 ±0.7	1.0E-04±7.7E-06	1	-	0.198±0.047	-	-
V	6	2.6±0.6	1.1E-04±2.5E-05	1	-	0.194±0.058	-	-

Note: E_R – energy recovery; E_C – energy consumption; K_{ef} - energy efficiency.

Although the energy production in the UMSB reactor was reduced in stage I compared to UASB reactor, there was self-sufficiency (Table 5.4). However, the HRT reduction to 10h and a slight increase in airflow (stage III, Table 5.1) showed a higher yield of energy recovered than the UASB reactor, despite having an energy efficiency of 0.915.

EROI analysis provides a useful approach for examining the disadvantages and advantages of different fuels and offers the possibility of looking into the future in ways that markets seem unable to do (FAJARDY; MAC DOWELL, 2018; HALL; BALOGH; MURPHY, 2009). EROI is a ratio of the energy obtained from an energy resource to the energy expended to produce that energy (CHENG et al., 2021). There are no studies investigating the energy balance of microaerobic reactors. The main ones found in the literature from other sources are cited by Cheng et al. (2021). EROI of 3 at processing to be a viable alternative to fossil fuels (HALL; BALOGH; MURPHY, 2009). Modern coal has been found between 20 and 67, between 1.6 and 12 for solar power, and between 0.8 and 10 for biofuels (FAJARDY; MAC DOWELL, 2018). EROI values for food waste and sewage sludge co-digestion are 3.53 to 7.48 (CHENG et al., 2021).

EROI ratios obtained in this research for the UMSB reactor were 7.9 to 18.8 (Table 5.4). Although the EROI values are high, the reduction can occur if other system costs are associated. The EROI values for biofuels are in the wide range of 14.4 and 64.8. The EROI values achieved in AD analysis are highly variable due to the different inputs and outputs that must be considered for energy recovery (FAJARDY; MAC DOWELL, 2018).

In general, we can assume that the UMSB reactor has an average EROI of 18, showing that the microaeration conditions applied in stages I to III are feasible for electrical energy recovery. Cheng et al. (2021) analyzed the EROI values for an anaerobic membrane bioreactor (AnMBR) treating food waste and sewage sludge, and values greater than three were reached, indicating viability. Likewise, Kanai et al. (2010) identified a portion of approximately 4 for distillery treated in AnMBR (HALL; BALOGH; MURPHY, 2009). A minimum EROI of 4 is necessary for the fuel not to be subsidized by fossil fuels (MORALES-POLO et al., 2020). It is noteworthy that the EROI values obtained in this research are based on the bench-scale system.

EROI was not calculated for the UASB reactor because the energy required for the system is close to zero, as shown in Table 5.4, which would result in a ratio at values above the limits found in the literature (CHENG et al., 2021; FAJARDY; MAC DOWELL, 2018; HALL; BALOGH; MURPHY, 2009; MURPHY et al., 2011). That is, the UASB reactor consumes a reduced amount of energy to generate energy higher than 1.6 kWh $KgCOD_{rem}^{-1}$. Comparing the studied reactors, it is possible to affirm that the UASB reactor has an almost perfect energy efficiency when compared to the UMSB reactor. However, the UMSB reactor has operational advantages over the UASB.

5.3.3.2 Energy potential – scalability

The energy assessment of the three operational conditions (stages I, II, and III) was performed to assess their scalability (Table 5.5). The experimental data from this research were used, such as COD removal efficiency and COD portion converted to methane, adopted a load generation 4.7 kgCOD kg_{swine}^{-1}, based on a 90 kg swine (LOBATO; CHERNICHARO; SOUZA, 2012; LOPES et al., 2020; ROSA; LOBATO; CHERNICHARO, 2020). Six pig farm scales were evaluated, ranging from 500 to 10,000 swine, generating an SWW from 23.6 a 471.0 m^3 d^{-1}. There was self-sufficiency in all the operating conditions (MACINTOSH et al., 2019), with the system EROI ranging from 11.6 to 18.7.

This is above other waste treatment technologies for methane recovery. Systems composed of AnMBR have reduced EROI values (3.5 to 7.5) due to the various energy consumption: heating, biogas sparging, extracting permeated, sludge cycle, heat loss, mixing and feeding (CHENG et al., 2021). Thus, the UMSB reactor proves to be more energy self-sufficient, producing a greater energy surplus, although the values achieved were lower than those obtained for modern coal from 20 to 67 (FAJARDY; MAC DOWELL, 2018).

A small part of the energy that can be recovered is used to meet the system demand, which can be evaluated by employing energy efficiency (K_{ef}). The values achieved are greater than 0.914, as shown in Table 5.5.

Table 5.5 – Energy assessment of the scalability of microaerobic reactors.

Stages	Reactor Volume	Nº swine	SWW flow	Methane	E_R	E_R	EROI	K_{ef}
	m³		m³ d⁻¹	Nm³ d⁻¹	kWh d⁻¹	kWh $kgCOD_{rem}^{-1}$		
I	12	500	23.6	20.3	141.4	0.81	13.9	0.928
	24	1,000	47.1	35.9	250.3	0.71	12.3	0.919
	59	2,500	117.8	136.4	952.1	1.08	18.7	0.947
	118	5,000	235.5	265.0	1,849.7	1.05	18.2	0.945
	177	7,500	353.3	397.5	2,774.6	1.05	18.2	0.945
	236	10,000	471.0	452.0	3,155.4	0.90	15.5	0.935
II	12	500	23.6	26.3	183.6	1.18	12.3	0.919
	24	1,000	47.1	56.8	396.2	1.27	13.3	0.925
	59	2,500	117.8	145.3	1,014.6	1.30	13.6	0.926
	118	5,000	235.5	276.8	1,932.5	1.24	12.9	0.923
	177	7,500	353.3	415.3	2,898.7	1.24	12.9	0.923
	236	10,000	471.0	539.8	3,768.4	1.21	12.6	0.921
III	10	500	23.6	29.4	205.3	1.39	13.7	0.927
	20	1,000	47.1	56.2	392.3	1.33	13.1	0.924
	49	2,500	117.8	124.2	866.7	1.18	11.6	0.914
	98	5,000	235.5	287.5	2,007.0	1.36	13.4	0.926
	147	7,500	353.3	460.7	3,215.8	1.46	14.4	0.930
	196	10,000	471.0	601.2	4,196.5	1.42	14.1	0.929

Note: E_R - Energy Recovery; Kef – Energy Efficiency

Though conceptually simple, there are many cautions associated with the calculation of this metric. The first lies in the definition of the system boundaries for which EROI is calculated. Another consequence of this boundary definition is that the criteria of having an EROI above one at extraction or processing might not be enough, as the EROI at the point of use could therefore be lower than 1 (FAJARDY; MAC DOWELL, 2018). Another challenge lies in differentiating energy inputs and outputs in terms of energy quality (MURPHY et al., 2011). The energy source quality is equally important when comparing the EROI of different technologies. It can also be measured by the nature of the service provided by the energy source (FAJARDY; MAC DOWELL, 2018). In addition, the EROI values can assume lower values, considering that the generated biogas quality interferes with the energy quality and quantity (LOGANATH; SENOPHIYAH-MARY, 2020a).

Despite all the reported aspects, the current investigation has identified air dosages that do not favor energy recovery and those that contribute to wastewater digestion and consequently generate methane, which provides the energy needed to run the reactor and produces a surplus. All these alternatives generate revenue (revenue from the avoided cost with electric energy and generation of credits with the electric energy concessionary) for the pig farm owner and obtain a better effluent quality (Table 5.1).

Microaeration (UMSB) in the right dosage contributes to a better digestion process of SWW. However, it is susceptible to some limitations (Table 5.6), which can be overcome in view of the strengths and opportunities offered by the external and internal sectors and the UASB reactor. Economic problems affecting the purchase of chemical fertilizers provide an opportunity to use the digested material in fertigation.

The increase in energy price generates the opportunity to apply the recovered energy to meet demands. Regarding climatic conditions, the energy generated can heat the pigs in cold periods and cool them in hot periods. This makes it possible to reduce the pigs' stress that affects their development and the meat quality. The most targeted weakness in a micro-aerated reactor is electricity consumption, but the biogas generated throughout the process can supply this demand, making the reactor self-sufficient.

Table 5.6 – SWOT matrix for the UASB and UMSB reactors

	UASB	
Internal origin	**Strengths**	**Weaknesses**
Organization attributes	• Biogas/methane and energy generation; • Energy self-sufficiency (low energy consumption); • Remediation of impacts caused by the release of wastewater into water bodies; • Reduction of GHG emissions; • Generation of stabilized digestate.	• Low capacity to remove nitrogen, phosphorus and pathogens. A post-treatment is usually required for the effluent; • Possibility of low methane concentration and presence of impurities, reducing the energy potential of biogas; • Methane losses during treatment; • Low efficiency of generators presents in Brazil – results in reduced energy generated, compared to technologies present in Europe.
External origin	**Opportunities**	**Threats**
Environment attributes	• Energy credits – concessionaire; • Demand for liquid fertilizers; • Increase in pork demand (meat); • Increase in demand for natural gas – biomethane; • Imported generators; • Energy crisis; • Fertilizer prices.	• Climate; • Legislation for agricultural wastewater discharge; • Generators in Brazil; • Distribution network of electricity; • Agricultural crisis; • Pig feed.
	UMSB	
Internal origin	**Strengths**	**Weaknesses**
Organization attributes	• Greater stability in COD removal; • Generation of biogas with higher methane concentration; • Increased recovery of electrical energy; • Energy self-sufficiency for micro-generation; • Reduction of GHG emissions; • Generation of stabilized digestate.	• Microaeration dose errors; • Qualified labor; • Increase of electric energy consumption – microaeration; • Need to adapt reactors already in operation; • Possibility of methane dilution and methane losses.
External origin	**Opportunities**	**Threats**
Environment attributes	• Energy credits – utility; • Demand for liquid fertilizers; • Increased demand for pigs (meat). • Increased demand for natural gas – biomethane; • Imported generators. • Energy crisis; • Fertilizer prices	• Climate; • Economy; • Price of energy Legislation for agricultural wastewater discharge; • Generators in Brazil; • Electricity distribution network; • Agricultural crisis; • Pig feed.

5.4 Conclusions

Microaeration has been found to have several positive impacts on SWW treatment. However, there is a limit of microaeration that favors methane recovery aiming to generate electric energy. Among the microaeration rates, the dose of 0.25 LO_2 $L_{feed}^{-1}d^{-1}$ at 10h HRT favored biogas production while maintaining a stable methane concentration (75.5%). The energy recovered from methane can still provide the energy required by the system, including the microaeration and feeding. However, there is a limit for microaeration dosage without interfering in the biogas dilution and methane concentration for electric energy recovery. The UMSB reactor scalability analysis showed that it could be self-sufficient under stage I to III conditions, with an EROI greater than 10 achieved for most of the scaled operating conditions, indicating a viable alternative source to fossil fuels.

6 FINAL CONCLUSIONS

Regarding the first specific objective, “To develop a model for estimating the energy potential of SWW treated in a UASB reactor”, it is concluded that:

- SWW AD generates biogas with a favorable concentration (74.8%) for electrical energy recovery, 1.6 to 2.6 kWh $kgCOD_{rem}^{-1}$, a value higher than those found in the literature studied;
- The model showed accuracy in estimating electric energy and methane in SWW AD;
- Model validation shows that the model developed allowed a more accurate estimation of biogas and electric energy production;
- The model can be applied as a tool for AD energy recovery of agricultural (liquid) waste, such as piggery, in UASB reactors, demonstrating its potential for investors.

Regarding the second specific objective, “To evaluate the energetic viability of using microaeration in UMSB reactors treating SWW, with emphasis on the system self-sufficiency”, it is concluded that:

- Microaerobic reactor (UMSB) achieved higher stability in COD removal efficiency (greater than 88.5%). At appropriate dosages such as 0.25 LO_2 $L_{feed}^{-1}d^{-1}$ with 10 and 12h HRT a biogas with larger volume and higher methane concentrations was found compared to the UASB reactor;
- Dosages higher the assimilation capacity of the reactor can cause methane dilution, making the electrical energy recovery unfeasible (below 40% methane);
- UMSB reactor with adequate dosages of air could remain energetically self-sufficient, keeping the operation financially feasible.

Regarding the third specific objective, “To study the possibility of applying the biogas recovered from the treatment of SWW in UASB and UMSB reactors for energy generation”, it is concluded that:

- The UASB reactor has the potential to generate 1.6 a 2.6 kWh $kgCOD_{rem}^{-1}$ and the UMSB reactor 1.2 a 2.3 kWh $kgCOD_{rem}^{-1}$. These values are well above those obtained for UASB reactors treating different categories of wastewater. Both reactors under specific conditions can be applied for electricity generation.

- However, some observations should be monitored in UMSB systems for better reactor performance, such as the values of HRT applied and the consequent airflow generated as a function of the SWW flow rate. Lower HRT values generate higher flows, causing the increase of the air dose in the reactor, which can lead to methane dilution and financial losses.

7 RECOMMENDATIONS

From the evaluation of the results obtained in the present work, it is recommended for future work:

- Evaluate the dissolved and gaseous methane losses in SWW AD in UASB reactors to delineate ranges, which can improve the model;
- Validate the model by applying it for estimation in real scale treatment systems and conditions, with the final aim of confirming the model accuracy;
- Evaluate practically (with a generator) how much energy can be recovered with biogas from UASB and UMSB reactors to validate the yields obtained in this research;
- Evaluate the best dosages of microaeration in full-scale reactors in order to validate the potential in methane generation, digestion efficiency, and stability;
- Propose a possible pretreatment given the amounts of particulate COD that can be identified in SWW.

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