UNIVERSITAT ROVIRA I VIRGILI

SUSTAINABLE FUEL PRODUCTION: A MULTICRITERIA ANALYSIS OF BIOMASS AND SEWAGE SLUDGE CONVERSION PROCESSES

Mostafa Zarandi

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Sustainable Fuel Production: A Multicriteria Analysis of Biomass and Sewage Sludge Conversion Processes

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DOCTORAL THESIS

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Sustainable Fuel Production: A Multicriteria Analysis of Biomass and Sewage Sludge Conversion Processes

Doctoral Thesis

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ROVIRA i VIRGILI

We state that the presented study, entitled, "Sustainable Fuel Production: A Multicriteria Analysis of Biomass and Sewage Sludge Conversion Processes" presented by Mostafa Zarandi for the award of the degree of Doctor, has been carried out under our supervision at the Department of Chemical Engineering of this university.

Tarragona, 31st August 2024

Doctoral Thesis Supervisor

Dr. Laureano Jiménez Esteller   Dr. Josep Maria Mateo Sanz

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Summary

The ongoing global energy landscape is undergoing significant changes, with a strong push towards sustainable and low-carbon energy sources. This shift is necessitated by the increasing urgency to tackle climate change while covering the rising global energy demand. Fossil fuels still dominate the energy sector, contributing to approximately 80% of primary energy consumption. However, the International Energy Agency (IEA) projects that the demand for liquid fuels, particularly crude oil and natural gas, will soon peak, further aggravating environmental issues like greenhouse gas (GHG) emissions. As the world faces the challenge of balancing energy needs with environmental sustainability, there is growing interest in alternative energy sources and technologies.

This PhD thesis explores innovative solutions for enhancing the sustainability of liquid fuel production, focusing on two critical areas: the extraction of biodiesel from sewage sludge in wastewater treatment plants (WWTPs) and the integration of biomass and natural gas in hybrid processes to produce liquid fuels.

The first part of the research investigates the potential of sewage sludge, a byproduct of wastewater treatment, as a viable feedstock for biodiesel production. The study evaluates various process alternatives, emphasizing the importance of incorporating circular economy principles to achieve economic and environmental efficiency. A key innovation in this research is the solvent extraction from wet sewage sludge, which bypasses the costly drying step. The works demonstrates that wet extraction processes with low solvent and acid usage outperforms dry alternatives in both economic and environmental metrics. Additionally, the research highlights the trade-offs associated with increasing the number of extraction stages, which, while improving financial returns, also elevate environmental impacts. A multi-criteria analysis was conducted to identify the optimal process configuration, balancing financial and environmental considerations. The analysis in chapter II revealed that a process with a 0.5:1 hexane-to-biomass ratio, a three-stage extractor, a 60-minute residence time, and a pH of 4 emerged as the most favorable option .

The second part of the thesis addresses the inefficiencies in the Biomass-to-Liquid (BtL) process, particularly its low hydrogen content, which limits its competitiveness compared to conventional liquid fuel production. To enhance the BtL process, the study explores the integration of rich hydrogen syngas from the Gas-to-Liquid (GtL) process, creating a hybrid Gas-Biomass-to-Liquid (GBtL) system. The techno-economic analysis conducted in this research identifies an optimal blending ratio of 4.27 between biomass and natural gas in the feedstock. This integration not only improves the overall efficiency of the process but also reduces its environmental

footprint. A life cycle assessment (LCA) of the hybrid system underscores the significant impact of biomass on global warming, with a 30% variation in GHG emissions observed when altering the biomass ratio in the feedstock. The research further evaluates different types of biomass feedstocks, providing insights into supply chain challenges and identifying the most suitable biomass types for sustainable fuel production in chapter III.

This thesis makes several key contributions to the field of sustainable energy. First, it provides a comprehensive assessment of the potential for biodiesel production from sewage sludge, offering a viable pathway for integrating wastewater treatment with energy generation. Second, it presents a novel approach to improving the efficiency of BtL processes through the integration of hydrogen-rich syngas from GtL processes, contributing to the development of more competitive and environmentally friendly liquid fuels. The research also highlights the importance of multi-criteria decision-making and life cycle assessment in optimizing process design, balancing economic, environmental, and social factors.

In summary, this thesis advances the understanding and development of sustainable liquid fuel production processes, providing valuable insights into the integration of circular economy principles in WWTPs and the enhancement of BtL processes through hybrid systems. These contributions are crucial for supporting decision-making in the energy sector, promoting the transition to low-carbon energy, and achieving global sustainability targets.

Resumen

El panorama energético mundial está experimentando cambios significativos, con un fuerte impulso hacia fuentes de energía sostenibles y sin emisiones de carbono. Este cambio es necesario debido a la creciente urgencia de abordar el cambio climático y satisfacer la creciente demanda mundial de energía. Los combustibles fósiles aún dominan el sector energético, contribuyendo aproximadamente al 80% del consumo mundial de energía primaria. Sin embargo, la Agencia Internacional de Energía prevé que la demanda de combustibles líquidos, en particular petróleo y gas natural, pronto alcanzará su máximo, agravando aún más los problemas ambientales como las emisiones de gases de efecto invernadero (GEI). A medida que el mundo se enfrenta al desafío de equilibrar las necesidades energéticas con la sostenibilidad ambiental, existe un creciente interés en las fuentes y tecnologías alternativas.

Esta tesis doctoral explora soluciones innovadoras para mejorar la sostenibilidad de la producción de combustibles líquidos, centrándose en dos áreas críticas: la extracción de biodiésel de lodos de depuradora en plantas de tratamiento de aguas residuales y la integración de biomasa y gas natural en procesos híbridos para producir combustibles líquidos. La primera parte de la investigación analiza el potencial de los lodos de depuradora, un subproducto del tratamiento de aguas residuales, como materia prima para la producción de biodiésel. El estudio evalúa varias alternativas, destacando la importancia de incorporar principios de economía circular para lograr tanto la eficiencia económica como la ambiental. Una innovación clave en este trabajo es la extracción con disolventes de lodos de depuradora húmedos, que evita el elevado coste del secado. El estudio demuestra que el proceso de extracción húmeda con bajo uso de disolvente y ácido supera a las alternativas secas tanto en métricas económicas como ambientales. Además, la investigación destaca las desventajas asociadas con el aumento del número de etapas de extracción, que, si bien mejoran el retorno financiero, elevan los impactos ambientales. Se realizó un análisis de multicriterio para identificar la configuración óptima del proceso, equilibrando las consideraciones económicas y ambientales. El análisis realizado en el capítulo 2 reveló que un proceso con una relación hexano-biomasa de 0,5:1, un extractor de tres etapas, un tiempo de residencia de 60 minutos y un pH de 4 como la opción más favorable. La segunda parte de la tesis aborda las ineficiencias del proceso de conversión de biomasa en líquido (BtL), en particular su bajo contenido en hidrógeno, que limita su competitividad en comparación con la producción convencional de combustibles líquidos. Para mejorar el proceso BtL, el estudio explora la integración de gas de síntesis rico en hidrógeno del proceso de conversión de gas en líquido (GtL), creando un sistema híbrido de gas-biomasa en líquido (GBtL). El análisis tecno-económico realizado identifica una *ratio* de mezcla óptima

de 4,27 entre biomasa y gas natural en la materia prima. Esta integración no solo mejora la eficiencia general del proceso, sino que también reduce su huella ambiental. Una evaluación del ciclo de vida del sistema híbrido subraya el impacto significativo de la biomasa en el calentamiento global, con una variación del 30% en las emisiones de GEI observada al alterar la relación de biomasa en la materia prima. La investigación evalúa además diferentes biomasas como materia prima, proveyendo información sobre los desafíos de la cadena de suministro e identificando los tipos de biomasa más adecuados para la producción de combustible sostenible, tal y como se muestra en el capítulo 3.

Esta tesis hace varias contribuciones clave al campo de la energía sostenible. En primer lugar, proporciona una evaluación integral del potencial de producción de biodiésel a partir de lodos de depuradora, ofreciendo una vía viable para integrar el tratamiento de aguas residuales con la generación de energía. En segundo lugar, presenta un enfoque novedoso para mejorar la eficiencia de los procesos BtL mediante la integración de gas de síntesis rico en hidrógeno de los procesos GtL, contribuyendo al desarrollo de combustibles líquidos más competitivos y respetuosos con el medio ambiente. La investigación también destaca la importancia de la toma de decisiones multicriterio y la evaluación del ciclo de vida para optimizar el diseño de procesos, equilibrando los factores económicos, ambientales y sociales.

En resumen, esta tesis avanza en la comprensión y el desarrollo de procesos de producción de combustibles líquidos sostenibles, brindando información valiosa sobre la integración de los principios de la economía circular en las plantas de tratamiento de aguas residuales y la mejora de los procesos BtL a través de sistemas híbridos. Estas contribuciones son cruciales para respaldar la toma de decisiones en el sector energético, promover la transición a la energía baja en carbono y lograr los objetivos globales de sostenibilidad.

Resum

El panorama energètic mundial està experimentant canvis significatius, amb una forta empenta cap a fonts d'energia sostenibles i baixes en emissions de carboni. Aquest canvi és necessari per la creixent urgència per fer front al canvi climàtic i satisfer la creixent demanda energètica mundial. Els combustibles fòssils encara dominen el sector energètic, contribuint a aproximadament el 80% del consum mundial d'energia primària. No obstant això, l'Agència Internacional de l'Energia (IEA) projecta que la demanda de combustibles líquids, especialment el petroli i el gas natural, arribarà aviat al seu punt màxim, agreujant encara més els problemes ambientals com les emissions de gasos d'efecte hivernacle (GEH). A mesura que el món s'enfronta al repte d'equilibrar les necessitats energètiques amb la sostenibilitat ambiental, hi ha un interès creixent per les fonts i tecnologies d'energia alternatives.

Aquesta tesi doctoral explora solucions innovadores per millorar la sostenibilitat de la producció de combustibles líquids, centrant-se en dues àrees crítiques: l'extracció de biodièsel dels fangs de depuradora a les depuradores d'aigües residuals i la integració de biomassa i gas natural en processos híbrids per produir combustibles líquids.

La primera part de la recerca investiga el potencial dels fangs de depuradora, un subproducte del tractament d'aigües residuals, com a matèria primera per a la producció de biodièsel. L'estudi avalua diverses alternatives de procés, destacant la importància d'incorporar principis d'economia circular per aconseguir l'eficiència econòmica i ambiental. Una innovació clau en aquesta investigació és l'extracció amb dissolvent dels fangs de depuradora humits, que evita el costós pas d'assecat. L'estudi demostra que els processos d'extracció humit amb un baix ús de dissolvents i àcids superen les alternatives seques tant en mètriques econòmiques com ambientals. A més, la investigació posa de manifest els compromisos associats a l'augment del nombre d'etapes d'extracció, que, alhora que millora el rendiment financer, també augmenta els impactes ambientals. Es va realitzar una anàlisi multicriteri per identificar la configuració òptima del procés, equilibrant les consideracions financeres i ambientals. L'anàlisi va revelar que un procés amb una relació hexà-biomassa de 0,5:1, un extractor de tres etapes, un temps de residència de 60 minuts i un pH de 4 va ser l'opció més favorable.

La segona part de la tesi aborda les ineficiències del procés Biomassa-a-Líquid (BtL), especialment el seu baix contingut en hidrogen, que limita la seva competitivitat en comparació amb la producció de combustible líquid convencional. Per millorar el procés BtL, l'estudi explora la integració de gas de síntesi d'hidrogen ric a partir del procés Gas-to-Liquid (GtL), creant un sistema híbrid Gas-Biomassa-Líquid (GBtL).

L'anàlisi tecnoeconòmica realitzada al capítol 2 en aquesta investigació identifica una relació de mescla òptima de 4,27 entre la biomassa i el gas natural com a matèria primera. Aquesta integració no només millora l'eficiència global del procés sinó que també redueix la seva petjada ambiental. L‘avaluació del cicle de vida (ACV) del sistema híbrid subratlla l'impacte significatiu de la biomassa en l'escalfament global, amb una variació del 30% en les emissions de GEH observades en alterar la relació de biomassa en la matèria primera. La investigació avalua encara més tipus de matèries primeres de biomassa, proporcionant informació sobre els reptes de la cadena de subministrament i identificant els tipus de biomassa més adequats per a la producció de combustibles sostenibles, com es pot consultar al capítol III.

Aquesta tesi fa diverses contribucions clau al camp de l'energia sostenible. En primer lloc, proporciona una avaluació exhaustiva del potencial de producció de biodièsel a partir de fangs de depuradora, oferint una alternativa viable per integrar el tractament d'aigües residuals amb la generació d'energia. En segon lloc, presenta una nova perspectiva per millorar l'eficiència dels processos BtL mitjançant la integració de gas de síntesi ric en hidrogen dels processos GtL, contribuint al desenvolupament de combustibles líquids més competitius i respectuosos amb el medi ambient. La investigació també destaca la importància de la presa de decisions multicriteri i l'avaluació del cicle de vida per optimitzar el disseny de processos, equilibrant els factors econòmics, ambientals i socials.

En resum, aquesta tesi avança en la comprensió i el desenvolupament de processos sostenibles de producció de combustibles líquids, proporcionant coneixements valuosos sobre la integració dels principis d'economia circular a les EDAR i la millora dels processos BtL mitjançant sistemes híbrids. Aquestes contribucions són crucials per donar suport a la presa de decisions en el sector energètic, promoure la transició cap a una energia baixa en carboni i assolir els objectius globals de sostenibilitat.

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Chapter I

Introduction

I. Introduction

I.1 Background and motivation

I.1.1 Introduction to the global energy landscape

The global energy landscape is undergoing a profound transformation driven by the need to address climate change and meet the increasing demand for energy. Currently, fossil fuels account for approximately 80% of global primary energy consumption, contributing significantly to greenhouse gas (GHG) emissions and environmental degradation. The International Energy Agency (IEA) projects that the demand for liquid fuels, particularly crude oil and natural gas, will soon peak, exacerbating the challenges associated with fossil fuel dependency. As the world grapples with balancing energy demands with environmental sustainability, there is a growing imperative to explore alternative energy sources and technologies that can reduce the carbon footprint of energy production and consumption [1,2].

I.1.2 The role of sustainable fuel production

In response to these challenges, sustainable fuel production has emerged as a critical area of research and development. Among the various approaches to sustainable fuel production, the use of biomass and sewage sludge as feedstocks for liquid fuel production is particularly promising. These feedstocks are abundant, renewable, and can be processed into biofuels that have a lower environmental impact compared to traditional fossil fuels.

Biomass-to-Liquid (BtL) processes and the conversion of sewage sludge to biodiesel represent two promising pathways to produce sustainable liquid fuels. However, both processes face significant technical and economic challenges, particularly in terms of efficiency and environmental impact. This PhD thesis focuses on enhancing the sustainability of these processes through innovative approaches and multicriteria analysis, aiming to identify the most viable options for large-scale implementation.

I.1.3 Biomass-to-Liquid processes: Opportunities and challenges

Biomass has long been recognized as a key resource for sustainable fuel production due to its widespread availability and potential to reduce GHG emissions. However, traditional BtL processes, which convert biomass into liquid fuels, often suffer from low hydrogen content, limiting their competitiveness with conventional fossil fuel production [3,4]. To address this issue, this research explores the integration of biomass with natural gas in a hybrid Gas-Biomass-to-Liquid (GBtL) system, which combines rich hydrogen syngas from the Gas-to-Liquid (GtL) process with biomass feedstocks. This integration not only improves the overall efficiency of the BtL process but also reduces its environmental footprint check biogenic subsection in chapter III for more details.

The techno-economic analysis conducted in this research identifies an optimal blending ratio of 4.27 between biomass and natural gas in the feedstock in chapter III.3.2. This ratio enhances the hydrogen content of the syngas, thereby improving the yield and quality of the liquid fuel produced. Moreover, a life cycle assessment (LCA) of the hybrid system in chapter III.3.3 underscores the significant impact of biomass on global warming potential, with a 30% variation in GHG emissions observed when altering the biomass ratio in the feedstock. This finding highlights the importance of carefully selecting biomass types and optimizing process parameters to minimize environmental impacts.

I.1.4 Sewage sludge: A viable feedstock for biodiesel production

Sewage sludge, a byproduct of wastewater treatment, represents another promising feedstock for biodiesel production. The disposal of sewage sludge poses significant environmental challenges, including the release of harmful pollutants and the generation of GHGs. However, the relatively high lipid content of sewage sludge makes it an attractive feedstock for biodiesel production through transesterification processes [5].

The research presented in this thesis evaluates various process alternatives for converting sewage sludge into biodiesel, with a focus on wet extraction methods that bypass the costly and energy-intensive drying step [6]. The study in chapter II.3 demonstrates that wet extraction processes, particularly those with low solvent and acid usage, outperform dry alternatives in both economic and environmental metrics. For example, a process configuration with a 0.5:1 hexane-to-biomass ratio, a three-stage extractor, a 60-minute residence time, and a pH of 4 was identified as the most favorable option based on a multicriteria analysis in chapter II 3.2. This process configuration offers a balance between financial returns and environmental impacts, making it a viable option for large-scale biodiesel production.

Moreover, the research highlights the potential for integrating circular economy principles into the biodiesel production process. By utilizing sewage sludge, a waste material, as a feedstock, the process not only produces a valuable fuel but also contributes to waste reduction and resource recovery in wastewater treatment plants (WWTPs). This integration of energy generation with waste management aligns with broader sustainability goals and offers a model for developing similar processes in other regions and industries.

I.1.5 Contribution to sustainable energy solutions

This PhD thesis makes several key contributions to the field of sustainable energy. First, it provides a comprehensive assessment of the potential for biodiesel production from sewage sludge, offering a viable pathway for integrating wastewater treatment with energy generation. Second, it presents a novel approach to improving the efficiency of BtL processes through the integration of hydrogen-rich syngas from GtL processes, contributing to the development of more competitive and environmentally friendly liquid fuels.

Additionally, the research underscores the importance of multicriteria decision-making and life cycle assessment in optimizing process design. By balancing economic, environmental, and social factors, this research offers practical insights and strong solutions for policymakers, engineers, and urban planners working on energy system design and implementation. These solutions are intended to bridge the gap between current practices and the ambitious targets set by global and regional climate strategies, supporting the transition to low-carbon energy and achieving global sustainability targets.

In conclusion, this thesis advances the understanding and development of sustainable liquid fuel production processes, providing valuable insights into the integration of circular economy principles in WWTPs and the enhancement of BtL processes through hybrid systems. These contributions are crucial for supporting decision-making in the energy sector, promoting the transition to low-carbon energy, and achieving global sustainability targets.

I.2 Simulation tools

In the development of sustainable fuel production processes, computer simulation tools play a pivotal role in analyzing and optimizing various technological pathways. These tools provide a virtual environment to model, simulate, and predict the behavior of complex systems under different operational conditions. By doing so, they allow researchers to gain valuable insights into the processes without the need for extensive physical experiments, which can be both costly and time-consuming. Moreover, simulations facilitate the evaluation of various scenarios and strategies, enabling decision-makers to optimize processes for both economic and environmental performance [7,8].

For the simulation of biomass and sewage sludge conversion processes into sustainable fuels, several advanced software tools have been employed. Each of these tools has distinct capabilities and features that make them suitable for modeling different aspects of the fuel production processes.

I.2.1 Process simulation software

Aspen Plus and Aspen HYSYS are two of the most widely used process simulation tools in chemical engineering, particularly for energy and fuel production. Aspen Plus is renowned for its ability to model steady-state processes, handle complex chemical reactions, and provide detailed material and energy balances. It supports a vast range of unit operations and is equipped with a comprehensive database of thermodynamic models and physical properties, making it among the best choice for simulating biomass conversion processes.

In the context of sewage sludge conversion to biodiesel, Aspen HYSYS v.11 has been utilized extensively to simulate various extraction and conversion pathways. For example, it allows the modeling of wet and dry extraction routes, including solvent recovery and reaction stages, providing detailed insights into the material and energy flows of each process alternative. Aspen HYSYS also supports dynamic simulation capabilities, which are beneficial for understanding the transient behavior of systems, especially when integrating multiple processes such as biomass and natural gas conversions. Within the software, components can be specified as either molecular components or pseudo-components, depending on their characterization and the level of detail required for the simulation. Additionally, the models can also include calculation blocks and Fortran blocks to perform more detailed calculations beyond what is handled by standard unit operation models, further enhancing the accuracy and depth of the simulations.

Moreover, Aspen HYSYS can be linked with other software tools like MATLAB, enabling enhanced data analysis and optimization. This integration, achieved through interoperability protocols written in MATLAB, is particularly useful for performing sensitivity analyses, multi-criteria evaluations and optimization. Using these protocols, various scenarios can be tested automatically to identify the optimal conditions for both economic and environmental performance.

I.2.2 Programming language

MATLAB is a high-level programming language and environment for numerical computation, visualization, and programming. In the context of sustainable fuel production, MATLAB is often used in conjunction with process simulation tools like Aspen HYSYS to automate complex calculations, perform sensitivity analyses, and optimize process parameters. MATLAB's robust computational capabilities and extensive library of functions allow for detailed data manipulation and the development of custom algorithms tailored to specific research needs. Some of the most useful MATLAB toolboxes in chemical engineering and process optimization include the Optimization Toolbox, which provides solvers for linear programming, nonlinear programming, and mixed-integer programming, allowing engineers to optimize process variables efficiently. Another key toolbox is the Curve Fitting Toolbox, which helps in modeling and analyzing reaction kinetics data by fitting curves to experimental data. Additionally, the Simulink and Simscape toolboxes are valuable for simulating and modeling dynamic systems and processes, enabling detailed analysis of chemical reactions and process controls.

In the studies involving sewage sludge and biomass, MATLAB v.2019b has been employed to develop an automated evaluation tool that links directly with Aspen HYSYS. This integration facilitates the automated calculation of economic and environmental indicators, streamlining the multi-criteria analysis process. By automating these calculations, researchers can quickly evaluate a wide range of process scenarios, ensuring that the most sustainable and cost-effective solutions are identified.

Fortran, on the other hand, is a powerful programming language used primarily for numerical and scientific computing. In the context of sustainable fuel production, Fortran is typically used for developing custom simulation models and performing detailed numerical analyses that require high computational efficiency. Notably, Fortran is also the language used in AspenPlus software as the basis of the equipment models, which underscores its utility in process simulation and modeling. The use of Fortran in conjunction with other simulation tools allows for the development of specialized models that can handle the complex interactions and detailed physics of biomass and sewage sludge conversion processes.

Excel and Fortran are also commonly used in the simulation and analysis of sustainable fuel production processes. Excel is often employed for data management, basic calculations, and visualization of results. Its accessibility and ease of use make it a valuable tool for preliminary data analysis and for creating simple models that do not require the advanced capabilities of more specialized software.

I.2.3 Environmental tools

SimaPro is a leading software for LCA, widely used to evaluate the environmental impacts of products and processes. In the context of biomass and sewage sludge conversion processes, SimaPro is utilized to conduct LCAs that consider all stages of fuel production, from raw material extraction to final fuel production. By using SimaPro, researchers can identify key areas where environmental improvements can be made, helping to reduce the overall carbon footprint of sustainable fuel production processes.

The Ecoinvent v.3.7.1 database is a comprehensive Life Cycle Inventory (LCI) database widely integrated with SimaPro v.9.2.0.1, one of the leading tools for life cycle assessment. Ecoinvent provides detailed datasets covering many sectors, including energy supply, agriculture, transport, biofuels, chemicals, construction materials, and more. These datasets are crucial for performing life cycle assessments, as they offer extensive information on the environmental impacts of products and processes. In SimaPro, the Ecoinvent database is used to extract inventories, allowing users to model the entire lifecycle of products from raw material extraction to disposal. The data from Ecoinvent is updated regularly to reflect new developments and to improve data accuracy and transparency, ensuring that the assessments are based on the most current and reliable information available.

The integration of SimaPro with process simulation results from tools like Aspen Plus and Aspen HYSYS allows for a comprehensive assessment of both economic and environmental performance. This combined approach ensures that the development of new fuel production processes not only meets technical and economic criteria but also aligns with environmental sustainability goals.

The use of these advanced simulation tools in sustainable fuel production research enables a comprehensive analysis of various technological pathways, helping to identify the most efficient and sustainable processes. By integrating multiple software tools as it is illustrated in Figure 1, researchers can perform detailed economic and environmental assessments, optimize process parameters, and develop innovative solutions that contribute to the global transition towards sustainable energy. As the energy sector continues to evolve, the role of simulation tools in driving sustainable innovation will only become more significant, ensuring that new fuel production technologies meet both the economic needs and environmental goals of the future.

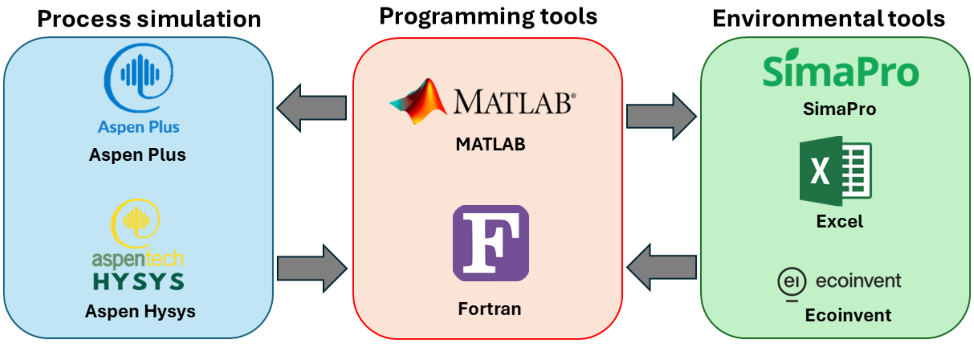

Figure 1. Main connections of the different simulation tools used in the thesis

I.3 Process design

Process design is a fundamental aspect of chemical and biochemical engineering, focusing on developing an optimal flowsheet configuration from numerous alternatives based on raw materials, unit operations, and desired products. Over the past several decades, significant advances in process systems engineering (PSE) have resulted in the development of methods to solve process synthesis problems, particularly for complex systems such as sustainable fuel production [9].

The hierarchical decomposition approach, developed before the widespread use of computers, involves breaking down the overall process design problem into smaller, more manageable sub-problems or decision levels. This method, pioneered by researchers like Siirola and Rudd [10], and later refined by Douglas [11], divides the synthesis problem into five distinct levels. The first decision involves determining whether the process should operate in a batch or continuous mode, considering factors such as product value and lifespan. The next level focuses on establishing the input-output structure, which includes decisions about raw materials, products, by-products, inert components, and their relationships within the process. The third level involves determining the need for recycle flows to minimize waste and improve resource utilization. At the fourth level, the design of separation systems for purifying products and removing impurities is addressed. Finally, the fifth level explores opportunities for process optimization, such as heat integration and resource recovery, to enhance overall efficiency. While this approach simplifies the process design by addressing one decision at a time, it often results in sub-optimal designs due to the lack of consideration for interactions between different decision levels, which are not accounted for in the final design [12,13].

Advancements in computing power and simulation technology have led to the development of simulation-based optimization methods. These methods integrate detailed process simulations with optimization algorithms to find optimal solutions for complex systems that are challenging to model using traditional mathematical programming techniques. Simulation-based optimization does not require an algebraic expression between the objective and decision variables, making it suitable for systems with significant uncertainty and non-linear behaviors [14]. This approach is particularly valuable in the context of sustainable fuel production, where researchers can assess the performance of different feedstocks, process conditions, and technologies under a range of scenarios by combining rigorous process simulations with optimization algorithms.

In the realm of sustainable fuel production, optimizing process design involves using advanced simulation tools to evaluate various conversion processes for both biomass and sewage sludge. For instance, converting biomass and sewage sludge into liquid fuels and biodiesel, respectively, requires careful consideration of feedstock composition, hydrogen content, energy balance, and environmental impacts. Tools like Aspen Plus and Aspen HYSYS are employed to simulate these conversion processes, allowing for detailed assessments of different process configurations and operational conditions. This includes evaluating the use of different biomass types, such as pine pellets, wood pellets, and eucalyptus, alongside the selection of optimal process conditions for biodiesel production from sewage sludge, such as solvent ratios, extraction times, and pH levels. The integration of LCAs further enhances this evaluation by providing insights into the environmental performance of various configurations, thereby guiding the selection of the most sustainable options. Through this approach, process design not only aims to maximize fuel yields and reduce greenhouse gas emissions but also to enhance economic viability by optimizing resource use and minimizing production costs.

In conclusion, the integration of advanced simulation tools and optimization techniques is crucial for designing sustainable fuel production processes. By leveraging methods such as hierarchical decomposition and simulation-based optimization, researchers can explore a wide range of process configurations and identify the most efficient and sustainable solutions. This structured approach to process design, which balances economic and environmental performance, is essential for developing more sustainable energy systems.

The integration of these systems is primarily aimed at lowering overall costs, enhancing productivity, and addressing environmental concerns. For instance, the transportation of biomass significantly influences process costs due to its lower energy density compared to natural coal and gas. Therefore, strategically locating biomass processing units and ensuring efficient supply and feedstock access are crucial. Using multiple feedstocks simultaneously can be an effective solution to these challenges, as it often leads to better efficiency and optimized operational performance than relying on a single feedstock.

I.4 Environmental assessment

Life Cycle Assessment (LCA) is an essential tool for evaluating the environmental impacts of products, processes, or services across their entire life cycle, from the extraction of raw materials to production, usage, and disposal. By adopting a "cradle-to-grave" approach, LCA provides a comprehensive assessment of all stages of a product’s life, identifying resource and energy inputs and outputs and their associated environmental impacts. This methodology is particularly valuable in the field of sustainable fuel production, where understanding the full environmental footprint of different fuel conversion processes is crucial for making informed decisions and promoting sustainability [15].

The LCA methodology is standardized by the International Organization for Standardization (ISO) under ISO 14040 and ISO 14044, which outline four key phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. These phases ensure a structured and consistent approach to evaluating environmental impacts, enabling comparisons between different products or processes [16,17].

I.4.1 Goal and scope definition

The first phase, goal and scope definition, sets the foundation for the LCA study by outlining its purpose, functional unit, system boundaries, and the specific impact categories to be assessed. This step is critical as it influences the subsequent phases of the LCA, shaping how data is collected and analyzed. For sustainable fuel production, the goal is to assess the environmental impacts of converting biomass and sewage sludge into liquid fuels and biodiesel, respectively. The functional unit, which is the basis for comparison, could be defined as the production of a certain amount of fuel (e.g., one liter of biodiesel) to ensure consistency across different processes. System boundaries delineate the life cycle stages included in the analysis, such as raw material extraction, processing, transportation, usage, and end-of-life disposal [16,17].

In sustainable fuel production, the scope definition often includes a "cradle-to-grave" perspective, covering all stages from raw material acquisition to fuel combustion and waste management. This comprehensive view is essential for capturing the full range of environmental impacts associated with each fuel type, including greenhouse gas emissions, energy use, and resource depletion. Defining the impact categories and the corresponding indicators, such as global warming potential (GWP) or ozone layer depletion, further helps in evaluating specific environmental concerns relevant to the fuel production processes [16,18].

I.4.2 Inventory analysis

The inventory analysis phase involves compiling a detailed inventory of all inputs and outputs within the system boundaries defined in the goal and scope phase. This includes data on resource consumption, energy use, emissions to air, water, and soil, and waste generation throughout the product’s life cycle. In the context of sustainable fuel production, this phase requires collecting data on biomass feedstocks, such as pine pellets, wood pellets, and eucalyptus, as well as sewage sludge used for biodiesel production. Inputs like fertilizers, water, and energy for cultivation, processing, and transportation are also accounted for, along with outputs such as emissions from combustion and waste products from processing [19,20].

Data collection for inventory analysis can be challenging due to the need for high-quality, site-specific data. To address this, LCA practitioners often rely on databases like Ecoinvent [21] and GaBi [22], which provide comprehensive datasets on industrial processes, including energy production, transportation, and waste management. These databases facilitate the accurate modeling of environmental impacts by providing standardized data for various inputs and outputs, thereby supporting the robustness of the LCA study.

I.4.3 Impact assessment

During the impact assessment phase, the collected inventory data is translated into potential environmental impacts using characterization factors that convert emissions and resource use into indicators of environmental harm. This phase typically includes several steps: classification, characterization, normalization, and weighting factors. Classification involves sorting the inventory data into relevant impact categories, such as climate change or human toxicity. Characterization quantifies the potential impacts using scientific models and indicators, such as CO2 equivalents for global warming potential [23,24].

For example, the ReCiPe 2016 framework is commonly used to assess impacts across three main areas: ecological quality, human health, and resource depletion. This framework allows for a detailed analysis of the environmental burdens associated with each stage of the fuel production process, from raw material extraction to final disposal. Normalization adjusts the characterized results to a common scale, making them comparable across different impact categories, while weighting assigns relative importance to each category based on stakeholder values or policy objectives [20,25,26].

I.4.4 Interpretation

The final phase of the LCA is the interpretation of the results, which involves analyzing the data to identify significant environmental impacts and potential areas for improvement. This phase is crucial for decision-makers, as it helps pinpointing where efforts should be focused to reduce environmental burdens and enhance sustainability. The interpretation process also includes evaluating the robustness of the results, considering uncertainties and sensitivities in the data and assumptions used in the study [16].

In the context of sustainable fuel production, the interpretation phase might reveal that certain feedstocks, such as eucalyptus or pine pellets, have higher associated GHG emissions due to transportation distances or energy-intensive processing methods. Conversely, the use of sewage sludge for biodiesel production might show lower environmental impacts, particularly if waste management benefits are accounted for in the analysis. Additionally, the shift to green fuels can sometimes lead to unintended burden shifting, where reducing one environmental impact, such as GHG emissions, inadvertently increases another, such as water use or land use. By identifying these differences and potential trade-offs, LCA helps guide decisions on feedstock selection, process optimization, and technology deployment to achieve more sustainable fuel production systems.

I.4.5 Application of LCA in biomass and sewage sludge conversion

In this thesis, LCA is applied to assess the environmental performance of converting biomass and sewage sludge into liquid fuels and biodiesel, respectively. The process begins with defining the goal and scope, which includes determining the functional unit (e.g., one liter of fuel) and setting the system boundaries to cover all relevant life cycle stages. Inventory data is collected using simulation tools like Aspen Plus and Aspen HYSYS, which model the conversion processes and provide detailed information on material and energy flows [20].

For biomass conversion, the LCA considers various feedstocks, such as pine pellets, wood pellets, and eucalyptus, and evaluates their environmental impacts based on factors like energy use, emissions, and resource depletion. The impact assessment phase uses characterization models to translate these data into environmental indicators, such as GWP and eutrophication potential, enabling a comprehensive comparison of different feedstocks and process configurations (chapter III.3).

Similarly, for sewage sludge conversion to biodiesel, the LCA examines different extraction methods, including wet and dry processes, to identify the most sustainable option. The impact assessment phase evaluates the environmental trade-offs of each method, considering factors like solvent use, energy consumption, and waste generation. By integrating these findings into the LCA framework, the study provides valuable insights into the environmental performance of various fuel production pathways, helping to identify opportunities for reducing impacts and enhancing sustainability.

LCA is a standardized methodology that provides a thorough evaluation of environmental impacts by considering all stages of a product’s life cycle. It helps businesses and policymakers making more informed decisions by offering insights into the environmental implications of different processes and products. This approach supports evidence-based policymaking, strategic planning, and product development by highlighting key areas where improvements can be made to reduce environmental impacts [24].

In conclusion, LCA is a powerful tool for assessing the environmental impacts of sustainable fuel production processes, as the financial perspective is key in any decision process. By following a standardized methodology, LCA provides a comprehensive view of the environmental burdens associated with different feedstocks and conversion methods, guiding decisions on process optimization and technology deployment. The application of LCA in this thesis demonstrates its value in evaluating the sustainability of biomass and sewage sludge conversion, offering a pathway towards more environmentally friendly fuel production systems.

I.5 Economic assessment

Economic Assessment is a crucial component in evaluating the feasibility and sustainability of fuel production processes [27]. In the context of chemical engineering and sustainable fuel production, economic assessments involve analyzing the costs, benefits, and financial viability of various production methods. This section will outline general methods and approaches used in economic assessments, followed by a detailed discussion of the specific methodologies applied in this thesis to evaluate the economic aspects of converting biomass and sewage sludge into sustainable fuels.

I.5.1 General methods and approaches in economic assessment

Economic assessment in chemical process design typically involves several key steps, including estimating capital and operating costs, analyzing profitability, and conducting sensitivity analyses. These assessments help determine whether a process is financially viable and how different variables impact the overall cost structure and profitability.

1. Capital and Operating Cost Estimation: The estimation of capital and operating costs is fundamental in economic assessments. Capital costs, or fixed costs, include expenses related to the construction of a plant, such as the purchase and installation of equipment, piping, instrumentation, and electrical systems. Operating costs, on the other hand, are recurring expenses related to the daily operation of the plant, including raw materials, utilities, labor, maintenance, and waste disposal [28].
2. Total Product Cost (TPC): Total product costs are commonly calculated on a daily, unit-of-product, or annual basis, with the annual cost basis often preferred for a comprehensive overview. TPC is a summation of all costs associated with the production process, including manufacturing costs (operating or production costs), general expenses (sales, administration, research, engineering), fixed charges, and variable production costs [28]. It provides a complete picture of the financial requirements for producing a product.
3. Profitability Analysis: This involves calculating metrics such as net present value (NPV), internal rate of return (IRR), payback period, and return on investment (ROI) to evaluate the economic performance of a project. Profitability analysis helps in determining whether a project will generate sufficient returns over its lifetime to justify the initial investment. This analysis considers both the revenues generated from product sales and the costs incurred during production [29].
4. Sensitivity Analysis: Sensitivity analysis examines how changes in key variables, such as raw material prices, production rates, and market conditions, affect the economic outcomes of a project. This analysis helps identifying the critical factors that influence profitability and assess the robustness of the economic model under different scenarios. It is particularly useful in identifying potential risks and optimizing process parameters to enhance financial performance [30].
5. Break-Even Analysis: This method determines the production level at which total revenues equal total costs, resulting in neither profit nor loss. The break-even point provides insight into the minimum

production capacity required for a project to be financially viable. It is an important tool for assessing the economic feasibility of a new process or plant expansion [31,32].

I.5.2 Economic assessment methods used in this thesis

In this thesis, two specific economic assessment methodologies were applied to evaluate the sustainability of converting biomass and sewage sludge into liquid fuels and biodiesel. The methodologies used include detailed cost estimation and profitability analysis, tailored to the unique characteristics of each feedstock and conversion process.

1. Cost estimation for biomass and sewage sludge conversion:

For both biomass and sewage sludge conversion processes, the economic assessment involved detailed cost estimation using various methods to calculate capital costs for each piece of equipment. These costs were derived using techniques like the Guthrie method, the Peters and Timmerhaus method, and Lang factors [28,32].

- Guthrie Method: The Guthrie method is a widely used approach for estimating the costs of chemical process equipment. It involves calculating the bare module cost (BMC), which includes both direct and indirect costs associated with purchasing and installing equipment. The BMC is calculated using Equation (1):

$$C_{BM} = C_{\mathrm{B}} \times F_{\mathrm{BM}} \tag{1}$$

where C_{BM} is the bare module cost, C_{B} is the base cost of the equipment, and F_{BM} is the bare module factor. The bare module factor accounts for additional costs such as installation, instrumentation, and piping. The base cost is typically derived from cost correlations based on equipment capacity and type, using a standard reference year and adjusted for inflation to the current year [28,32].

The bare module factor F_{BM} can be calculated using Equation (2) that accounts for different aspects of installation:

$$F_{BM} = (1 + fd + fp + fi + fc + fe) \tag{2}$$

where:

fd = direct costs (e.g., materials, labor),

fp = piping costs,

fi = instrumentation costs,

fc = controls costs,

fe = electrical costs.

By adding these components, the bare module factor reflects a comprehensive set of installation expenses.

- Peters and Timmerhaus Method: The Peters and Timmerhaus method [28] is another commonly used approach for estimating capital costs, especially when scaling up or down from known equipment sizes. This method uses cost-capacity equations, which are expressed in Equation (3):

$$C = C_{\text{ref}} \left(\frac{S}{S_{\text{ref}}} \right)^{n} \tag{3}$$

where:

C = cost of the equipment to be estimated,

C_{ref} = known cost of the reference equipment,

S = size or capacity of the equipment being considered,

S_{ref} = size or capacity of the reference equipment,

n = scaling exponent (typically ranging from 0.6 to 0.7 for most chemical process equipment).

This equation allows for estimating the cost of equipment of different sizes based on a known reference, considering the economies of scale.

- Lang Factors: Lang factors are another technique used to estimate total capital investment based on the purchased cost of major equipment. The total capital investment C_{total} is estimated by multiplying the total equipment cost by a Lang factor, which accounts for the total installed costs, including installation, piping, electrical work, and other indirect costs as formulated in Equation (4):

  $$C_{total} = F_{Lang} \times C_{equip} \tag{4}$$

  where:

  C_{total} = total capital investment,

  F_{Lang} = Lang factor (typically ranges from 3 to 5 depending on the complexity of the process),

  C_{equip} = total purchased equipment cost.

  Lang factors provide a quick way to approximate total capital investment when detailed cost information is not available [28].

For the biomass conversion process, equipment costs were calculated using these methods for key components such as reactors, heat exchangers, distillation columns, and compressors. The equipment costs were then aggregated to determine the total capital investment required for the plant.

For the sewage sludge conversion to biodiesel, similar methods were applied to estimate the costs of equipment used in the extraction and conversion processes. The capital costs for equipment like centrifuges, mixers, and extraction columns were calculated using the Guthrie method and Peters and Timmerhaus method.

2. Operating and maintenance costs:

Operating costs for both processes included raw material costs, utilities (such as electricity, water, and steam), labor, and waste management. For biomass conversion, the cost of raw materials was based on market prices for various feedstocks like pine pellets, wood pellets, and eucalyptus. For sewage sludge conversion, the feedstock cost was minimal since sewage sludge is a waste product; however, preprocessing costs such as dewatering and transportation were considered [20].

Maintenance costs were estimated as a percentage of the capital costs, reflecting the routine maintenance and periodic replacement of equipment components. These costs were factored into the total cost of ownership for the plant, providing a comprehensive view of the economic requirements for sustained operation.

3. Profitability Analysis: Profitability analysis for both biomass and sewage sludge conversion processes was conducted using metrics such as NPV, ROI, IRR, and payback period. The NPV was calculated by discounting the expected cash flows from the sale of liquid fuels and biodiesel over the project’s lifetime to their present value, using a discount rate that reflects the cost of capital. The IRR was computed to determine the discount rate at which the NPV of the project would be zero, indicating the project's break-even point in terms of profitability.

The payback period was assessed to determine the time required for the project to recover its initial investment from net cash inflows. A shorter payback period was preferred as it indicates a lower risk and quicker recovery of capital.

4. Sensitivity Analysis: Sensitivity analysis was performed to evaluate the impact of variations in key economic parameters on the profitability of the biomass and sewage sludge conversion processes. Parameters such as feedstock cost, product price, utility cost, and operating efficiency were varied within realistic ranges to assess their effects on profitability. This analysis helped identify the most sensitive factors influencing economic performance and provided insights into optimizing process conditions to enhance financial viability [20].

In summary, the economic assessment methods applied in this thesis provide a comprehensive evaluation of the financial feasibility of converting biomass and sewage sludge into sustainable fuels. By integrating detailed cost estimation, profitability analysis, and sensitivity analysis, the study offers valuable insights into the economic challenges and opportunities associated with these conversion processes. This approach ensures that the proposed sustainable fuel production methods are not only environmentally friendly but also economically viable, supporting their potential for large-scale adoption and contributing to the transition towards a sustainable energy future.

I.6 Thesis outline

This thesis is presented as case study doctoral dissertation. The first chapter introduces the scope and objectives of the research, laying the foundation for the detailed studies that follow. The second chapter, presented as a journal article, focuses on the multicriteria analysis of biodiesel production from sewage sludge, evaluating various process configurations for their economic and environmental impacts. The third chapter, also structured as a journal article, explores the environmental and economic benefits of hybrid natural gas and biomass conversion to liquid fuels, integrating insights from both fossil and renewable resources. Together, these chapters provide a comprehensive examination of sustainable fuel production technologies, with each chapter contributing unique insights and methodologies. The thesis concludes with a summary of the methodologies and findings, underscoring their significance in advancing sustainable fuel production.

I.6.1 Multicriteria analysis of sewage sludge-based biodiesel production (article 1)

This chapter provides a comprehensive review of biodiesel production from sewage sludge, emphasizing the integration of sustainable practices and circular economy principles. The paper utilizes a multicriteria analysis to assess various methods for converting sewage sludge into biodiesel, focusing on economic viability, environmental impact, and technological efficiency. Thirty-two process configurations, including wet extraction, dry extraction, and *in situ* transesterification, are analyzed to identify the most effective and sustainable pathways for biodiesel production as it is demonstrated in Figure 2.

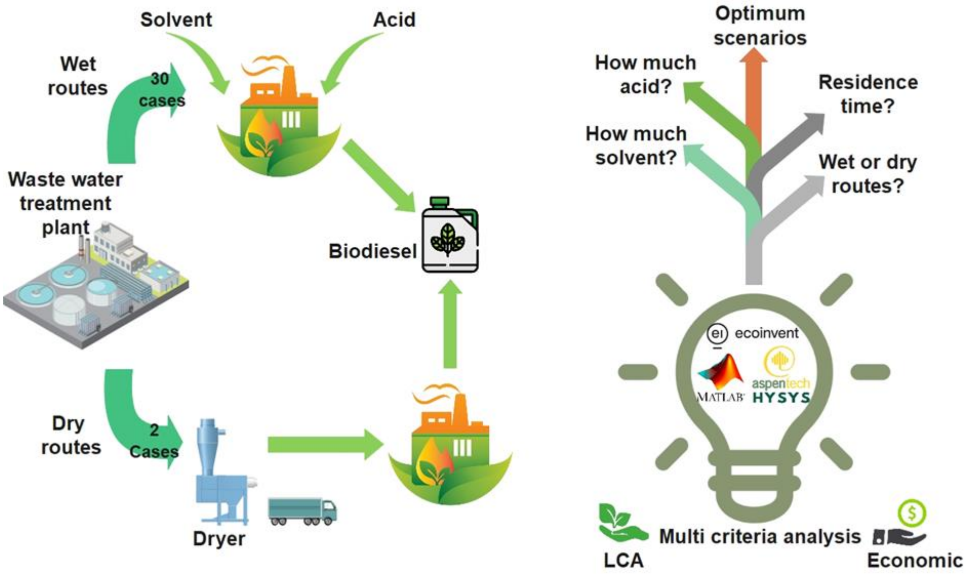

Figure 2. Graphical abstract of Article 1: Multicriteria Analysis of Sewage Sludge-Based Biodiesel Production [20].

Key findings indicate that wet extraction, which eliminates the need for the energy-intensive drying step, offers significant economic and environmental benefits over traditional dry extraction methods. The optimal configuration involves a hexane-to-biomass ratio of 0.5:1, utilizing a three-stage extractor with a 60-minute residence time and a pH of 4. This setup maximizes the yield of fatty acid methyl esters (FAME) while minimizing costs and environmental impacts.

The methodology integrates advanced simulation tools such as Aspen Hysys® and Matlab® to model different scenarios and assess their performance based on various parameters like solvent ratios, extraction stages, and pH levels. Sensitivity analysis is also performed to determine the impact of changing process parameters on overall outcomes, providing a robust framework for future research in sustainable biodiesel production from waste materials.

Detailed findings and methodologies are presented in Chapter II, offering valuable insights into the optimization of biodiesel production processes and the sustainable utilization of sewage sludge as a feedstock.

I.6.2 Exploring the environmental and economic benefits of hybrid natural gas and biomass conversion to liquid fuels

This chapter explores the integration of natural gas and biomass to produce liquid fuels, focusing on the environmental and economic advantages of hybrid conversion processes. The paper investigates the enhancement of biomass-to-liquid (BtL) processes by integrating hydrogen-rich syngas from the gas-to-liquid (GtL) process, creating a hybrid system known as natural gas-biomass to liquid fuels (GBtL). This approach aims to improve the efficiency and sustainability of fuel production by leveraging the complementary characteristics of natural gas and biomass as it is shown in Figure 3.

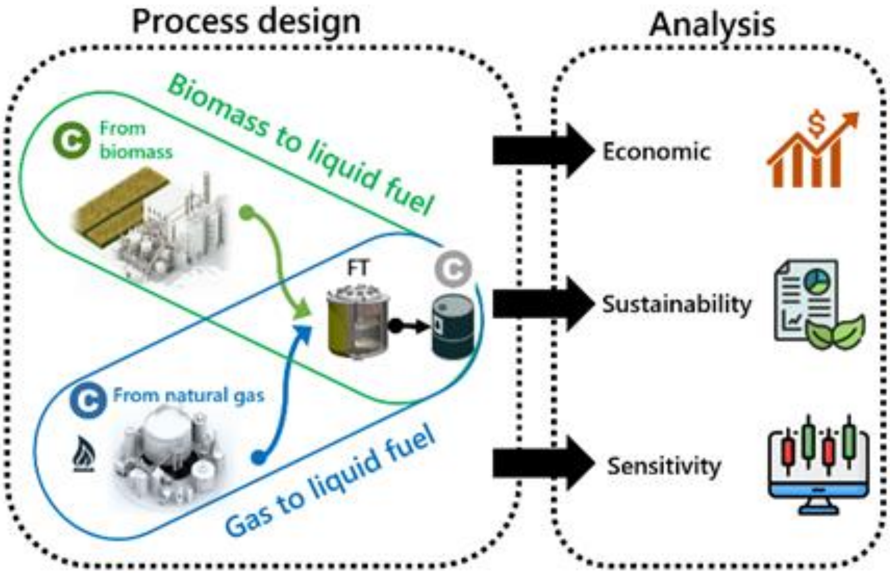

Figure 2. Graphical abstract of Article 3: Exploring the Environmental and Economic Benefits of Hybrid Natural Gas and Biomass Conversion to Liquid Fuels.

The study conducts a techno-economic analysis to determine the optimal blending ratio of biomass and natural gas, finding that a mass ratio of 4.27 offers the best balance between economic viability and environmental performance. The LCA of the hybrid system highlights the significant impact of biomass feedstock on global warming, with a 30% variation in emissions observed when altering the biomass ratio in the feedstock by 30%.

Using process simulation tools like Aspen Plus v11, the paper models the GBtL process, comparing various types of biomass feedstocks to evaluate their economic and environmental performance. The research demonstrates that hybridizing natural gas and biomass conversions can reduce greenhouse gas emissions by nearly half compared to fossil fuel-based processes while maintaining economic competitiveness.

Overall, this paper provides a detailed analysis of the potential benefits of integrating natural gas and biomass for liquid fuel production, emphasizing the importance of optimizing feedstock ratios and process conditions to enhance sustainability and reduce environmental impacts. The methodologies and conclusions drawn from this research are further elaborated in Chapter III, contributing to the development of more sustainable and flexible fuel production technologies.

I.7 General conclusions

This thesis provides an extensive evaluation of sustainable fuel production technologies, specifically focusing on biodiesel production from sewage sludge and hybrid natural gas and biomass conversion to liquid fuels. The following conclusions summarize the key findings, contributions, and implications of this research:

- Integration of sustainable feedstocks for fuel production: This thesis emphasizes the utilization of non-traditional feedstocks, such as sewage sludge and biomass, for producing liquid fuels. Both feedstocks offer significant environmental benefits over conventional fossil fuels due to their renewable nature and ability to reduce GHG emissions. By converting waste materials and renewable resources into fuels, the research aligns with global sustainability goals and circular economy principles.
- Economic and environmental viability of sewage sludge-based biodiesel production: The research highlights the feasibility of producing biodiesel from sewage sludge through optimized wet extraction methods. The study demonstrates that avoiding the energy-intensive drying step, coupled with lower solvent and acid usage,

results in significant cost savings and reduced environmental impact. The optimal configuration identified includes a hexane-to-biomass ratio of 0.5:1, a three-stage extractor, a 60-minute residence time, and a pH of 4. This configuration maximizes the yield of fatty acid methyl esters (FAME) while minimizing operational costs and emissions, making it a viable option for large-scale biodiesel production.

- Advancement in hybrid conversion processes for liquid fuels: By integrating hydrogen-rich syngas from natural gas with biomass feedstocks, the thesis proposes a novel hybrid conversion process known as GBtL. This process enhances the efficiency and sustainability of BtL fuel production by improving hydrogen content and overall process yield. The techno-economic analysis identifies an optimal biomass-to-natural gas blending ratio of 4.27, which significantly improves both economic viability and environmental performance, reducing GHG emissions by nearly half compared to conventional fossil fuel-based processes.
- LCA and multicriteria decision-making: The application of LCA in this research provides a comprehensive evaluation of the environmental impacts associated with each fuel production pathway. The LCA results underscore the importance of selecting the appropriate feedstock and optimizing process parameters to minimize environmental footprints. For instance, the LCA of the hybrid natural gas and biomass conversion system highlights a 30% variation in GWP based on biomass ratio adjustments, demonstrating the critical role of feedstock selection in reducing emissions.
- Optimization of process parameters for enhanced sustainability: The research employs advanced simulation tools like Aspen HYSYS, Aspen Plus, and MATLAB to model various scenarios and optimize process parameters. Sensitivity analyses conducted within these simulations reveal that specific process conditions, such as solvent ratios, extraction times, and feedstock compositions, significantly impact both economic outcomes and environmental performance. This optimization framework allows for the identification of the most sustainable and cost-effective production configurations, supporting the broader goal of sustainable energy transition.

- Contribution to circular economy principles: The thesis contributes to circular economy principles by demonstrating how waste materials, such as sewage sludge, can be transformed into valuable resources through biodiesel production. By diverting sewage sludge from traditional disposal methods and utilizing it as a feedstock, the research not only reduces waste management challenges but also supports resource recovery, recycling in WWTPs and circular economy principles. This integration of waste management with energy production aligns with broader sustainability objectives and offers a model for similar applications in other industries.

- Technological innovations in fuel production: The studies presented in this thesis introduce several technological innovations in fuel production. For example, the hybrid conversion of natural gas and biomass to liquid fuels represents a novel approach that leverages the complementary properties of both feedstocks to enhance process efficiency and sustainability. Similarly, the optimized wet extraction methods for sewage sludge-based biodiesel production demonstrate innovative process improvements that reduce energy consumption and environmental impact, advancing the field of biofuel technology.

- Impacts on global energy transition: This thesis contributes to the global energy transition by providing viable alternatives to fossil fuel-based energy systems. The demonstrated potential of sewage sludge and biomass as sustainable feedstocks for liquid fuel production supports the diversification of energy sources and the reduction of dependence on fossil fuels. By promoting cleaner, more sustainable energy production methods, this research aligns with international efforts to mitigate climate change and achieve net-zero emissions targets.

- Economic benefits and market competitiveness: In addition to environmental benefits, the research also highlights the economic advantages of the proposed fuel production methods. The techno-economic analyses conducted in the thesis reveal that both sewage sludge-based biodiesel production and hybrid natural gas and biomass conversion processes can be economically competitive with traditional fossil fuel production, particularly when optimized for cost-efficiency. These findings suggest that sustainable fuel production technologies have the potential to compete in the market, offering a promising pathway for scaling up and widespread adoption.

- Conclusion and prospects: Overall, this thesis provides a comprehensive analysis of sustainable fuel production processes, offering valuable insights into the integration of renewable feedstocks and innovative technologies. By advancing the understanding of biodiesel production from sewage sludge and hybrid natural gas and biomass conversion, the research supports the development of more sustainable and resilient energy systems. Future research should focus on further refining these processes, exploring additional feedstocks, and expanding the application of multicriteria decision-making tools to enhance sustainability across the energy sector.

I.8 Future work

Throughout this thesis, several key challenges and potential avenues for expanding the current findings have been identified. The following suggestions outline the primary areas where further research could be beneficial, building on the insights gained from this work.

I.8.1 Implementation of prospective life cycle assessment for biomass projects:

A valuable direction for future research involves conducting a prospective LCA for BtL and GBtL processes. As decarbonization of the electricity mix progresses, particularly with increasing adoption of renewable energy sources, the environmental impacts associated with these processes are likely to change significantly. A prospective LCA would provide insights into how future changes in energy systems could alter the GHG emissions and overall environmental performance of biomass-based fuel production [33]. This assessment could help identify potential opportunities for further reducing the carbon footprint of these processes by optimizing energy consumption patterns and integrating emerging low-carbon technologies.

I.8.2 Development of regional biomass databases and feedstock optimization for GBtL plants:

Another area of future research is the development of comprehensive databases that catalog the types and availability of biomass in different regions. This data could be used to optimize the mixture of feedstocks for integrated GBtL plants tailored to the specific biomass profiles of each region. The demonstrated benefits of hybrid conversion processes and sewage sludge utilization suggest that policymakers should consider supporting these technologies through incentives, subsidies, or regulatory frameworks that encourage their adoption. By understanding the regional variations in biomass resources, it would be possible to enhance the economic and environmental performance of GBtL plants. Optimization could involve selecting the most appropriate blend of biomass types to achieve the best balance of hydrogen content, process efficiency, and GHG emission reductions, thereby improving the sustainability and viability of biomass conversion technologies.

I.8.3 Expansion of biodiesel production from sewage sludge:

Building on the promising results of biodiesel production from sewage sludge, future research could expand on the integration of biodiesel production with wastewater treatment processes. Using the international Benchmark Simulation Model 2 (BSM2), this study modeled a WWTP integrated with a biodiesel production facility to evaluate the combined system's economic and environmental performance. Further studies could focus on refining this model to optimize the interactions between the WWTP and the biodiesel plant, considering different sludge processing and extraction techniques. By assessing the entire integrated system, this research aims to enhance resource recovery, improve overall sustainability, and reduce the environmental impact of the entire process.

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Chapter II

Multicriteria analysis of sewage sludge-based biodiesel production

II. Multicriteria analysis of sewage sludge-based biodiesel production

Multicriteria analysis of sewage sludge-based biodiesel production

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II.1 Introduction

The rising awareness of environmental issues, such as global warming, air quality and water scarcity, makes the environmental performance of a process a key indicator for their competitiveness in the market. There is an increasing demand from society for reliable information for traceability of the products. This issue is more significant when dealing with fuels production due to the large dependence of the current lifestyle in developed countries, the environmental burdens and the rising prices as consequences of resource depletion and geopolitical events.

All these factors promote the research on alternative sources of energy to reduce (and in the mid-range replace) the use of fossil fuels. In this line, biofuels will be part of the solution. The world demand for biofuels was around 2 million barrels of oil equivalent per day in 2020 and projections indicate about a 50% growth rate until 2030, while to align with the net-zero emission scenario, it is expected to have a nearly triple biofuels production rate (IEA, 2021). Increasing attention is paid to the processing technologies to achieve, or at least approach, this challenging objective.

Biodiesel, the second most common form of biofuels, can be obtained from vegetable and animal fat oils by catalytic transesterification with linear monohydroxy alcohols. First-generation biodiesel, mainly based on edible vegetable feedstocks, has been gradually replaced by second-generation biodiesel, produced from different types of non-edible biomass such as woody crops and agricultural wastes, thus avoiding the threat over food supplies and biodiversity. However, second-generation biodiesel based on vegetable raw materials depends on agricultural crops, so they compete for scarce cropland, fresh water and fertilizers. Also, the feedstock cost represents the main part of the production cost. In the literature, different feedstocks have been investigated from non-edible crops: *Jatropha* [35], *Cynara cardunculus* [36], waste animal fat [37],waste cooking oil [38] and algae [39]. Nevertheless, the research on these potential resources must face difficulties related to the quality of the biodiesel produced, especially in the case of wastes and residues.

Considering all these issues, sludge-based biodiesel is among the most feasible solutions. Sewage sludge (SS) is less expensive than other raw materials considering that its production in wastewater treatment facilities is expected to increase due to growing urbanization and industrialization [40–42]. The SS has been used in vast applications such as adsorbents, catalysts and fertilizers [43].

Data in some countries shows that wastewater sludge has one of the highest potentials for biodiesel production in comparison with other feedstocks in terms of quantity, collection, and cost [44]. On the other hand, the handling, treatment and disposal of this waste will pose additional costs and environmental burdens. The municipal SS is a good quality source of polar lipids fraction and fatty acids (C_{10} to C_{18}) to produce Fatty Acid Methyl Esters (FAME) [5]. The biodiesel is produced through the transesterification of the oil or fat with a short chain alcohol (usually methanol or ethanol) in the presence of an acid, alkali or enzyme catalyst, where the quality of the resulting biodiesel (e.g., octane number and oxidative stability) depends on the ratio of the different fatty esters. Although the alkali catalyst has a high reaction rate, they require high energy consumption and their feedstock's Free Fatty Acid (FFA) content is limited. Recently, enzyme catalysts have emerged, providing high catalyst activities and specific surface area but from the operational point of view, it is expensive due to the complex preparation steps [45]. The sewage sludge can be collected at two different points of the wastewater treatment plant: the primary sludge, located after the primary clarifier, and the second or activated sludge after the aerobic biological treatment. Figure 1 shows a schematic representation of a wastewater plant connected to a biodiesel production plant. The maximum yield of FAME that can be achieved with primary sludge is higher than with the secondary sludge (≈14.5% and ≈2.5%, respectively). For feedstocks with a high amount of Free Fatty Acids (FFA) and water contents, acid catalysts with transesterification reactions are the best option [46,47].

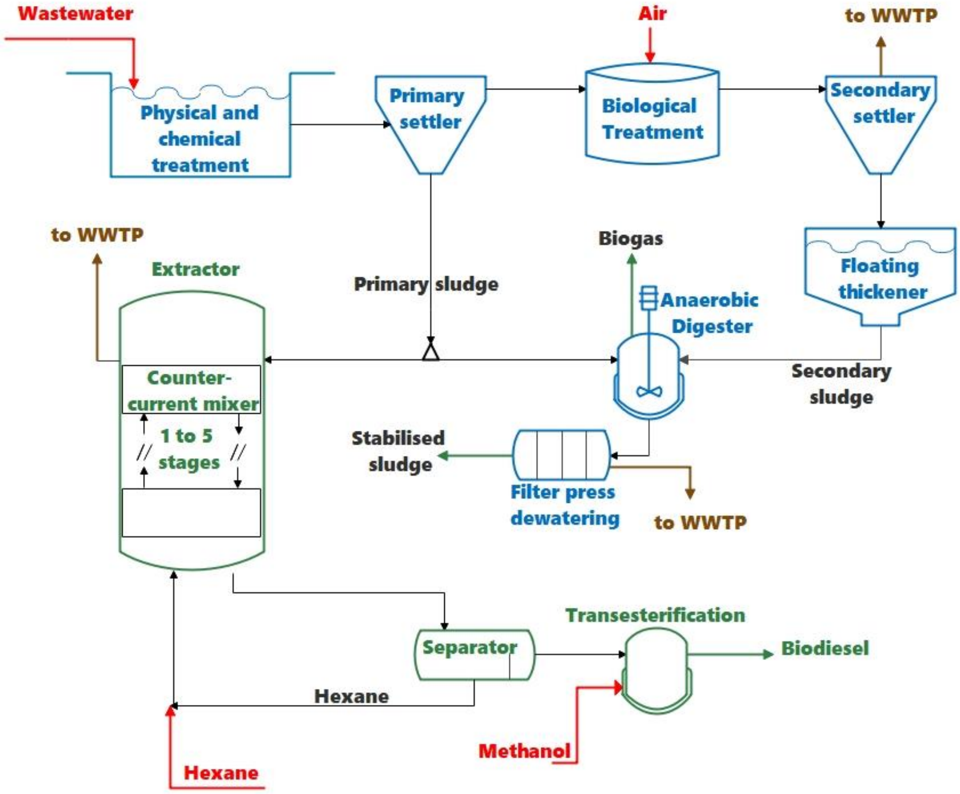


Figure 1. Schematic of a biodiesel production plant connected to the wastewater treatment.

The economy of this process is the main bottleneck to make it competitive with the state-of-the-art technologies. There are many studies about the feasibility of using lipid from sewage sludge as a source for biodiesel. Dufreche et al. (2007) compared the conversion of secondary sludge to biodiesel with different solvents obtaining the most significant conversion using an extraction stage with a mixture of methanol, n-hexane and acetone before an *in situ* transesterification. The authors also presented an estimation of the processing cost on which subsequent studies were inspired. Mondala et al. (2009) propose an *in situ* transesterification of primary and secondary sludge with methanol to dry sewage sludge ratio of 12:1 (w/w) and 5% (v/v) of H_2SO_4. Pokoo-Aikins et al. (2010) modeled the process to optimize the economic aspect, including safety evaluation, compare several extraction solvents, acid esterification pretreatment and alkali transesterification. Kwon et al. (2012) presented an economic analysis of the thermochemical non-catalytic conversion of lipids but assumed that the drying costs are compensated by government subsidies for avoiding the sludge disposal. In the study of Zhang et al. (2013), the sludge lipids conversion to biodiesel in one (direct transesterification) and two stages (extraction plus transesterification) are compared to microalgal-based biodiesel production in terms of energy balance and CO_2 emissions.

In all the aforementioned studies the sewage sludge has to be dried before extraction. The sludge drying typically comprises a concentration step with centrifugation or flocculation plus settling, followed by dewatering plus thermal drying [53]. The route is similar to the one used for microalgae biomass dewatering [54]. As mentioned before, some authors did not include these costs (assuming that government subsidies will cover this part), while others estimate the expenses well below the values resulting from our calculations, although for the best of our knowledge, it can represent ≈50% of the operating cost of the plant. Therefore, new routes for eliminating the costly drying stage and extracting lipid from wet sludge could enhance the feasibility of the process. The experimental result shows that for materials with high lipid content, using direct extraction methods is more efficient [55–57].

It is expected that using wastewater for biodiesel production should strongly decrease the environmental impact compared to conventional fossil fuels. Solvent usage clearly affects the environmental impact of the process, so assessing the environmental impact from a life-cycle approach will provide the perspective to compare different alternatives [45,58,59]. Regarding the environmental criterion, the literature is not rich on biodiesel production from wastewater, although environmental assessment was done for other types of feedstocks, processes, and products [60–63]. Zhang et al. (2013) calculated the GHG of a two-step biodiesel production from wastewater sludge based on emission coefficients. Dufour and Iribarren (2012) reported greenhouse gas emissions of biodiesel production comparing different sources of free fatty acid-rich wastes, including sewage sludge, although only the dry route was evaluated based on the economic results of Revellame et al. (2011). The mentioned studies in the context of biodiesel production from sewage sludge did not consider the trade-off between economic and environmental assessment simultaneously to recommend the most efficient process based on different aspects.

Herein we present a simultaneous economic and environmental evaluation, including Life Cycle Analysis (LCA) of the biodiesel production after lipids extraction from primary sludge directly in the aqueous phase (wet route), by conventional liquid-liquid extraction. The lipids wet extraction route and the effects of pretreatments were studied by Olkiewicz et al. (2015, 2014) which laid the foundations for building a simulation based on experimental data. The wet extraction pathway is compared with two dry extraction routes: conventional extraction followed by lipids conversion and *in situ* transesterification, where extraction and conversion occur in one stage.

The multicriteria evaluation of the 32 different scenarios and technological alternatives is based on the rigorous simulation of all alternatives. The use of Aspen Hysys® v11 allows modeling unit operations based on pre-built and/or customized modules, that enables access to the material and energy balances, and the equipments sizing. These data are required to compute the economic and environmental indicators. Furthermore, Aspen Hysys® can be linked to external tools like Matlab® R2021a. The Matlab® toolbox empowers accessing, registering, modifying and optimizing the simulation, enabling the automation of the evaluation by computing the corresponding metrics and analyzing different scenarios. Moreover, a sensitivity analysis of process variables was carried out.

The aim of this work is to analyze the biodiesel production from primary sewage sludge based on the experiments carried out at the laboratory scale focused on the lipid extraction stage. The comparison of different scenarios and technological alternatives is performed by the simulation-based automated evaluation tool [67]. This computational procedure includes the calculation of economic and environmental indicators to characterize the current state of the technologies and the key variables in their economic and environmental performance. To the best of our knowledge, there is no similar study in the literature that follows a multi-criteria approach with detailed economic and environmental calculations.

Particularly, the presented study aims at demonstrating the feasibility of the best wet extraction route among the different potential alternatives for primary sludge lipids recovery. The same approach and methodology can be used for similar processes to define the benefits and drawbacks of different scenarios. This methodology will unveil the prospective effects of each alternative on different aspects simultaneously, as implementation can be based on different priorities.

II.2 Materials and methods

The procedure followed in the multicriteria analysis is presented in this section. For the ensuing calculations, the location of the biodiesel production plant is a key element in the definition of the system boundaries. Specifically, expenses and emissions related to transport activities of the primary sewage sludge entering the process and the resultant sludge after extraction must be carefully regarded. The philosophy behind this analysis has a wider scope: the efficient design of integrated technologies and management for the energy valorization of different effluents from Wastewater Treatment Plants (WWTP).

We assume that The biodiesel production facility is supplied by a WWTP located at the same site. In this sense, a nearby urban WWTP producing 60 m^3/h of sewage sludge was considered, which corresponds to a capacity of 2 million of equivalent inhabitants. The hypothetical biodiesel production plant has a capacity of treating 475000 metric tons per year of primary sludge (4% of solids), which is equivalent to produce between 2000 and 4700 t/year of biodiesel depending on the yield achieved by the different process alternatives. These technological options and how they have been modeled are described in subsections 2.1 and 2.2. Subsection 2.3 details the computational approach followed to automate the simulation-based multicriteria evaluation and the subsequent monetisation and sensitivity analyses.

II.2.1 Process simulation assumptions

The automated characterization approach is based on the simulation of the plant in Aspen Hysys v11. Some components have been defined as hypothetical solid; this is the case of the inorganic matter and ash content in the sludge, the organic matter different from lipids, the non-saponifiable lipids and the potassium sulfate, for which average molecular weights and densities are defined. Moreover, proxy compounds are used to represent similar substances. More precisely, a mixture of m-palmitate and m-oleate was selected to characterize the biodiesel product, the palmitic acid represents the FFA content, the triolein assumes the role of triglycerides and a saturated fatty acid ester was selected to characterize the non-saponifiable lipids (*i.e.*, cetyl palmitate). The composition of primary sewage sludge, and particularly its lipids composition, was simulated based on to the experimental results obtained by Olkiewicz et al. (2014) (see Table 1).

Table 1. Primary sewage sludge composition [6].

Component	Total %
Water	96
Solids (4%):	
Inorganic content (21.4%)	0.86
Organic content (78.6%):	
Protein (33.2%)	1.04
Carbohydrates (32.0%)	0.96
Lipids (34.8%):	
Non-saponifiables (20%)	0.22
Saponifiables (80%):	
Triglycerides (4%)	0.04
Free fatty acids (96%)	0.84

The Peng-Robinson Soave (PRSV) equation of state was selected to predict all physico-chemical properties. PRSV can predict more accurately the phase behavior of hydrocarbon systems and handle non-ideal systems with equivalent, or better, accuracy than activity coefficient models. Furthermore, PRSV performs rigorous three-phase flash calculations for aqueous systems containing water, methanol or glycols, as well as systems containing hydrocarbons in the second liquid phase.

Figure 2 outlines the process alternatives assessed in this study. The base case scenario is defined for each alternative in subsection 2.2 as reference points for the subsequent sensitivity analysis; it comprises the composition of the sewage sludge, including the lipid content, extraction and reaction conditions, flue gas availability for drying, sewage sludge availability, etc.

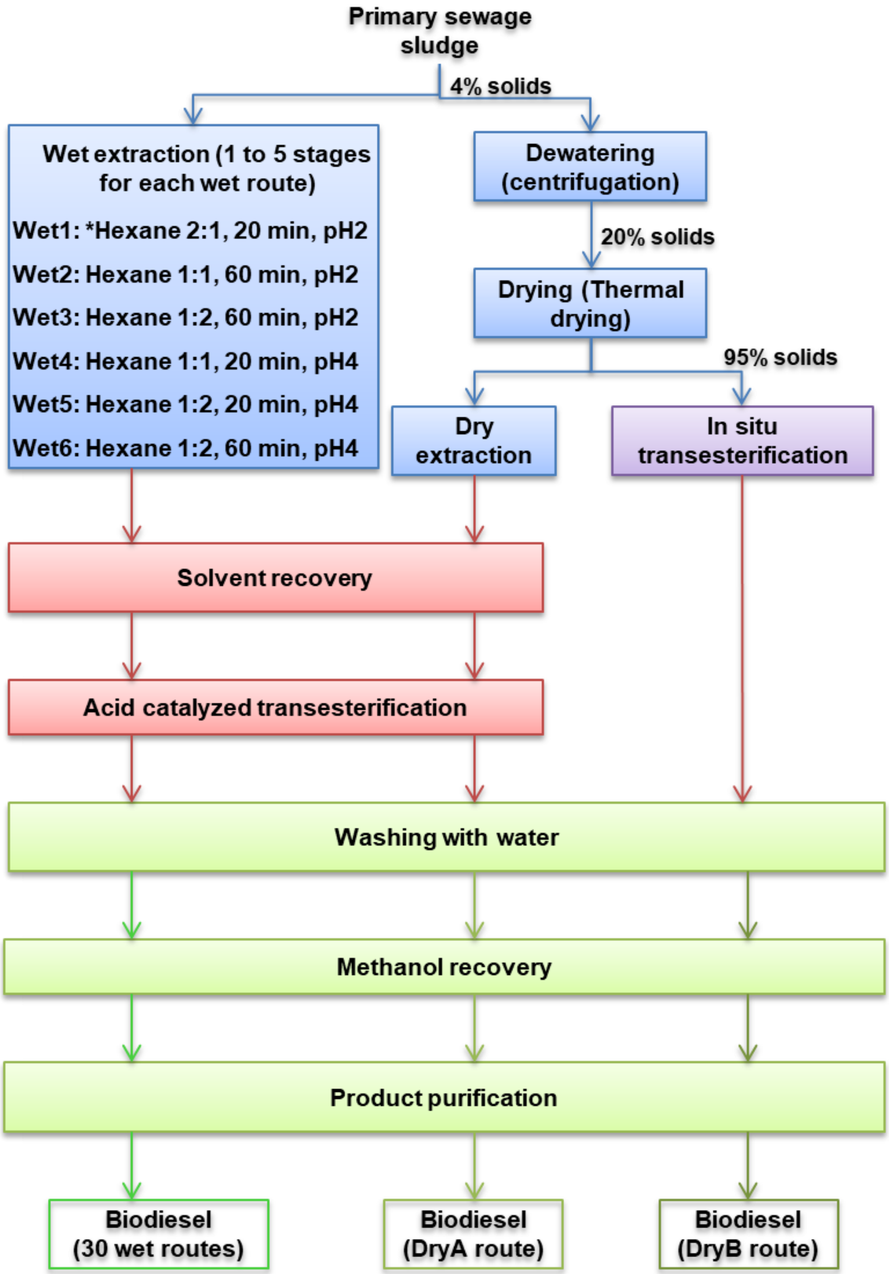


Figure 2. Simplified flow diagram of the 32 alternatives for biodiesel production of sewage sludge (*Hexane to sludge volumetric ratio).

II.2.2 Process alternatives

Three process alternatives were selected to find the best technological solution. Particularly, this paper compares the wet extraction procedure developed at laboratory scale [6] over traditional alternatives that include lipids extraction from dry sludge. The key aspect to developed wet extraction route is that the primary sludge is not dehydrated, with the consequent significant reduction in the costs.

II.2.2.1 Wet extraction

The simplified flowsheet for the liquid-liquid extraction route (Wet route) and the material balance are shown in Figure 3. The primary sewage sludge composition is based on Table 1 and the complete stream balance is detailed in Figure S1 of the Supplementary materials. The primary sludge is stabilized with acid prior the extraction, promoting the separation of the lipids in the sludge. Approximately 1.5% v/v of hydrochloric acid is needed to reach operating conditions (pH=2). However, working with pH=4 decreases the extraction efficiency by around 5% but improves the overall economic results by reducing the amount of acid in the input, thus 0.8% v/v is added. The lipid extraction takes place in a series of countercurrent liquid-liquid extraction mixers, where n-hexane is used as a solvent. The equilibrium and operating data were taken from the experimental work carried out by Olkiewicz et al. (2014).

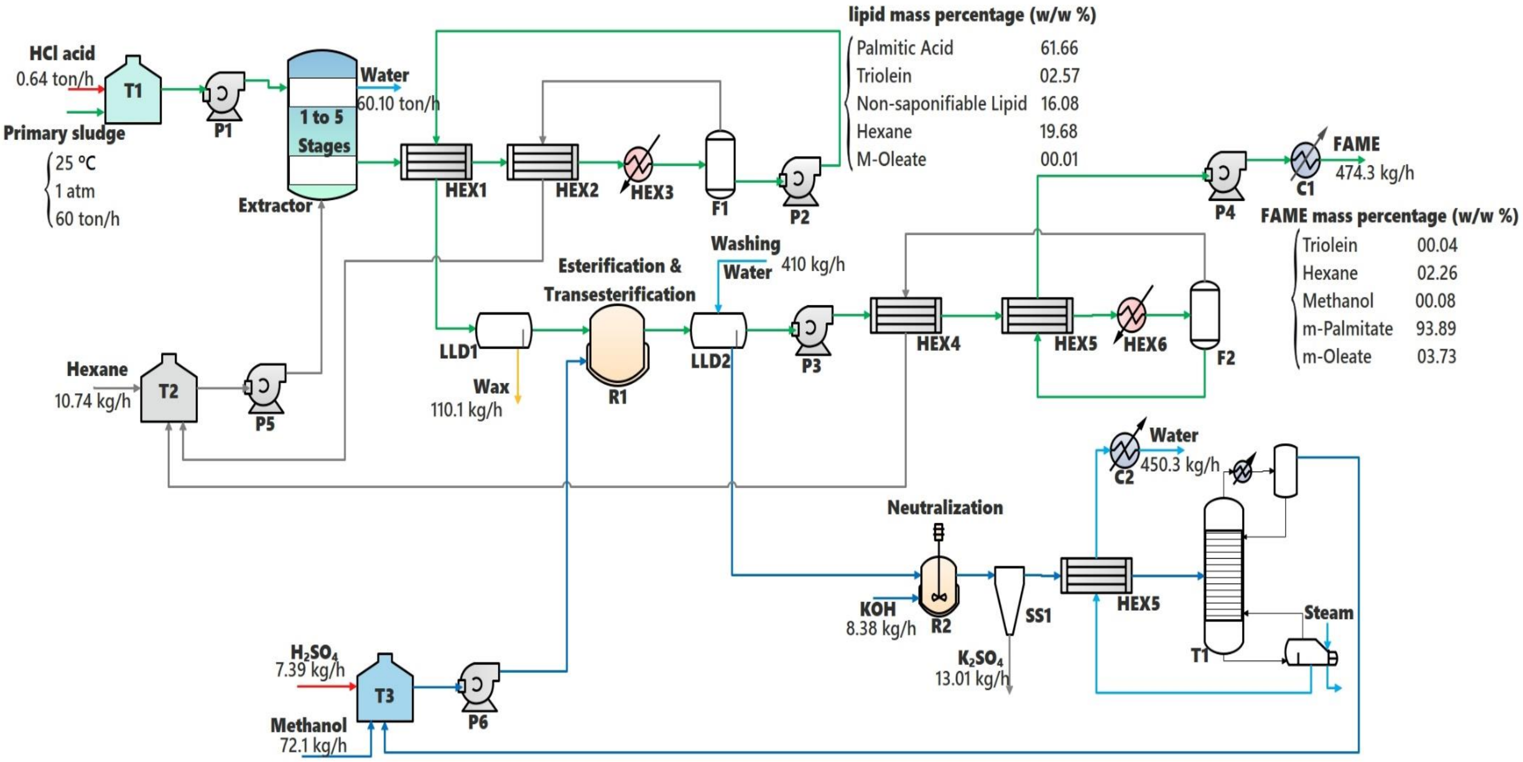


Figure 3. Simplified flow diagram for biodiesel production from primary sludge: ‘Wet’ alternative. T: tank; HEX: shell and tube heat exchanger; C: cooler; H: heater; P: pump; R: reactor; T: distillation column; F: 2-phase flash; SS: solid separator; LLD: liquid-liquid decanter.

For the base case scenario, the economic analysis yields better results when combining three mixer/settlers in series (Extractor) with 0.5:1 (v/v) of hexane:sludge ratio and 60 min of residence time (see Table S1 of the Supplementary materials). However, a multicriteria analysis of the number of stages, hexane ratio, extraction time and pH was carried out, including both economic and environmental indicators as decision criteria.

After the extraction stages, more than 96% of water can be reused in the wastewater treatment plant for further processing and exploitation; therefore, no additional expenditure is considered for the waste treatment in the base case scenario. On the other hand, the extract is headed to an equilibrium-flash separator (F1), where over 99% of n-hexane is recovered and recycled to the extraction stage. Along with the lipid content, a percentage of wax and sterol are extracted, but they must be removed from the lipids stream before the esterification and transesterification reactions to improve the quality of the biodiesel. Therefore, crystallization fractionation is applied to split fats and oils into a liquid part with the low-melting point and a solid fraction with the high melting point. Particularly, traditional fractionation consists of two stages: temperature-controlled crystallization combined with moderate agitation, and separation by filtration [68].

Since the FFA content in the lipids is considerably high, an acid catalyzed reaction system with methanol as a reactant is proposed to produce FAME. Under these conditions, two reactions take place (R1): acid esterification of the FFA to process FAME and water, and acid transesterification of the triglycerides to procure FAME and glycerol. Based on the experimental data [6], almost 100% of the esterification occurs instantaneously, while a yield of near 99% is achieved for the transesterification under the following conditions: methanol to lipids molar ratio of 6:1, 1% (v/v) of sulfuric acid as catalyst with respect to the methanol input, reactor temperature of 60ºC and 4 hours of residence time. Those results are in agreement with Usman et al. (2023) study.

The product stream is sent to a decanter (LLD2), where contact with washing water forces the separation of two phases. The light phase is forwarded to a flash separation (F2) to further reduce the amount of n-hexane and traces of methanol that accompanied the biodiesel, achieving a product with 98% of FAME [69]. The heavy phase contains water, methanol, a low quantity of glycerol as a by-product of the transesterification reaction, and the acid used as catalyst. To recover the excess methanol to be recycled in the esterification/transesterification reaction, the heavy phase is first neutralized (R2) by the addition of potassium hydroxide obtaining a salt (K2SO4) that is segregated (SS1) and may be ascertained as a valuable by-product.

Then, the neutralized stream is sent to a distillation column (T1) to recover the methanol and to obtain water with traces of glycerol (0.4%) that may be reused in the wastewater treatment plant.

II.2.2.2 Dry extraction

This alternative, called DryA hereinafter, includes the drying of the sludge prior to the extraction stage. We modified the model of Zhang et al. (2013) based on experimental results [6]. The primary sewage sludge is dewatered in a same way to the microalgae biomass, first by centrifugation from a concentration of 5 to 20% of solids and then thermally dried until 95% as described in previous works [39,67]. The new emerging methods for dewatering sewage sludge such as vacuum preloading or pressure filtration are not considered in this study due to the associated maintenance difficulties they entail [70]. The calculation of the drying stage is modeled and automatically linked as an input to the simulation.

A mixture of hexane, methanol and acetone (3:1:1 v/v/v) is used as a solvent in an extraction reactor at 50 ºC for 1 hour. For an extraction efficiency of 96% [52], 1 liter of the solvent mixture is needed for each kilogram of dry sludge. After the solvent recovery, the lipids are mixed with methanol (6:1 molar) and sulfuric acid (1% v/v in methanol), at 50º C to carry out the esterification and transesterification reactions, with an efficiency of 99% [66]. The experimental results showed that the drying stage reduces the percentage of saponifiable lipids in the sludge, and thus it can be equivalent to a reduction of nearly 40% in the reaction yield [66]. Then, the process follows a similar sequence to the wet extraction: solvent recovery, water washing and product purification. For more information about the base case scenario of alternative DryA, see the Figure S2 of the Supplementary materials.

II.2.2.3 In situ transesterification

This process alternative, from now on called DryB, is based on the route proposed by Dufreche et al. (2007) and Mondala et al. (2009), where the acid catalyzed esterification-transesterification reaction takes place simultaneously with the extraction, driven by a mixture of 12:1 methanol to sludge mass ratio and 5% (v/v) of H2SO4. This process intensification reduces the number of equipment involved. The comparison of alternatives and the sensitivity analysis (Section 3) provide further insights into the advantages and disadvantages of this pathway. The yield of FAME used by Mondala et al. (2009) was 10 wt% of the total processed sludge; however, we simulated a winterization step (i.e., removing saturated fatty acid content by improving the cold flow properties) prior to the reaction step like in the previous alternatives. The process is similar to the Dry extraction for product purification and solvent recovery sections. A water washing column forces the separation of the heavy and the light phases, mostly composed of m-palmitate, until the biodiesel purity is reached. Meanwhile, 95% of the methanol is recovered after the neutralization in a distillation column. See Figure S3 of the Supplementary materials for additional information of DryB route.

II.2.3 Automated evaluation tool

An evaluation tool programmed in Matlab® R2021a was used for the multicriteria analysis of the process alternatives and scenarios [67,71]. The evaluation procedure comprises the following main steps:

i) The bidirectional connection between Matlab® and Aspen.Hysys®.

ii) The automation of the scenario and corresponding parameters in the simulation enables performing sensitivity analysis and optimization in a straightforward manner.

iii) Collection of data needed to evaluate the performance of each scenario. These data comprise the operating conditions and design parameters of the equipments, the streams, and the energy requirements of each process alternative.

iv) Calculation of the specific metrics for the economic (see subsection 2.3.1) and environmental characterization (see subsection 2.3.2) of each scenario.

v) Optionally, the different metrics are aggregated by impact categories or in a unique score indicator for comparison [72].

vi) Finally, the evaluation results are recorded and depending on the purpose of the study are used to establish the new scenario. For instance, if a variable, or a set of variables, has to be optimized, the algorithm programmed in Matlab Toolbox® starts the iterative procedure.

Figure 4 illustrates the procedure of the automated evaluation tool to clarify the connections between each step and the tools used.

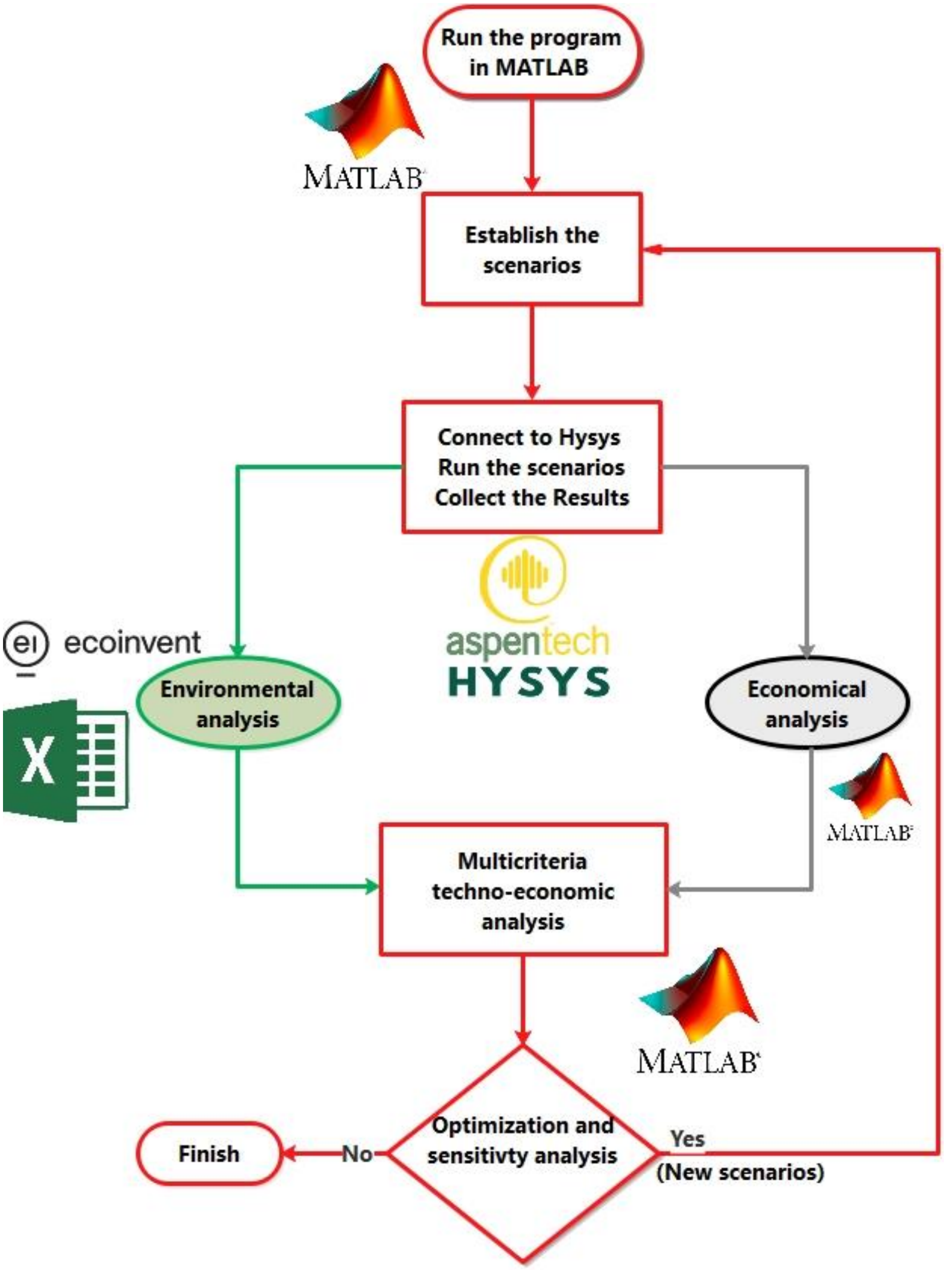


Figure 4. Algorithm of the automated evaluation tool.

II.2.3.1 Economic module

The Total Capital Investment (TCI) and the Total Manufacturing Cost (TMC) are calculated for each process alternative based on reference [73]. The TCI is formulated based on the total bare cost using the equipment module costing technique [74]. The tool also collects all data from all units modeled. By adding the contingencies and fees, and the auxiliary facilities to the total bare module, we estimated the fixed capital cost, to which the working capital including energy expenses is finally added to obtain the TCI. The TMC is based on the direct manufacturing cost that includes the raw material, utilities, labor fees, and other costs directly related to the process. Then, the fixed manufacturing cost (e.g., overheads, taxes, insurance, etc.) and the general expenses (e.g., research and development, administration, distribution and selling, etc.) are summed to the direct expenses to obtain the TMC. Finally, the tool also calculates additional economic indicators like the Break-Even Price (BEP), which is the minimum selling price of the product, and the profitability of the plant which is used to compare alternatives.

II.2.3.2 Environmental module

The environmental evaluation of the alternatives is carried out using Life Cycle Assessment (LCA) (ISO, 2006). The scope covers from cradle-to-gate, thus including all the activities before producing biodiesel (extraction, transformation and transport of raw materials and utilities). The functional unit is one kilogram of wastewater. The data for the Life Cycle Inventory (LCI) is obtained from the input and output flows provided by the simulation (LCIA data is extracted from Ecoinvent v3.8 APOS by Matlab, see Table S2 of the Supplementary material). The ReCiPe method [26] was selected as the Life Cycle Impact Assessment (LCIA) to link the inventory data and the environmental damages. The allocation system used is the point of substitution (APOS). Although the ReCiPe procedure proposes default normalization and weighting factors so the damaging impact can be expressed by an overall score, an alternative to fixed weights is used in this study to incorporate into the analysis economic considerations. In this sense, the aggregated index is calculated by varying the values of the weighting factors within the [0,1] interval (i.e., null and total predominance, respectively). The results are processed to extract a set of predicting rules to identify the most promising options corresponding to regions of weighting factors dominance.

II.3 Results and discussions

II.3.1 Alternatives comparison for the base case scenario

Both economic and environmental criteria yield almost the same ranking (see Table S1 and S3 of the Supplementary materials for the detailed results). Table S3 of the Supplementary materials shows the LCA results of the alternatives, including a dry path and the six wet extraction alternatives that combine different solvent ratios, extraction times, pH, and number of extraction stages. The DryB path is the worst case from both the environmental and economic perspectives. According to ReCiPe and economic profit, the DryB route has 10 times more impact in environmental assessment and around 5 times worst economic performance, compared to the other routes. Thus, this alternative is not further considered in the following analysis. High usage of utilities imposed negative impacts on the DryB case which confirms Dufour and Iribarren (2012) conclusions. In Figure 5 the ReCiPe impacts of scenarios are ranked basically by the amount of hexane, acid usage and number of extraction stages. It is worth mentioning that almost the same ranking is obtained when the alternatives are sorted based on energy criteria. Energy consumption has a direct relation with the environmental impacts of each scenario [64] (Check table S1 of Supplementary materials).

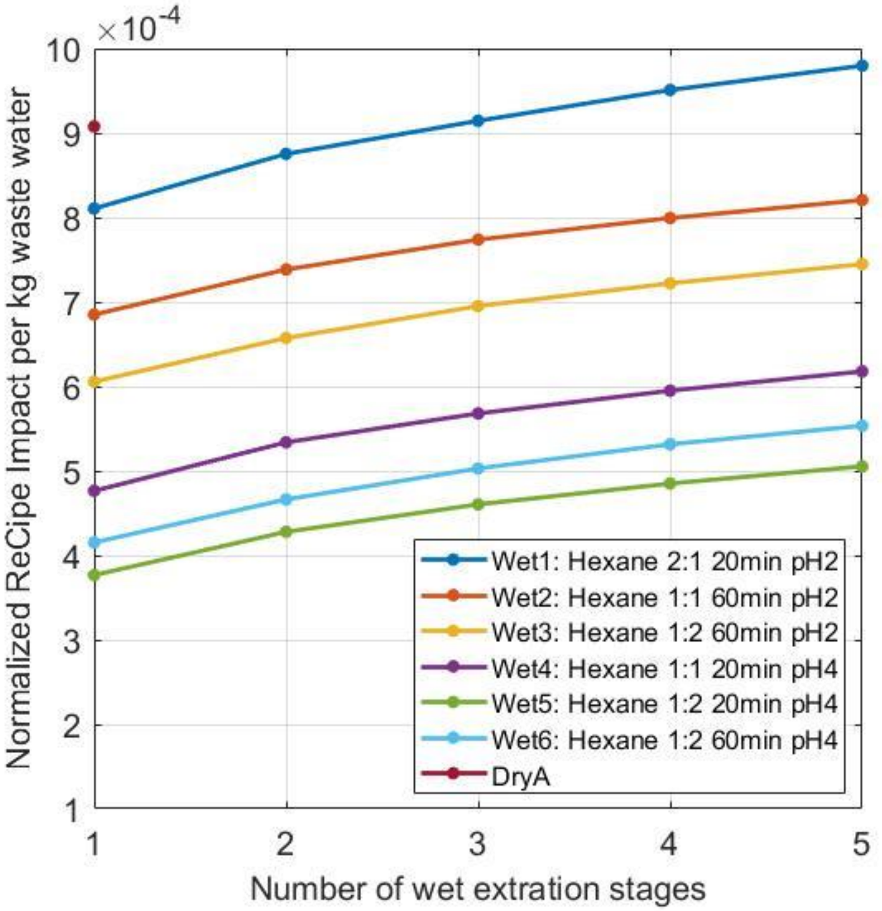


Figure 5. ReCiPe impact comparison between alternatives.

The distribution of impacts among the different categories in Figure 6 reveals that global warming and fine particulate matter formation account for up to 70% of the impact.

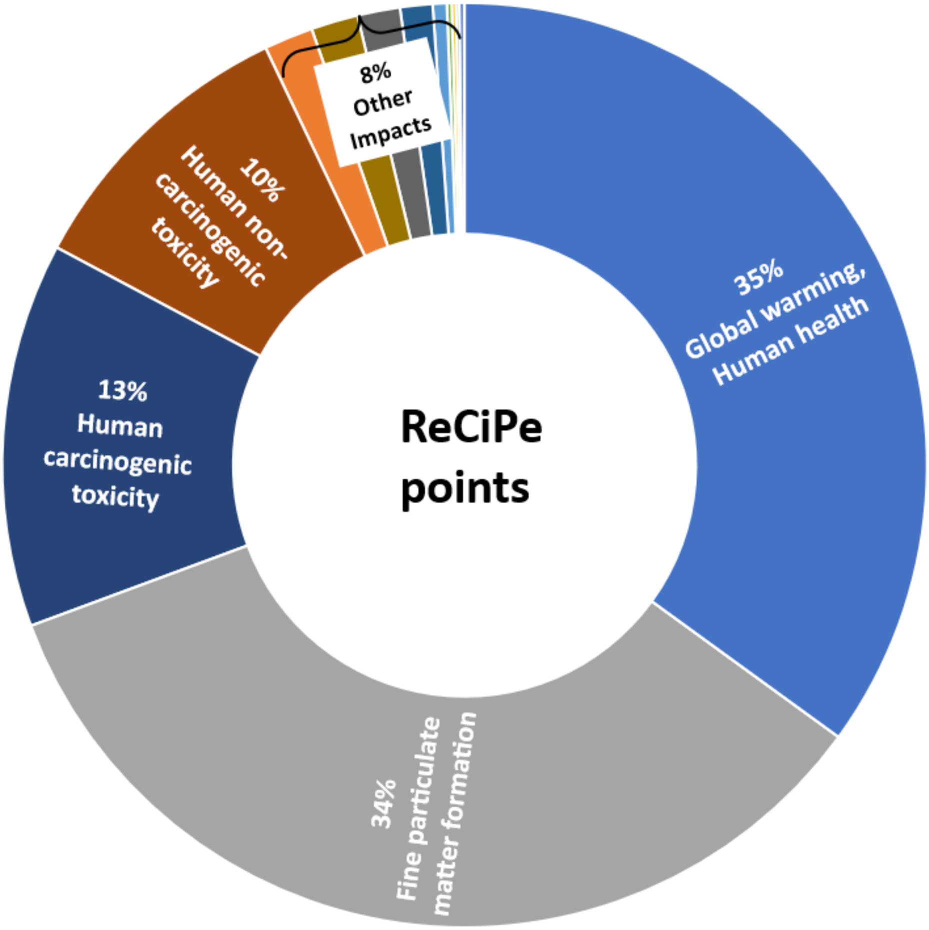


Figure 6. Distribution of ReCiPe impact factors for the base case (Wet3).

The base case scenario releases 272 g of CO2 eq/kg biodiesel can be classified in the low-range emission compared to the biodiesel production from waste cooking oil [75]. A deeper insight into global warming and fine particulate matter formation is demonstrated in Figure 7, where raw materials and steam generation (heating utility) indicators impose the highest effects on the environmental terms. The results are relative values and the base (maximum value) is the contribution of fine particular matter formation impact by the acquisition of the raw materials. The coefficient of the byproduct is negative, as a credit for the system. In this way, the production of K2SO4 is also considered as a negative impact in the subsequent calculations. A critical parameter is the amount of energy used for heating (90ºC) the stream before the separation of solvent (H1 unit in Figure 3). The heating required ranges from 0.3 MW to 1.3 MW, thus having a high environmental impact for the scenarios associated with higher hexane to sludge ratio. Another important parameter in the environmental analysis is the amount of acid used. In the wet route, the use of hydrochloric acid can be reduced by increasing the pH during operation from 2 to 4, in a trade-off between the acid consumption and the extraction efficiency.

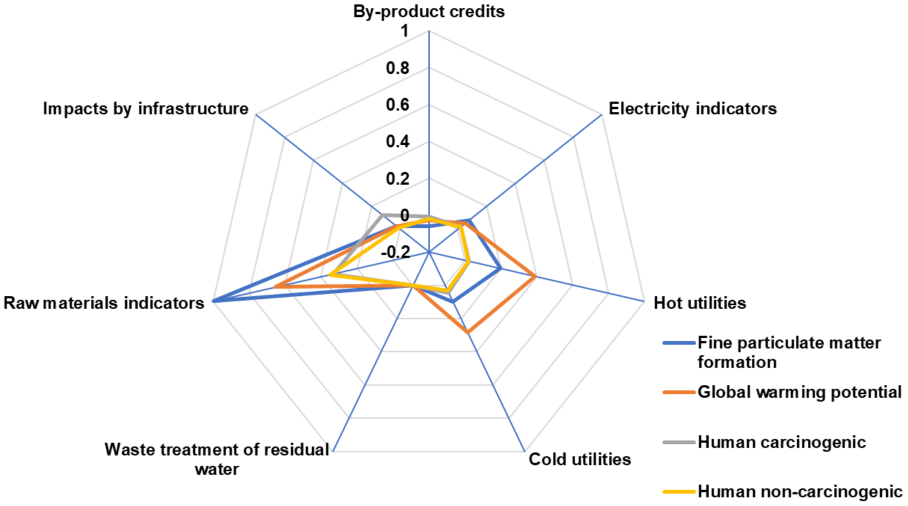


Figure 7. Comparison of each indicator's effects on global warming potential and fine particulate matter.

II.3.2 Multicriteria evaluation

Although the minimum environmental impact coincides with the minimum number of extraction stages, the maximum profit is achieved in the scenarios with two and three extraction stages which is aligned to Olkiewicz et al. (2016b) experimental work. Cases with lower environmental impacts and higher profit are the best options to convert sewage sludge (Figure 8). Wet6 turns out to be the first selection alternative due to the best economic result and the second least harmful scenario for the environment. The vertical placement of alternatives represents that residence time has a significant effect on the profit of the process (60 compared to 20 min) and the amount of hexane and acid have the subsequent effectiveness in the profit of the plant.

In the cases with high extraction efficiency and reactor conversion or high-price biodiesel, scenarios with greater production capacity are better ranked (wet cases with a higher number of extractions and Dry1 case) and vice versa. For instance, by decreasing the biodiesel by 10%, the Wet6 with two stages is the best alternative. Therefore, the slope and the maximum point in Figure 8 will change accordingly.

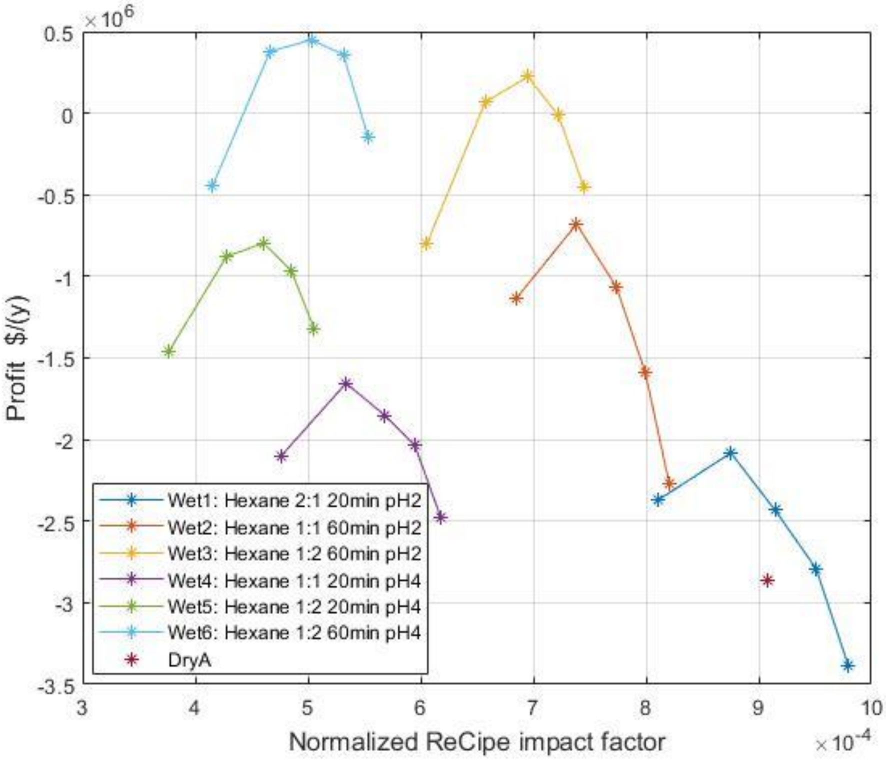
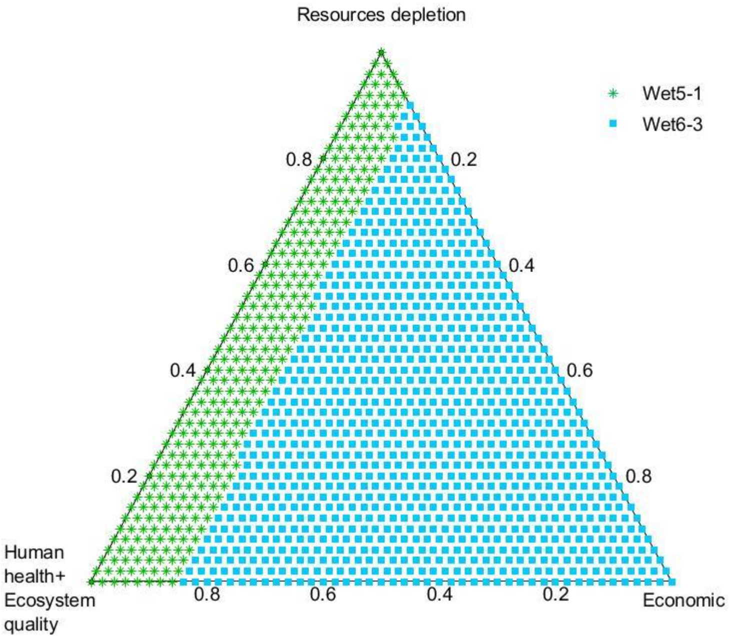
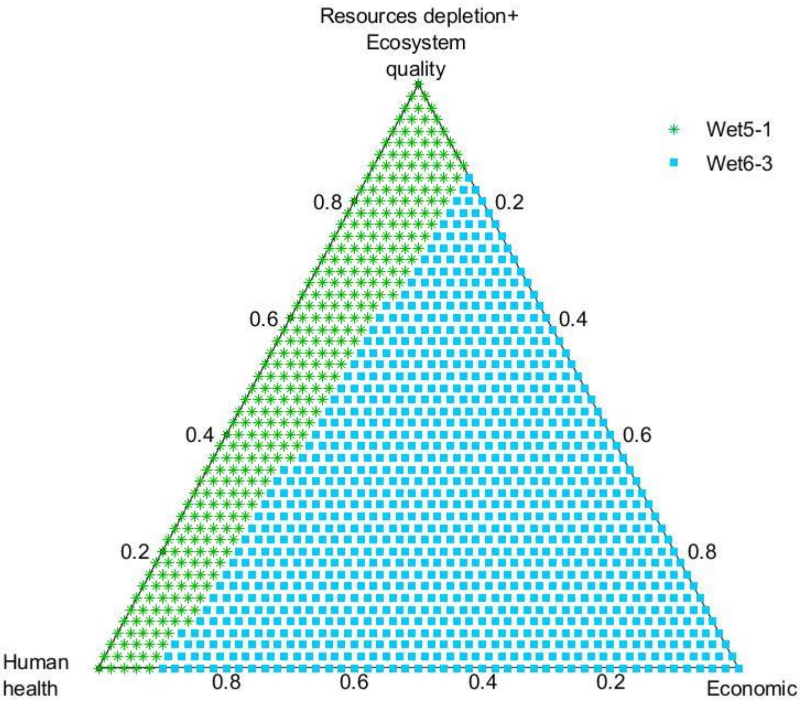


Figure 8. Profit *vs.* ReCiPe impact score for process alternatives.

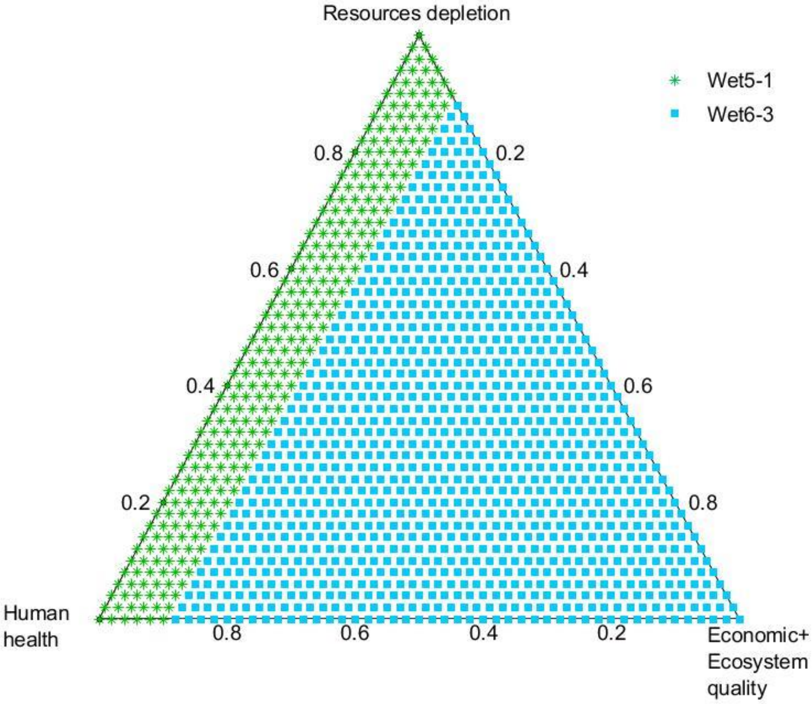
In all multicriteria analyses (Figure 8), there is no straightforward answer to which is the best scenario, as it might depend on the specific criteria prioritized by the decision-makers. A weighting factor analysis was conducted to guide decision-makers in considering the preferences on the different impact categories: human health, ecosystem quality, resource depletion and economic profitability. Therefore, each category impact is treated individually without applying the fixed weighting factors assigned in the midpoint to endpoint calculation phase of the life cycle impact assessment. The geometric mean of the ratios of the different indicators with respect to the Wet1 route [72] is used to normalize the environmental and economic indicators to obtain a single score. The resulting total index for a given process alternative represents its position with respect to the base case: i.e., better (lower than 1) or worse option (higher than 1). Finally, the mixing triangles [76] in Figure 9 show the areas of the predominance of a particular alternative. In this case, due to the challenges to show 4 dimensions, the mixing triangle plots with a summation of two vertex were used as projections of the solution. Figure 9 shows two areas of predominance, on the left sides, the best alternative is the Wet5 route with 1 stage extraction when more importance is given to the environmental concerns, while on the right sides the economic criterion is predominant and the best alternative is Wet6 route with 3 stages extraction. In the boundary layer between these two scenarios, the Wet6 with 2 stages becomes more favorable. In the central area of equitable weights, the best alternative is by rough Wet6-3.



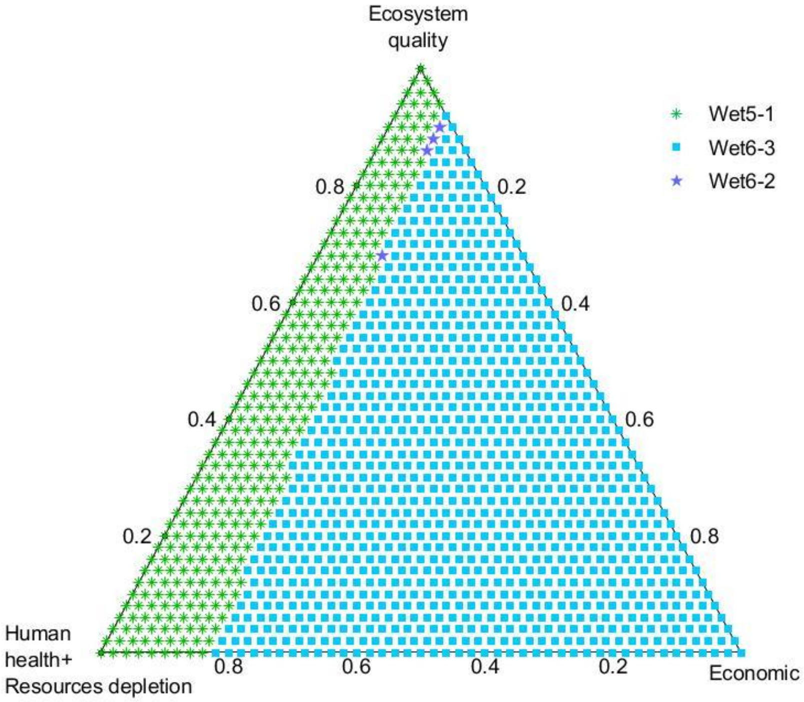
a) Human health and ecosystem quality in the same vertex



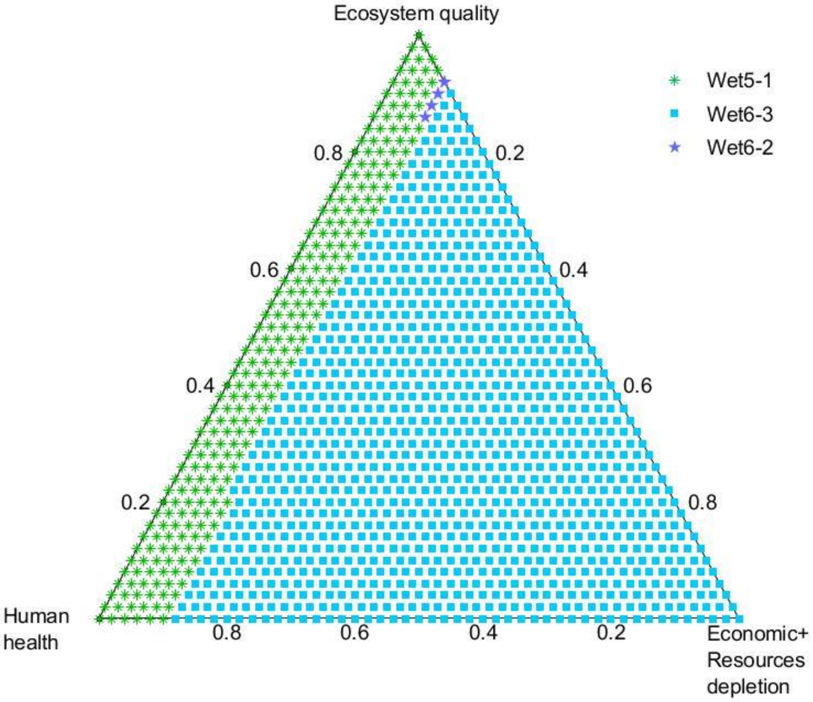
b) Resource depletion and ecosystem quality in the same vertex



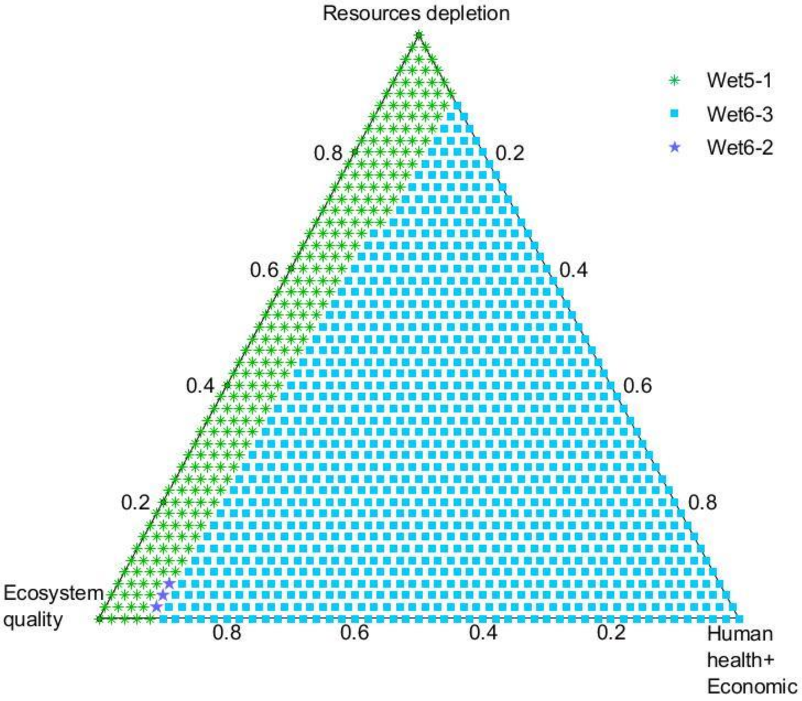
c) Economic and ecosystem quality in the same vertex



d) Human health and resource depletion in the same vertex



e) Economic and resource depletion in a same vertex



f) Human health and economic in the same vertex

Figure 9. Mixing triangles analyzing the best process scenarios as a function of the weighting factors.

II.3.3 Monetisation

There are several approaches to highlight environmental impacts and make them more tangible for the decision-maker. Monetisation is an approach to objectivize the environmental effects by considering the external costs. Although this method is sensitive to the initial assumption and has uncertainties associated, the monetized environmental impact can be aggregated with the plant expenses to consider the trade-off between the economic and environmental results.

The monetized impact values are based on the ReCiPe 2016 midpoint categories; whenever the midpoint values were not available, the endpoint values were used. According to Ponsioen et al. (2020), for each Disability-Adjusted- Life Years

(DALYs) in the human health category we should include 72000 €, while for each species·year in the ecosystem category 11.5×106 € is considered to quantify the external environmental costs. The monetized impact for the two main scenarios from Figure 9 (Wet5, Wet6) was 3.3×104 $ and 4.8×104 $, respectively. Figure 10 depicts the economic results of all the scenarios by considering the externalities. Final results indicate that the alternative with 1:2 (v/v) of hexane:sludge ratio, 60 minutes residence time, pH 4 and 3 extraction stages has the best performance.

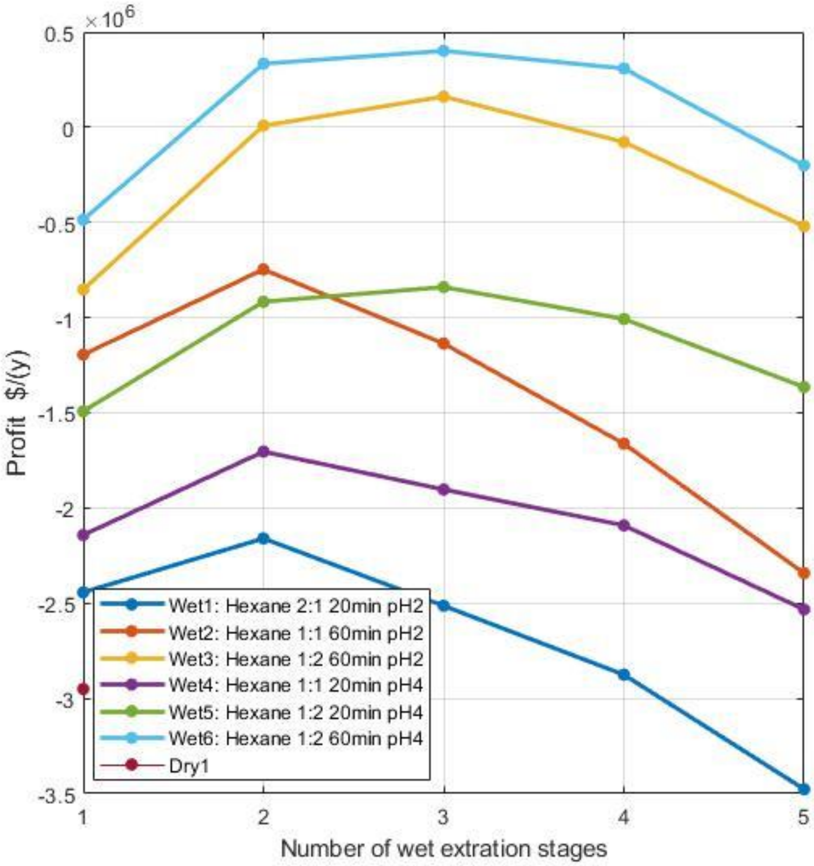
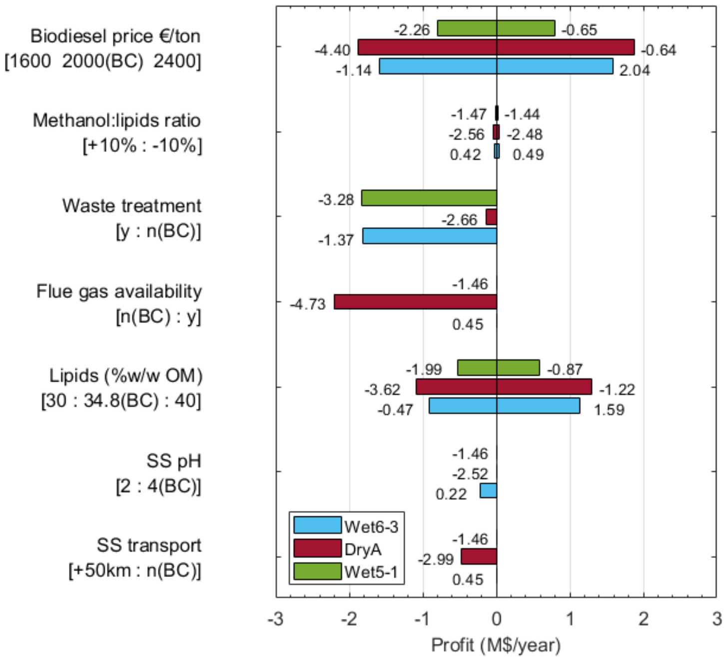


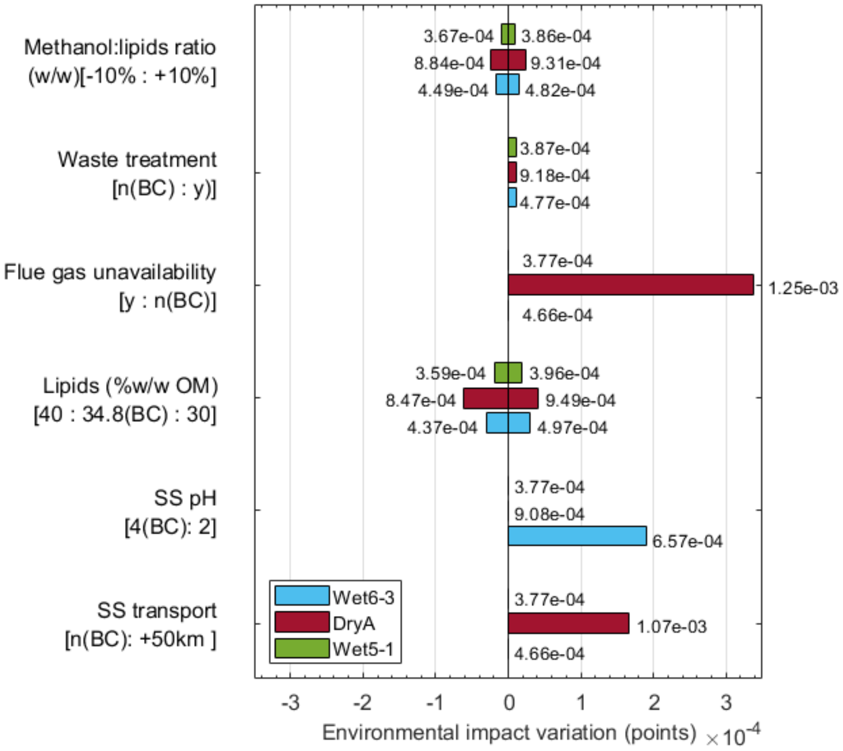
Figure 10. Profit of the scenarios by considering the externality costs.

II.3.4 Sensitivity analysis

The sensitivity analysis was conducted between three alternatives covering the overall range: The best economic case (Wet6-3 extractive stages), the best environmental case (Wet5-1 extractive stage) and the best dry route (DryA). To do so, six different scenarios were defined for the selected alternatives while three of them were generally applied for all the cases. The three other remaining were defined based on the unavailability of flue gas for drying in the dry route, the transport distance for the dried biomass in the dry route, changing the pH from 4 to 2 for the Wet6-3 case to show the effect of the hydrochloric acid on the biodiesel selling price. Figure 11 illustrates the significant advantage of extra flue gas for the drying route by 90% effectiveness in the economic and 38% effectiveness in the environmental indicator, respectively. On the other hand, a 10% change in the methanol to lipid ratio has less than a 3% effect on the process performance. Disregarding the wastewater treatment for the wet routes has a crucial effect on the profit of the plant while it does not affect the environmental aspect in the dry route due to the low amount of water in the primary sludge. Fluctuations in the biodiesel market may lead to choosing different scenarios as optimum. For instance, by 10% decreasing the biodiesel price, the Wet6 with two stages will be the best alternative among all scenarios.


Biodiesel price €/ton
[1600 2000(BC) 2400]
-2.26
-0.65
-4.40
-0.64
-1.14
2.04
Methanol:lipids ratio
[+10% : -10%]
-1.47
-1.44
-2.56
-2.48
0.42
0.49
Waste treatment
[y : n(BC)]
-3.28
-2.66
-1.37
Flue gas availability
[n(BC) : y]
-1.46
-4.73
0.45
Lipids (%w/w OM)
[30 : 34.8(BC) : 40]
-1.99
-0.87
-3.62
-1.22
-0.47
1.59
SS pH
[2 : 4(BC)]
-1.46
-2.52
0.22
SS transport
[+50km : n(BC)]
-1.46
-2.99
0.45
Wet6-3
DryA
Wet5-1
-3
-2
-1
0
1
2
3
Profit (M$/year)

(a)



(b)

Figure 11. Sensitivity analysis of the selected alternatives for the economic (a) and environmental (b) aspects.

II.4 Conclusions

Our analysis revealed an alignment between economic and environmental criteria in ranking different alternatives. Multicriteria analysis clarified that the wet routes are the preferred alternative for biodiesel production under the defined conditions, although the availability of flue gas for drying the biomass makes the dry routes competitive. Hexane, acid usage, and energy consumption were identified as key parameters affecting environmental impacts. Multicriteria evaluation favored scenarios with two or three extraction stages for optimal economic performance and relatively low environmental impacts.

A weighting factor analysis allowed for decision customization by indicating the best process scenario based on specific weightings of the different criteria. The monetisation is also used to accumulate the environmental impacts in terms of costs. Although these externalities do not change the ranking between the scenarios, considering the avoided cost of establishing a WWTP and higher externality costs due to the strict regulation on environmental damage could change the priorities if new policies such as government subsidiaries are implemented.

II.5 Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 945413 and from the Universitat Rovira i Virgili (URV). The authors acknowledge the financial support from the Spanish Government (PID2021-127713OA-I00, PID2021-123511OB-C33, PID2021-124139NB-C22 & TED2021-129851B-I00).

II.6 Supplementary materials

The supplementary materials for the article “Multicriteria analysis of sewage sludge-based biodiesel production” are presented in this section:

The simulated flowsheet in Aspen Hysys and the mass balances are obtained for the wet and two dry routes. Figure S1 demonstrates the main sections of Wet3 with three stages as the base case. The calculation for solvent, methanol, extraction recovery and other parameters is done in the calculator blocks (square shape silver blocks). The input data are degrees of freedom with blue color and the calculated data are in black.

In this case, the following parameters are calculated: sewage sludge composition, hexane recovery, equilibrium data based on experiments, residence times of equipment, sizing of equipments, reactor kinetics and reaction yields. In total, around 70 variables and parameters are calculated based on these calculators for each of the 32 scenarios , this automatic calculations help to reduce the complexity of the calculations and the convergence time of the flowsheet when an external optimization software is used (i.e., Matlab). Also the automatic extraction of data improves the post-processing steps in the economic analysis and in the environmental assessment.

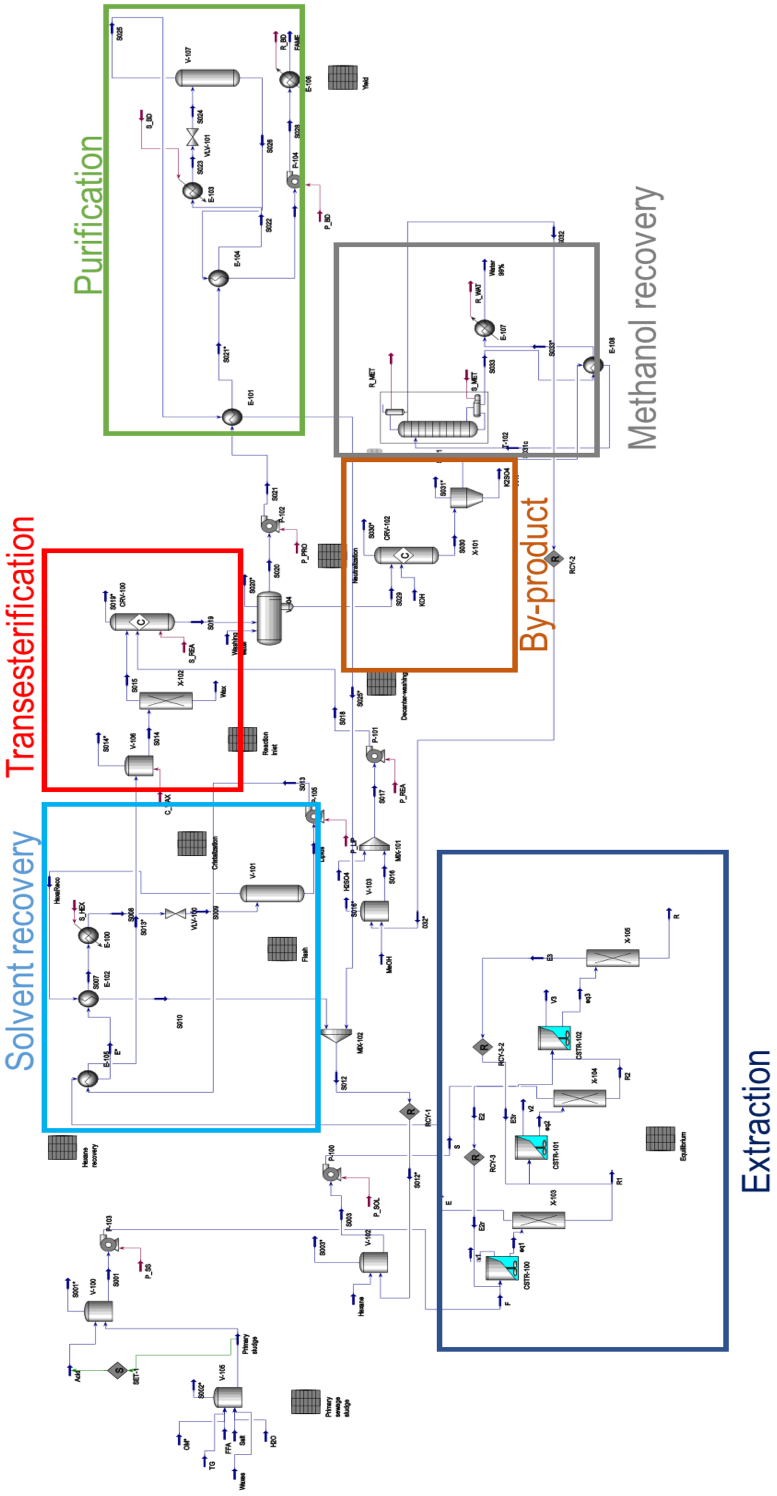


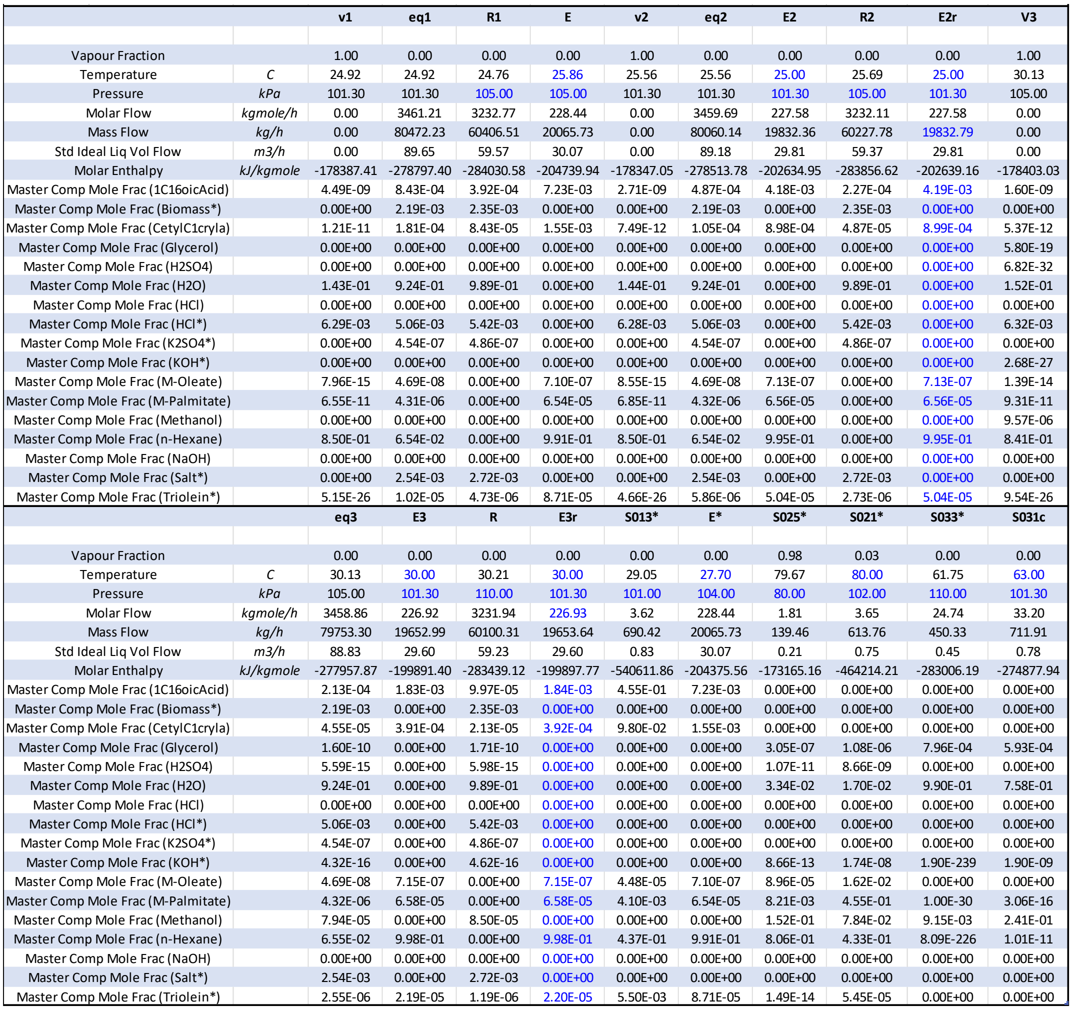
Figure S1(a): Aspen Hysys flowsheet of the base case

	Unit	**F**	**rimary sludg**	**TG**	**OM***	**FFA**	**Salt**	**H2O**	**Acid**	**S001**	**S**
Vapour Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Temperature	*C*	24.89	25.00	25.00	25.00	25.00	25.00	25.00	25.00	24.89	53.27
Pressure	*kPa*	115.00	101.30	101.32	101.30	101.30	101.30	101.30	101.32	101.30	120.00
Molar Flow	*kgmole/h*	3233.62	3216.11	0.02	7.59	1.97	8.79	3197.32	17.51	3233.62	226.75
Mass Flow	*kg/h*	60639.17	60000.00	21.01	1229.93	504.17	513.60	57600.00	639.17	60639.17	19525.51
Std Ideal Liq Vol Flow	*m3/h*	59.84	59.49	0.02	0.82	0.57	0.21	57.72	0.35	59.84	29.46
Molar Enthalpy	*kJ/kgmole*	-284157.59	-284536.75	-158510.77	0.00	-821355.59	0.00	-285599.47	-214582.87	-284157.92	-193877.82
Master Comp Mole Frac (1C16oicAcid)		6.08E-04	6.11E-04	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	6.08E-04	1.54E-05
Master Comp Mole Frac (Biomass*)		2.35E-03	2.36E-03	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.35E-03	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		1.31E-04	1.31E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E-04	3.25E-07
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E-09
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.52E-14
Master Comp Mole Frac (H2O)		9.89E-01	9.94E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	9.89E-01	2.67E-04
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		5.42E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	5.42E-03	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.59E-15
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.16E-07
Master Comp Mole Frac (M-Palmitate)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.59E-05
Master Comp Mole Frac (Methanol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.21E-03
Master Comp Mole Frac (n-Hexane)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.98E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		2.72E-03	2.73E-03	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	2.72E-03	0.00E+00
Master Comp Mole Frac (Triolein*)		7.34E-06	7.38E-06	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.34E-06	1.19E-16
		S003	**Hexane**	**S001***	**S010**	**S007**	**S012***	**S003***	**MeOH**	**S016***	**S016**
Vapour Fraction		0.00	0.00	1.00	0.00	0.90	0.00	1.00	0.00	1.00	0.00
Temperature	*C*	53.25	25.00	24.89	51.98	73.00	53.27	53.25	25.00	60.14	60.14
Pressure	*kPa*	80.00	101.32	101.30	80.00	104.00	80.00	80.00	101.32	101.00	101.00
Molar Flow	*kgmole/h*	226.75	0.12	0.00	224.82	228.44	226.63	0.00	2.25	0.00	10.68
Mass Flow	*kg/h*	19525.51	10.74	0.00	19375.31	20065.73	19514.77	0.00	72.10	0.00	332.63
Std Ideal Liq Vol Flow	*m3/h*	29.46	0.02	0.00	29.24	30.07	29.44	0.00	0.09	0.00	0.41
Molar Enthalpy	*kJ/kgmole*	-193885.11	-199469.80	-233377.38	-194051.78	-168510.45	-193882.04	-166742.85	-247422.02	-202460.79	-244619.00
Master Comp Mole Frac (1C16oicAcid)		1.54E-05	0.00E+00	2.02E-06	1.55E-05	7.23E-03	1.54E-05	3.88E-11	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		3.25E-07	0.00E+00	1.30E-08	3.28E-07	1.55E-03	3.26E-07	2.92E-14	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		2.44E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.44E-09	8.28E-13	0.00E+00	0.00E+00	7.89E-31
Master Comp Mole Frac (H2SO4)		8.52E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.53E-14	5.69E-21	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		2.67E-04	0.00E+00	8.64E-01	0.00E+00	0.00E+00	2.67E-04	4.16E-02	0.00E+00	6.31E-02	6.31E-02
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		0.00E+00	0.00E+00	1.36E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		6.59E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.59E-15	1.61E-25	0.00E+00	5.93E-09	5.94E-09
Master Comp Mole Frac (M-Oleate)		7.16E-07	0.00E+00	0.00E+00	3.33E-10	7.10E-07	7.16E-07	1.57E-13	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		6.59E-05	0.00E+00	0.00E+00	3.98E-07	6.54E-05	6.59E-05	4.92E-10	0.00E+00	7.31E-16	7.31E-16
Master Comp Mole Frac (Methanol)		1.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.21E-03	3.90E-03	1.00E+00	9.37E-01	9.37E-01
Master Comp Mole Frac (n-Hexane)		9.98E-01	1.00E+00	0.00E+00	1.00E+00	9.91E-01	9.98E-01	9.55E-01	0.00E+00	3.17E-11	3.17E-11
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		1.19E-16	0.00E+00	8.40E-10	3.36E-20	8.71E-05	1.19E-16	1.97E-35	0.00E+00	0.00E+00	0.00E+00
		H2SO4	**S017**	**S018**	**S019***	**KOH**	**S030***	**S030**	**S031***	**K2SO4 99%**	**S031**
Vapour Fraction		0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00
Temperature	*C*	25.00	59.57	59.57	60.00	25.00	41.38	41.38	41.38	41.38	41.38
Pressure	*kPa*	101.32	101.00	110.00	101.32	101.32	101.32	101.32	101.32	101.32	101.32
Molar Flow	*kgmole/h*	0.08	10.75	10.75	0.00	0.15	0.00	33.27	0.00	0.07	33.20
Mass Flow	*kg/h*	7.39	340.02	340.02	0.00	8.38	0.00	724.92	0.00	13.01	711.91
Std Ideal Liq Vol Flow	*m3/h*	0.00	0.42	0.42	0.00	0.00	0.00	0.78	0.00	0.00	0.78
Molar Enthalpy	*kJ/kgmole*	-911341.69	-249491.28	-249490.79	-189174.03	-277396.26	-231767.60	-276476.55	-277125.16	11646.94	-277125.16
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		0.00E+00	7.84E-31	7.84E-31	2.55E-09	0.00E+00	5.93E-04	5.92E-04	5.93E-04	5.93E-07	5.93E-04
Master Comp Mole Frac (H2SO4)		9.50E-01	6.94E-03	6.94E-03	1.55E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		5.00E-02	6.30E-02	6.30E-02	4.41E-02	0.00E+00	7.58E-01	7.56E-01	7.58E-01	7.58E-04	7.58E-01
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.24E-03	0.00E+00	9.99E-01	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	5.90E-09	5.90E-09	3.82E-19	1.00E+00	1.90E-09	1.90E-09	1.90E-09	1.90E-12	1.90E-09
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	4.08E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		0.00E+00	7.26E-16	7.26E-16	2.79E-06	0.00E+00	3.06E-16	3.05E-16	3.06E-16	3.06E-19	3.06E-16
Master Comp Mole Frac (Methanol)		0.00E+00	9.30E-01	9.30E-01	6.22E-01	0.00E+00	2.41E-01	2.41E-01	2.41E-01	2.41E-04	2.41E-01
Master Comp Mole Frac (n-Hexane)		0.00E+00	3.15E-11	3.15E-11	3.34E-01	0.00E+00	1.01E-11	1.01E-11	1.01E-11	1.01E-14	1.01E-11
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	0.00E+00	4.68E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

		S032	S033	032*	S008	HexaReco	Lipids	S009	S019	S020*	S020
Vapour Fraction		0.00	0.00	0.00	0.98	1.00	0.00	0.98	0.00	1.00	0.00
Temperature	*C*	69.72	101.91	69.72	90.00	88.94	88.94	88.94	60.00	61.21	61.21
Pressure	*kPa*	101.00	110.00	101.00	103.50	80.00	80.00	80.00	101.32	101.32	101.32
Molar Flow	*kgmole/h*	8.46	24.74	8.43	228.44	224.82	3.62	228.44	14.02	0.00	3.65
Mass Flow	*kg/h*	261.58	450.33	260.52	20065.73	19375.31	690.42	20065.73	920.31	0.00	613.76
Std Ideal Liq Vol Flow	*m3/h*	0.33	0.45	0.32	30.07	29.24	0.83	30.07	1.12	0.00	0.75
Molar Enthalpy	*kJ/kgmole*	-243868.51	-279990.55	-243870.42	-163310.67	-157609.55	-517609.91	-163310.67	-312508.74	-187664.87	-471720.44
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	7.23E-03	1.55E-05	4.55E-01	7.23E-03	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	0.00E+00	1.55E-03	3.28E-07	9.80E-02	1.55E-03	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		2.11E-79	7.96E-04	1.00E-30	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.41E-03	3.52E-10	1.08E-06
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.33E-03	4.40E-16	8.66E-09
Master Comp Mole Frac (H2O)		8.00E-02	9.90E-01	8.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E-01	2.29E-01	1.70E-02
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		7.47E-09	1.90E-239	7.53E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.52E-09	1.04E-18	1.74E-08
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	7.10E-07	3.33E-10	4.48E-05	7.10E-07	4.23E-03	8.26E-09	1.62E-02
Master Comp Mole Frac (M-Palmitate)		1.20E-15	1.00E-30	9.26E-16	6.54E-05	3.98E-07	4.10E-03	6.54E-05	1.19E-01	5.84E-06	4.55E-01
Master Comp Mole Frac (Methanol)		9.20E-01	9.15E-03	9.20E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.92E-01	2.00E-01	7.84E-02
Master Comp Mole Frac (n-Hexane)		3.98E-11	8.09E-226	4.02E-11	9.91E-01	1.00E+00	4.37E-01	9.91E-01	1.13E-01	5.71E-01	4.33E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	0.00E+00	8.71E-05	3.36E-20	5.50E-03	8.71E-05	1.42E-05	1.90E-24	5.45E-05

		S029	Vashing wate	S025	S026	S021	S023	S024	S027	S022	S028
Vapour Fraction		0.00	0.00	1.00	0.00	0.00	0.48	0.49	0.00	0.31	0.00
Temperature	*C*	61.21	25.00	168.86	168.86	61.21	170.00	168.86	106.41	108.00	106.41
Pressure	*kPa*	101.32	101.32	80.00	80.00	102.32	109.00	80.00	95.00	110.00	101.00
Molar Flow	*kgmole/h*	33.13	22.76	1.81	1.84	3.65	3.65	3.65	1.84	3.65	1.84
Mass Flow	*kg/h*	716.54	409.99	139.46	474.31	613.76	613.76	613.76	474.31	613.76	474.31
Std Ideal Liq Vol Flow	*m3/h*	0.78	0.41	0.21	0.54	0.75	0.75	0.75	0.54	0.75	0.54
Molar Enthalpy	*kJ/kgmole*	-276474.81	-285599.47	-157994.37	-672700.00	-471720.15	-418042.88	-418042.88	-708576.24	-446088.20	-708573.67
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		5.95E-04	0.00E+00	3.05E-07	1.85E-06	1.08E-06	1.08E-06	1.08E-06	1.85E-06	1.08E-06	1.85E-06
Master Comp Mole Frac (H2SO4)		2.25E-03	0.00E+00	1.07E-11	1.71E-08	8.66E-09	8.66E-09	8.66E-09	1.71E-08	8.66E-09	1.71E-08
Master Comp Mole Frac (H2O)		7.55E-01	1.00E+00	3.34E-02	9.79E-04	1.70E-02	1.70E-02	1.70E-02	9.79E-04	1.70E-02	9.79E-04
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		4.21E-24	0.00E+00	8.66E-13	3.44E-08	1.74E-08	1.74E-08	1.74E-08	3.44E-08	1.74E-08	3.44E-08
Master Comp Mole Frac (M-Oleate)		3.31E-18	0.00E+00	8.96E-05	3.20E-02	1.62E-02	1.62E-02	1.62E-02	3.20E-02	1.62E-02	3.20E-02
Master Comp Mole Frac (M-Palmitate)		3.06E-16	0.00E+00	8.21E-03	8.93E-01	4.55E-01	4.55E-01	4.55E-01	8.93E-01	4.55E-01	8.93E-01
Master Comp Mole Frac (Methanol)		2.42E-01	0.00E+00	1.52E-01	6.38E-03	7.84E-02	7.84E-02	7.84E-02	6.38E-03	7.84E-02	6.38E-03
Master Comp Mole Frac (n-Hexane)		1.02E-11	0.00E+00	8.06E-01	6.75E-02	4.33E-01	4.33E-01	4.33E-01	6.75E-02	4.33E-01	6.75E-02
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		1.15E-20	0.00E+00	1.49E-14	1.08E-04	5.45E-05	5.45E-05	5.45E-05	1.08E-04	5.45E-05	1.08E-04

		FAME	Water 99%	S012	Waxes	S013	S014	S014*	S015	Wax	S002*
Vapour Fraction		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00
Temperature	*C*	35.00	35.00	53.25	25.00	89.19	5.00	5.00	5.00	4.92	25.00
Pressure	*kPa*	101.00	110.00	80.00	101.32	101.32	101.00	101.00	101.32	101.32	101.30
Molar Flow	*kgmole/h*	1.84	24.74	226.63	0.42	3.62	3.62	0.00	3.26	0.35	0.00
Mass Flow	*kg/h*	474.31	450.33	19514.76	131.29	690.42	690.42	0.00	580.30	110.13	0.00
Std Ideal Liq Vol Flow	*m3/h*	0.54	0.45	29.44	0.15	0.83	0.83	0.00	0.71	0.13	0.00
Molar Enthalpy	*kJ/kgmole*	-745204.25	-284997.77	-193885.31	-782295.48	-517602.83	-549032.31	-170510.42	-522334.03	-794673.80	-241910.14
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	1.54E-05	0.00E+00	4.55E-01	4.55E-01	3.45E-07	5.05E-01	0.00E+00	1.86E-06
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	3.25E-07	1.00E+00	9.80E-02	9.80E-02	8.52E-08	0.00E+00	1.00E+00	4.76E-09
Master Comp Mole Frac (Glycerol)		1.85E-06	7.96E-04	2.43E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2SO4)		1.71E-08	0.00E+00	8.50E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		9.79E-04	9.90E-01	2.66E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		3.44E-08	1.90E-239	6.90E-15	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		3.20E-02	0.00E+00	7.15E-07	0.00E+00	4.48E-05	4.48E-05	6.20E-11	4.97E-05	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		8.93E-01	1.00E-30	6.58E-05	0.00E+00	4.10E-03	4.10E-03	2.45E-08	4.55E-03	0.00E+00	0.00E+00
Master Comp Mole Frac (Methanol)		6.38E-03	9.15E-03	1.21E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (n-Hexane)		6.75E-02	8.09E-226	9.98E-01	0.00E+00	4.37E-01	4.37E-01	1.00E+00	4.85E-01	0.00E+00	0.00E+00
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		1.08E-04	0.00E+00	1.19E-16	0.00E+00	5.50E-03	5.50E-03	1.47E-18	6.10E-03	0.00E+00	2.10E-29



		v1	eq1	R1	E	v2	eq2	E2	R2	E2r	V3
Vapour Fraction		1.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00
Temperature	*C*	24.92	24.92	24.76	25.86	25.56	25.56	25.00	25.69	25.00	30.13
Pressure	*kPa*	101.30	101.30	105.00	105.00	101.30	101.30	101.30	105.00	101.30	105.00
Molar Flow	*kgmole/h*	0.00	3461.21	3232.77	228.44	0.00	3459.69	227.58	3232.11	227.58	0.00
Mass Flow	*kg/h*	0.00	80472.23	60406.51	20065.73	0.00	80060.14	19832.36	60227.78	19832.79	0.00
Std Ideal Liq Vol Flow	*m3/h*	0.00	89.65	59.57	30.07	0.00	89.18	29.81	59.37	29.81	0.00
Molar Enthalpy	*kJ/kgmole*	-178387.41	-278797.40	-284030.58	-204739.94	-178347.05	-278513.78	-202634.95	-283856.62	-202639.16	-178403.03
Master Comp Mole Frac (1C16oicAcid)		4.49E-09	8.43E-04	3.92E-04	7.23E-03	2.71E-09	4.87E-04	4.18E-03	2.27E-04	4.19E-03	1.60E-09
Master Comp Mole Frac (Biomass*)		0.00E+00	2.19E-03	2.35E-03	0.00E+00	0.00E+00	2.19E-03	0.00E+00	2.35E-03	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		1.21E-11	1.81E-04	8.43E-05	1.55E-03	7.49E-12	1.05E-04	8.98E-04	4.87E-05	8.99E-04	5.37E-12
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.80E-19
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.82E-32
Master Comp Mole Frac (H2O)		1.43E-01	9.24E-01	9.89E-01	0.00E+00	1.44E-01	9.24E-01	0.00E+00	9.89E-01	0.00E+00	1.52E-01
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		6.29E-03	5.06E-03	5.42E-03	0.00E+00	6.28E-03	5.06E-03	0.00E+00	5.42E-03	0.00E+00	6.32E-03
Master Comp Mole Frac (K2SO4*)		0.00E+00	4.54E-07	4.86E-07	0.00E+00	0.00E+00	4.54E-07	0.00E+00	4.86E-07	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.68E-27
Master Comp Mole Frac (M-Oleate)		7.96E-15	4.69E-08	0.00E+00	7.10E-07	8.55E-15	4.69E-08	7.13E-07	0.00E+00	7.13E-07	1.39E-14
Master Comp Mole Frac (M-Palmitate)		6.55E-11	4.31E-06	0.00E+00	6.54E-05	6.85E-11	4.32E-06	6.56E-05	0.00E+00	6.56E-05	9.31E-11
Master Comp Mole Frac (Methanol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.57E-06
Master Comp Mole Frac (n-Hexane)		8.50E-01	6.54E-02	0.00E+00	9.91E-01	8.50E-01	6.54E-02	9.95E-01	0.00E+00	9.95E-01	8.41E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	2.54E-03	2.72E-03	0.00E+00	0.00E+00	2.54E-03	0.00E+00	2.72E-03	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		5.15E-26	1.02E-05	4.73E-06	8.71E-05	4.66E-26	5.86E-06	5.04E-05	2.73E-06	5.04E-05	9.54E-26
		eq3	**E3**	**R**	**E3r**	**S013***	**E***	**S025***	**S021***	**S033***	**S031c**
Vapour Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.03	0.00	0.00
Temperature	*C*	30.13	30.00	30.21	30.00	29.05	27.70	79.67	80.00	61.75	63.00
Pressure	*kPa*	105.00	101.30	110.00	101.30	101.00	104.00	80.00	102.00	110.00	101.30
Molar Flow	*kgmole/h*	3458.86	226.92	3231.94	226.93	3.62	228.44	1.81	3.65	24.74	33.20
Mass Flow	*kg/h*	79753.30	19652.99	60100.31	19653.64	690.42	20065.73	139.46	613.76	450.33	711.91
Std Ideal Liq Vol Flow	*m3/h*	88.83	29.60	59.23	29.60	0.83	30.07	0.21	0.75	0.45	0.78
Molar Enthalpy	*kJ/kgmole*	-277957.87	-199891.40	-283439.12	-199897.77	-540611.86	-204375.56	-173165.16	-464214.21	-283006.19	-274877.94
Master Comp Mole Frac (1C16oicAcid)		2.13E-04	1.83E-03	9.97E-05	1.84E-03	4.55E-01	7.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		2.19E-03	0.00E+00	2.35E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		4.55E-05	3.91E-04	2.13E-05	3.92E-04	9.80E-02	1.55E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		1.60E-10	0.00E+00	1.71E-10	0.00E+00	0.00E+00	0.00E+00	3.05E-07	1.08E-06	7.96E-04	5.93E-04
Master Comp Mole Frac (H2SO4)		5.59E-15	0.00E+00	5.98E-15	0.00E+00	0.00E+00	0.00E+00	1.07E-11	8.66E-09	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		9.24E-01	0.00E+00	9.89E-01	0.00E+00	0.00E+00	0.00E+00	3.34E-02	1.70E-02	9.90E-01	7.58E-01
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl*)		5.06E-03	0.00E+00	5.42E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		4.54E-07	0.00E+00	4.86E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		4.32E-16	0.00E+00	4.62E-16	0.00E+00	0.00E+00	0.00E+00	8.66E-13	1.74E-08	1.90E-239	1.90E-09
Master Comp Mole Frac (M-Oleate)		4.69E-08	7.15E-07	0.00E+00	7.15E-07	4.48E-05	7.10E-07	8.96E-05	1.62E-02	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		4.32E-06	6.58E-05	0.00E+00	6.58E-05	4.10E-03	6.54E-05	8.21E-03	4.55E-01	1.00E-30	3.06E-16
Master Comp Mole Frac (Methanol)		7.94E-05	0.00E+00	8.50E-05	0.00E+00	0.00E+00	0.00E+00	1.52E-01	7.84E-02	9.15E-03	2.41E-01
Master Comp Mole Frac (n-Hexane)		6.55E-02	9.98E-01	0.00E+00	9.98E-01	4.37E-01	9.91E-01	8.06E-01	4.33E-01	8.09E-226	1.01E-11
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		2.54E-03	0.00E+00	2.72E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		2.55E-06	2.19E-05	1.19E-06	2.20E-05	5.50E-03	8.71E-05	1.49E-14	5.45E-05	0.00E+00	0.00E+00

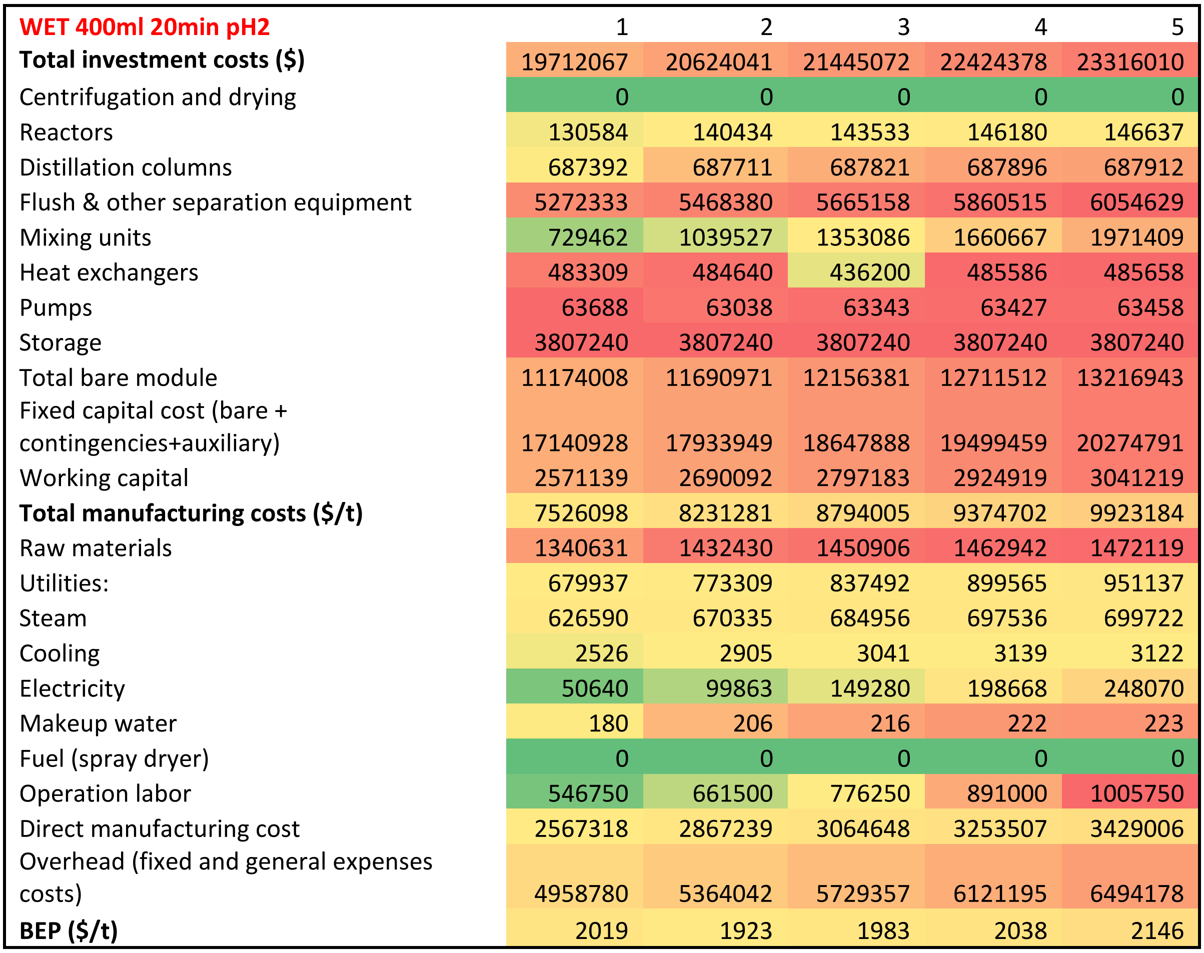
Figure S1(b): Mass balance of the base case flowsheet

Figure S1: Base case flowsheet and mass balance of the wet route with 1:2 (v/v) of hexane:sludge ratio, pH=2 and 60-minute residence time.

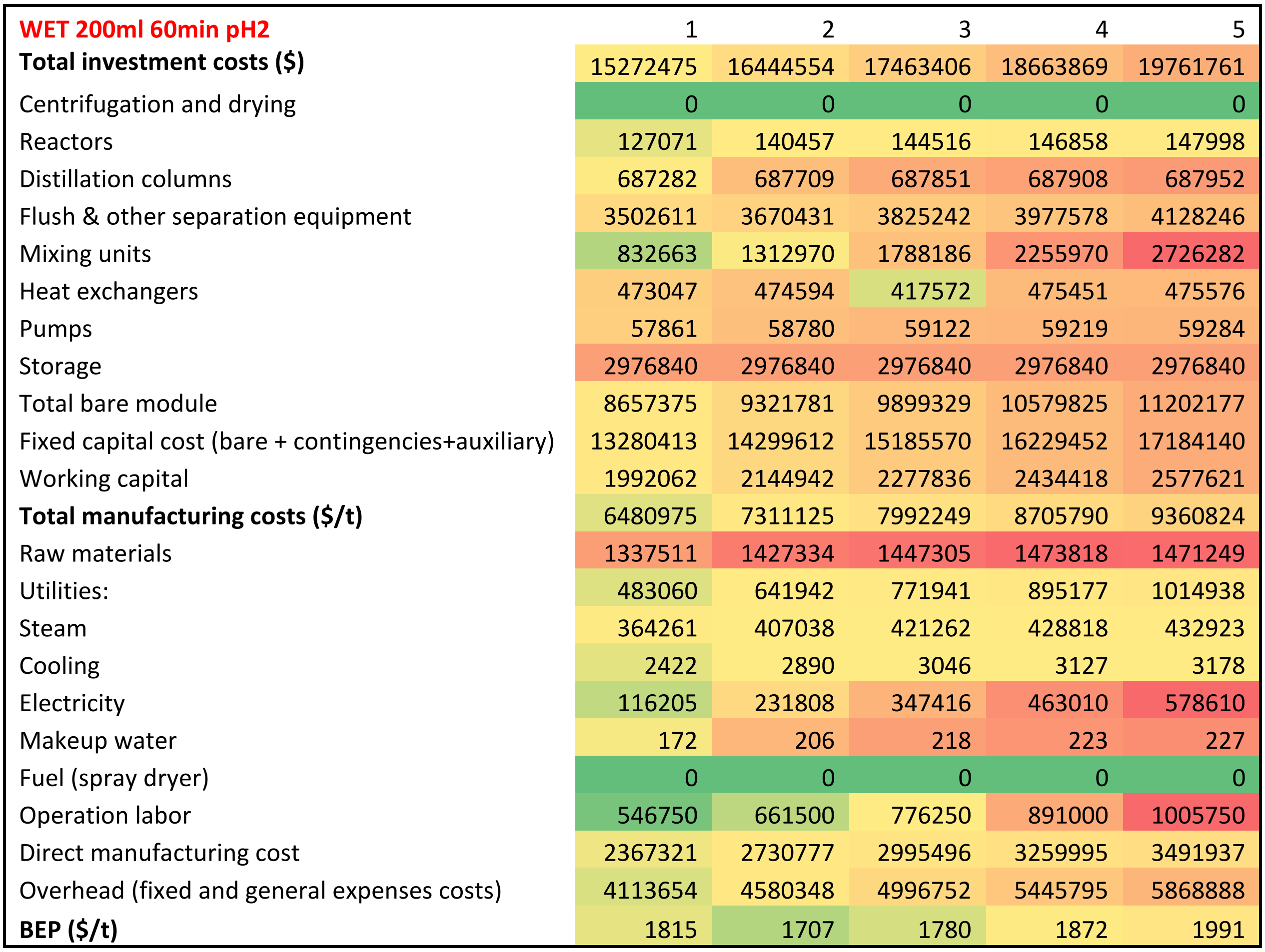
The economic results of the 32 scenarios are classified in Table S1. By increasing the number of extraction stages, the production of each scenario is increased but the profit and break-even point have different behaviors. The expenses for each category is compared with other alternatives in the same category by changing color from green (low values) to red (high values).

Table S1: Detailed economic result of the 32 alternatives (TIC: Total Investment Cost; TMC: Total Manufacture Cost; and BEP: Break-Even Point).

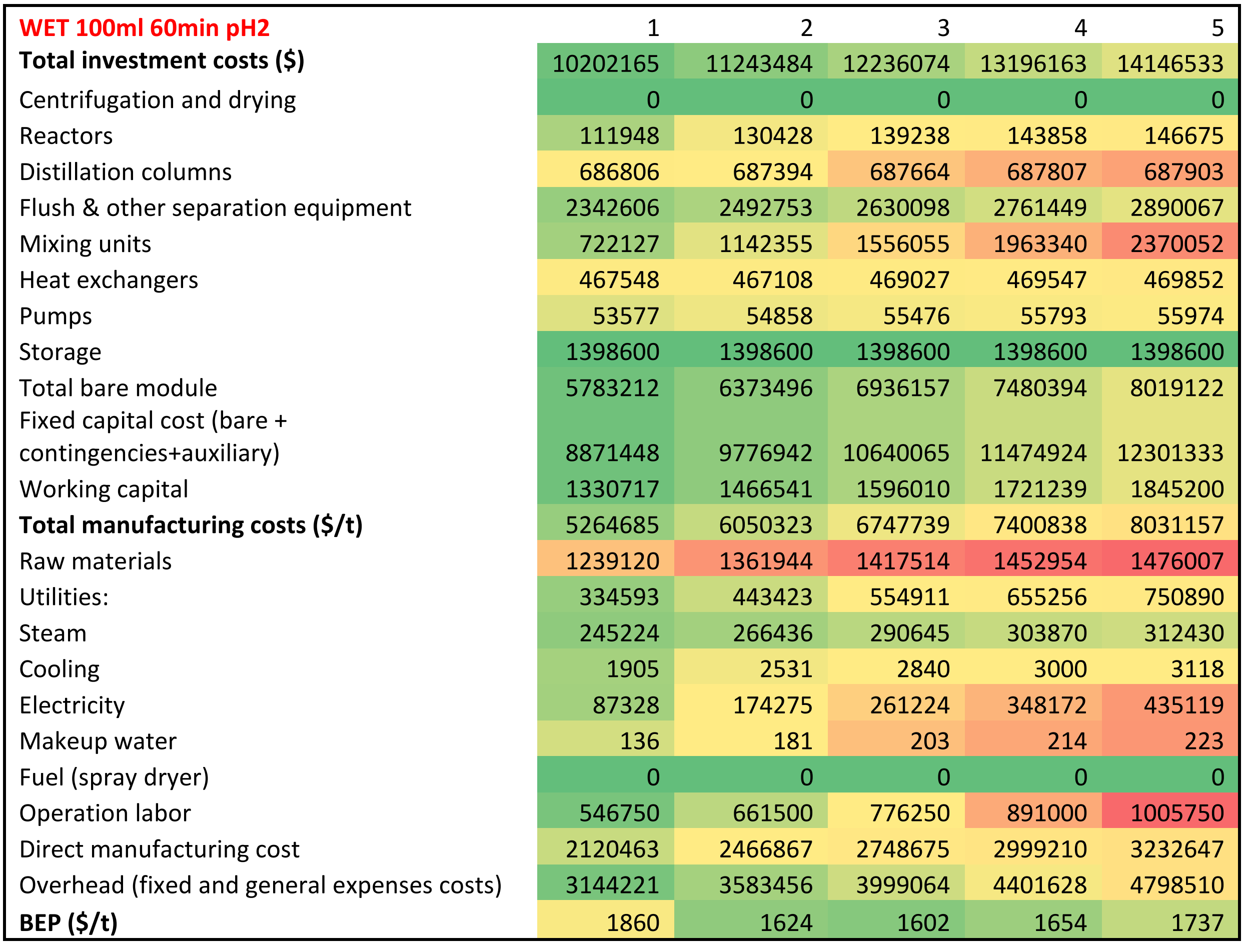
Alternatives	# stages	Production (t/y)	TIC ($)	TMC ($/t)	Energy ($/t)	Profit ($/y)	BEP ($/t)	Monitized Profit ($/y)
WET 400mL 20min pH2	1	3687.99	1.97E+07	7.53E+06	1.36E+06	-2.37E+06	2018.67	-2.37E+06
WET 400mL 20min pH2	2	4232.77	2.06E+07	8.23E+06	1.55E+06	-2.08E+06	1922.70	-2.08E+06
WET 400mL 20min pH2	3	4384.91	2.14E+07	8.79E+06	1.67E+06	-2.43E+06	1983.38	-2.43E+06
WET 400mL 20min pH2	4	4551.41	2.24E+07	9.37E+06	1.80E+06	-2.79E+06	2037.78	-2.79E+06
WET 400mL 20min pH2	5	4578.05	2.33E+07	9.92E+06	1.90E+06	-3.39E+06	2145.60	-3.39E+06
WET 200mL 60min pH2	1	3527.18	1.53E+07	6.48E+06	9.66E+05	-1.13E+06	1815.49	-1.13E+06
WET 200mL 60min pH2	2	4229.60	1.64E+07	7.31E+06	1.28E+06	-6.80E+05	1706.61	-6.80E+05
WET 200mL 60min pH2	3	4433.97	1.75E+07	7.99E+06	1.54E+06	-1.07E+06	1780.37	-1.07E+06
WET 200mL 60min pH2	4	4597.91	1.87E+07	8.71E+06	1.79E+06	-1.59E+06	1871.58	-1.59E+06
WET 200mL 60min pH2	5	4649.21	1.98E+07	9.36E+06	2.03E+06	-2.27E+06	1991.47	-2.27E+06
WET 100mL 60min pH2	1	2797.69	1.02E+07	5.26E+06	6.69E+05	-7.99E+05	1859.84	-7.99E+05
WET 100mL 60min pH2	2	3674.80	1.12E+07	6.05E+06	8.87E+05	6.74E+04	1624.30	6.74E+04
WET 100mL 60min pH2	3	4154.92	1.22E+07	6.75E+06	1.11E+06	2.24E+05	1602.09	2.24E+05
WET 100mL 60min pH2	4	4416.91	1.32E+07	7.40E+06	1.31E+06	-1.18E+04	1653.71	-1.18E+04
WET 100mL 60min pH2	5	4565.84	1.41E+07	8.03E+06	1.50E+06	-4.52E+05	1737.02	-4.52E+05
WET 200mL 20min pH4	1	2689.26	1.02E+07	4.70E+06	8.24E+05	-2.10E+06	2144.51	-2.10E+06
WET 200mL 20min pH4	2	3546.04	1.12E+07	5.48E+06	9.94E+05	-1.65E+06	1949.46	-1.65E+06
WET 200mL 20min pH4	3	3979.11	1.22E+07	6.17E+06	1.10E+06	-1.85E+06	1985.21	-1.85E+06
WET 200mL 20min pH4	4	4269.90	1.32E+07	6.74E+06	1.01E+06	-2.04E+06	2014.96	-2.04E+06
WET 200mL 20min pH4	5	4431.73	1.41E+07	7.46E+06	1.09E+06	-2.48E+06	2113.31	-2.48E+06
WET 100mL 20min pH4	1	2010.29	9.75E+06	4.38E+06	4.50E+05	-1.46E+06	2159.21	-1.46E+06
WET 100mL 20min pH4	2	2645.38	1.04E+07	5.01E+06	5.83E+05	-8.78E+05	1870.82	-8.78E+05
WET 100mL 20min pH4	3	2990.98	1.11E+07	5.55E+06	6.77E+05	-7.97E+05	1833.68	-7.97E+05
WET 100mL 20min pH4	4	3195.85	1.17E+07	6.06E+06	7.53E+05	-9.62E+05	1873.14	-9.62E+05
WET 100mL 20min pH4	5	3293.65	1.23E+07	6.54E+06	8.19E+05	-1.32E+06	1963.30	-1.32E+06
WET 100mL 60min pH4	1	2591.38	1.48E+07	5.61E+06	6.56E+05	-4.48E+05	1724.17	-4.48E+05
WET 100mL 60min pH4	2	3179.28	1.55E+07	6.27E+06	8.73E+05	3.78E+05	1528.77	3.78E+05
WET 100mL 60min pH4	3	3395.39	1.63E+07	6.82E+06	1.09E+06	4.49E+05	1523.73	4.49E+05
WET 100mL 60min pH4	4	3545.46	1.70E+07	7.22E+06	1.30E+06	3.60E+05	1555.47	3.60E+05
WET 100mL 60min pH4	5	3618.52	1.77E+07	7.73E+06	1.49E+06	-1.47E+05	1661.18	-1.47E+05
DryA	1	4700.42	2.24E+07	9.65E+06	3.51E+06	-2.76E+06	2030.77	-2.23E+07
DryB	1	4424.58	2.48E+07	1.94E+07	2.10E+07	-1.33E+07	4377.26	-2.35E+07



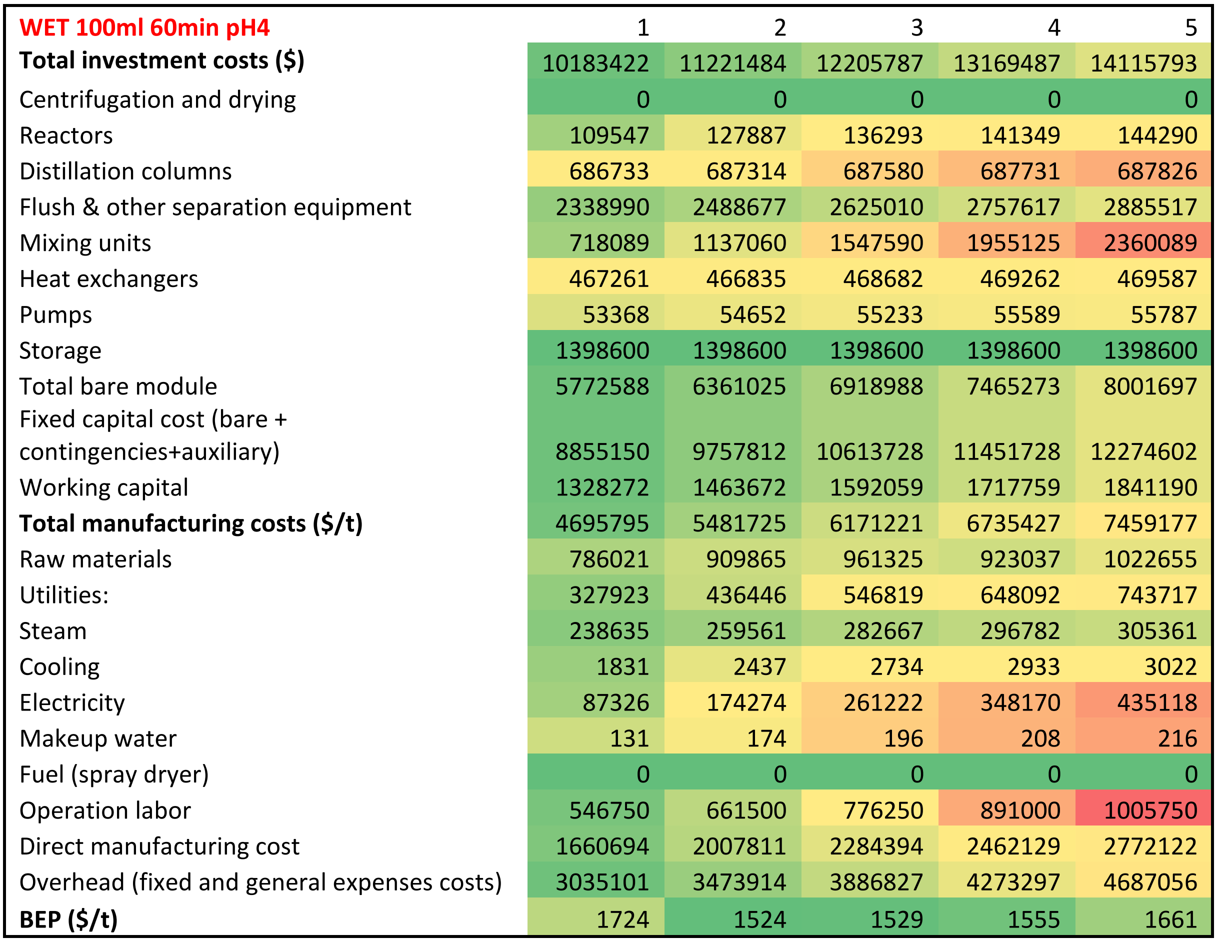
WET 400ml 20min pH2	1	2	3	4	5
Total investment costs ($)	19712067	20624041	21445072	22424378	23316010
Centrifugation and drying	0	0	0	0	0
Reactors	130584	140434	143533	146180	146637
Distillation columns	687392	687711	687821	687896	687912
Flush & other separation equipment	5272333	5468380	5665158	5860515	6054629
Mixing units	729462	1039527	1353086	1660667	1971409
Heat exchangers	483309	484640	436200	485586	485658
Pumps	63688	63038	63343	63427	63458
Storage	3807240	3807240	3807240	3807240	3807240
Total bare module	11174008	11690971	12156381	12711512	13216943
Fixed capital cost (bare + contingencies+auxiliary)	17140928	17933949	18647888	19499459	20274791
Working capital	2571139	2690092	2797183	2924919	3041219
Total manufacturing costs ($/t)	7526098	8231281	8794005	9374702	9923184
Raw materials	1340631	1432430	1450906	1462942	1472119
Utilities:	679937	773309	837492	899565	951137
Steam	626590	670335	684956	697536	699722
Cooling	2526	2905	3041	3139	3122
Electricity	50640	99863	149280	198668	248070
Makeup water	180	206	216	222	223
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	2567318	2867239	3064648	3253507	3429006
Overhead (fixed and general expenses costs)	4958780	5364042	5729357	6121195	6494178
BEP ($/t)	2019	1923	1983	2038	2146



WET 200ml 60min pH2	1	2	3	4	5
Total investment costs ($)	15272475	16444554	17463406	18663869	19761761
Centrifugation and drying	0	0	0	0	0
Reactors	127071	140457	144516	146858	147998
Distillation columns	687282	687709	687851	687908	687952
Flush & other separation equipment	3502611	3670431	3825242	3977578	4128246
Mixing units	832663	1312970	1788186	2255970	2726282
Heat exchangers	473047	474594	417572	475451	475576
Pumps	57861	58780	59122	59219	59284
Storage	2976840	2976840	2976840	2976840	2976840
Total bare module	8657375	9321781	9899329	10579825	11202177
Fixed capital cost (bare + contingencies+auxiliary)	13280413	14299612	15185570	16229452	17184140
Working capital	1992062	2144942	2277836	2434418	2577621
Total manufacturing costs ($/t)	6480975	7311125	7992249	8705790	9360824
Raw materials	1337511	1427334	1447305	1473818	1471249
Utilities:	483060	641942	771941	895177	1014938
Steam	364261	407038	421262	428818	432923
Cooling	2422	2890	3046	3127	3178
Electricity	116205	231808	347416	463010	578610
Makeup water	172	206	218	223	227
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	2367321	2730777	2995496	3259995	3491937
Overhead (fixed and general expenses costs)	4113654	4580348	4996752	5445795	5868888
BEP ($/t)	1815	1707	1780	1872	1991



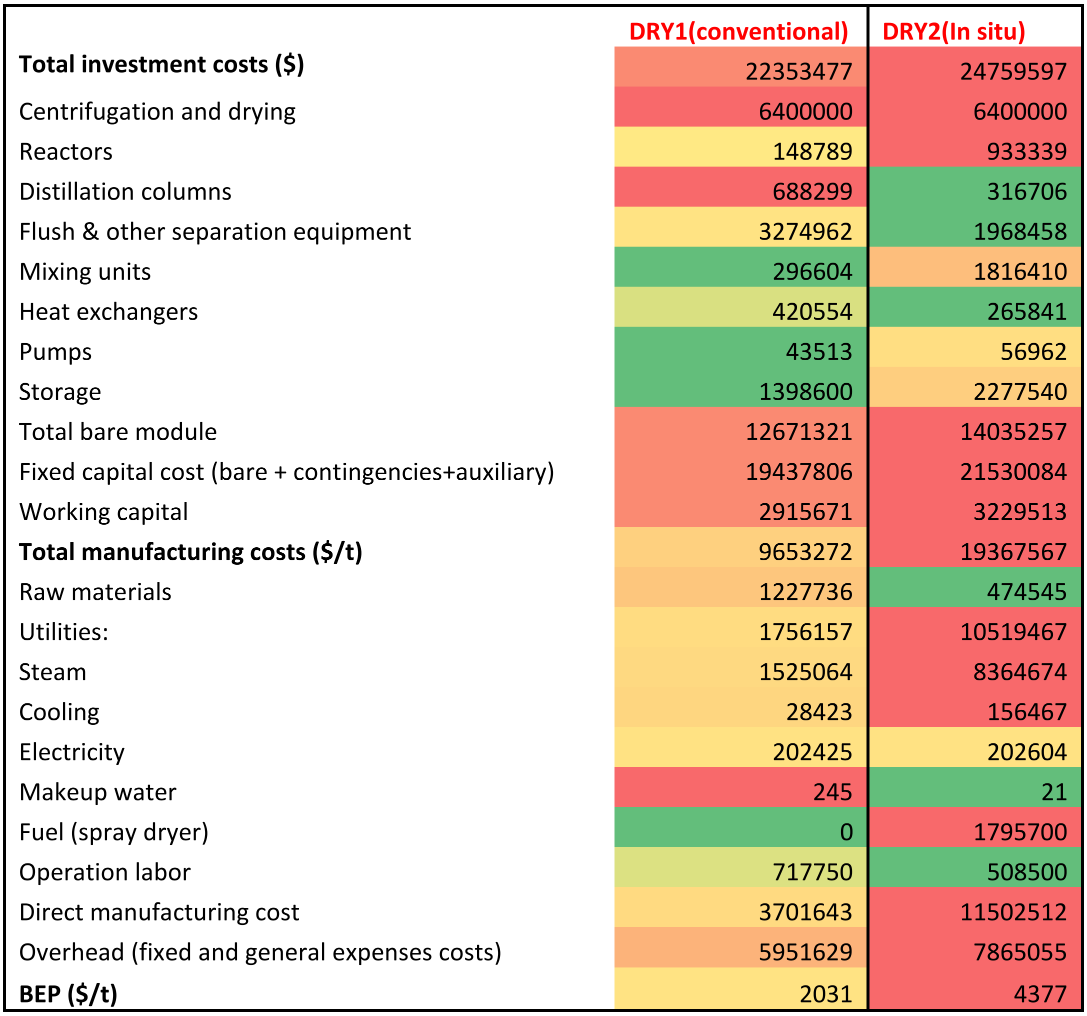
WET 100ml 60min pH2	1	2	3	4	5
Total investment costs ($)	10202165	11243484	12236074	13196163	14146533
Centrifugation and drying	0	0	0	0	0
Reactors	111948	130428	139238	143858	146675
Distillation columns	686806	687394	687664	687807	687903
Flush & other separation equipment	2342606	2492753	2630098	2761449	2890067
Mixing units	722127	1142355	1556055	1963340	2370052
Heat exchangers	467548	467108	469027	469547	469852
Pumps	53577	54858	55476	55793	55974
Storage	1398600	1398600	1398600	1398600	1398600
Total bare module	5783212	6373496	6936157	7480394	8019122
Fixed capital cost (bare + contingencies+auxiliary)	8871448	9776942	10640065	11474924	12301333
Working capital	1330717	1466541	1596010	1721239	1845200
Total manufacturing costs ($/t)	5264685	6050323	6747739	7400838	8031157
Raw materials	1239120	1361944	1417514	1452954	1476007
Utilities:	334593	443423	554911	655256	750890
Steam	245224	266436	290645	303870	312430
Cooling	1905	2531	2840	3000	3118
Electricity	87328	174275	261224	348172	435119
Makeup water	136	181	203	214	223
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	2120463	2466867	2748675	2999210	3232647
Overhead (fixed and general expenses costs)	3144221	3583456	3999064	4401628	4798510
BEP ($/t)	1860	1624	1602	1654	1737



WET 100ml 60min pH4	1	2	3	4	5
Total investment costs ($)	10183422	11221484	12205787	13169487	14115793
Centrifugation and drying	0	0	0	0	0
Reactors	109547	127887	136293	141349	144290
Distillation columns	686733	687314	687580	687731	687826
Flush & other separation equipment	2338990	2488677	2625010	2757617	2885517
Mixing units	718089	1137060	1547590	1955125	2360089
Heat exchangers	467261	466835	468682	469262	469587
Pumps	53368	54652	55233	55589	55787
Storage	1398600	1398600	1398600	1398600	1398600
Total bare module	5772588	6361025	6918988	7465273	8001697
Fixed capital cost (bare + contingencies+auxiliary)	8855150	9757812	10613728	11451728	12274602
Working capital	1328272	1463672	1592059	1717759	1841190
Total manufacturing costs ($/t)	4695795	5481725	6171221	6735427	7459177
Raw materials	786021	909865	961325	923037	1022655
Utilities:	327923	436446	546819	648092	743717
Steam	238635	259561	282667	296782	305361
Cooling	1831	2437	2734	2933	3022
Electricity	87326	174274	261222	348170	435118
Makeup water	131	174	196	208	216
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	1660694	2007811	2284394	2462129	2772122
Overhead (fixed and general expenses costs)	3035101	3473914	3886827	4273297	4687056
BEP ($/t)	1724	1524	1529	1555	1661

WET 100ml 20min pH4	1	2	3	4	5
Total investment costs ($)	9747313	10440265	11084638	11708740	12320359
Centrifugation and drying	0	0	0	0	0
Reactors	93289	108804	116134	120238	122489
Distillation columns	686240	686718	686935	687057	687134
Flush & other separation equipment	2316537	2462307	2597355	2727948	2855750
Mixing units	513174	741247	962468	1180602	1396763
Heat exchangers	465425	467202	468100	468617	468876
Pumps	52108	53303	53861	54170	54322
Storage	1398600	1398600	1398600	1398600	1398600
Total bare module	5525374	5918182	6283452	6637231	6983934
Fixed capital cost (bare + contingencies+auxiliary)	8475924	9078491	9638816	10181513	10713355
Working capital	1271389	1361774	1445822	1527227	1607003
Total manufacturing costs ($/t)	4384776	5007586	5550128	6055968	6538748
Raw materials	699660	783468	828988	856178	871375
Utilities:	225244	291690	338274	376313	409427
Steam	197215	236989	257155	268876	275716
Cooling	1370	1826	2044	2170	2254
Electricity	26560	52745	78929	105112	131296
Makeup water	98	130	146	155	161
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	1471654	1736658	1943511	2123492	2286552
Overhead (fixed and general expenses costs)	2913122	3270929	3606617	3932476	4252196
BEP ($/t)	2159	1871	1834	1873	1963

WET 200ml 20min pH4	1	2	3	4	5
Total investment costs ($)	14765111	15544877	16274853	16983062	17693209
Centrifugation and drying	0	0	0	0	0
Reactors	107225	120008	124743	127436	128880
Distillation columns	686664	687060	687218	687293	687339
Flush & other separation equipment	3474635	3641299	3796673	3949253	4100226
Mixing units	594225	853462	1105949	1355271	1605088
Heat exchangers	473738	475723	476435	473089	473261
Pumps	56442	57398	57726	57859	57961
Storage	2976840	2976840	2976840	2976840	2976840
Total bare module	8369770	8811789	9225584	9627040	10029595
Fixed capital cost (bare + contingencies+auxiliary)	12839227	13517284	14152046	14767880	15385399
Working capital	1925884	2027593	2122807	2215182	2307810
Total manufacturing costs ($/t)	5614122	6267639	6815694	7221749	7726486
Raw materials	777868	855741	885545	901509	914133
Utilities:	412193	496834	551088	506920	546039
Steam	375102	424739	444224	365384	369882
Cooling	1778	2169	2344	2434	2469
Electricity	35187	69771	104353	138929	173511
Makeup water	126	155	167	173	176
Fuel (spray dryer)	0	0	0	0	0
Operation labor	546750	661500	776250	891000	1005750
Direct manufacturing cost	1736811	2014074	2212883	2299429	2465921
Overhead (fixed and general expenses costs)	3877311	4253565	4602812	4922320	5260565
BEP ($/t)	2145	1949	1985	2015	2113



	DRY1(conventional)	DRY2(In situ)
Total investment costs ($)	22353477	24759597
Centrifugation and drying	6400000	6400000
Reactors	148789	933339
Distillation columns	688299	316706
Flush & other separation equipment	3274962	1968458
Mixing units	296604	1816410
Heat exchangers	420554	265841
Pumps	43513	56962
Storage	1398600	2277540
Total bare module	12671321	14035257
Fixed capital cost (bare + contingencies+auxiliary)	19437806	21530084
Working capital	2915671	3229513
Total manufacturing costs ($/t)	9653272	19367567
Raw materials	1227736	474545
Utilities:	1756157	10519467
Steam	1525064	8364674
Cooling	28423	156467
Electricity	202425	202604
Makeup water	245	21
Fuel (spray dryer)	0	1795700
Operation labor	717750	508500
Direct manufacturing cost	3701643	11502512
Overhead (fixed and general expenses costs)	5951629	7865055
BEP ($/t)	2031	4377

The flowsheet of DryA /Figure S2), has almost the same sections than the wet routes (solvent recovery, methanol recovery, etc.).

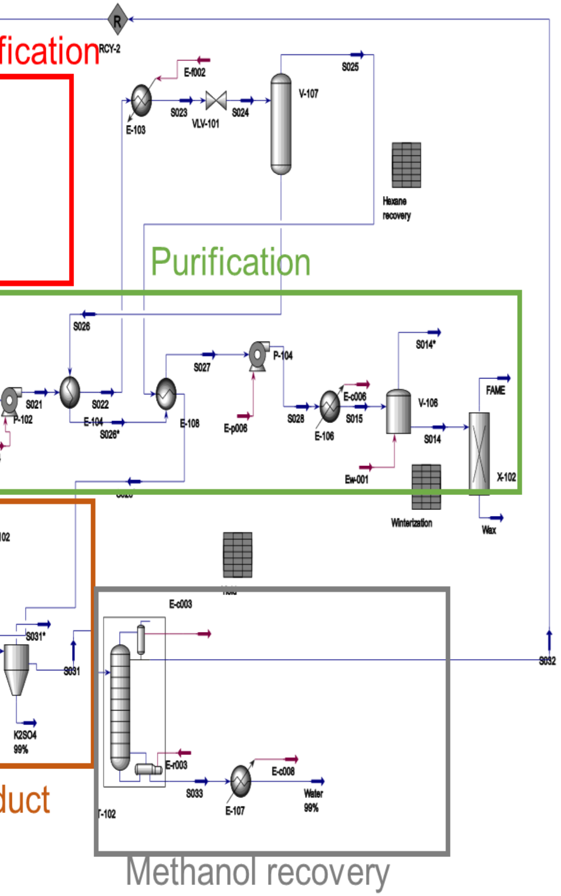


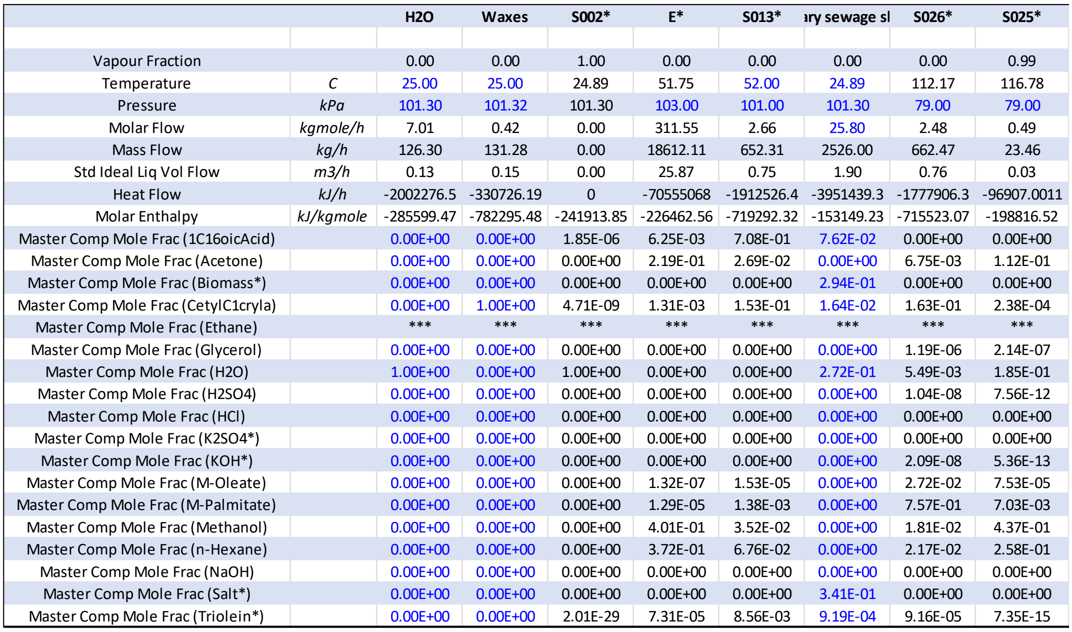
Figure S2(a): Aspen Hysys flowsheet of DryA route.

	Unit	**S**	**S003**	**Hexane**	**S010**	**S007**	**S012***	**S003***	**MeOH**	**S016***	**S016**
Vapour Fraction		0.00	0.00	0.00	1.00	0.01	0.00	1.00	0.00	1.00	0.00
Temperature	*C*	46.64	46.62	25.00	109.96	57.00	46.62	46.62	25.00	60.90	60.90
Pressure	*kPa*	120.00	70.00	101.32	70.00	103.00	70.00	70.00	101.32	101.00	101.00
Molar Flow	*kgmole/h*	310.87	310.87	0.63	308.89	311.55	309.35	0.00	2.43	0.00	12.61
Mass Flow	*kg/h*	18074.39	18074.39	54.55	17959.80	18612.11	17981.98	0.00	78.00	0.00	393.17
Std Ideal Liq Vol Flow	*m3/h*	25.28	25.28	0.08	25.12	25.87	25.15	0.00	0.10	0.00	0.49
Heat Flow	*kJ/h*	-69355321	-69357035	-126253.28	-56898682	-70218250	-69019441	0	-602271.925	0	-3083055.63
Molar Enthalpy	*kJ/kgmole*	-223097.98	-223103.49	-199469.80	-184201.32	-225381.47	-223110.31	-190740.49	-247422.02	-202386.08	-244447.73
Master Comp Mole Frac (1C16oicAcid)		2.05E-04	2.05E-04	0.00E+00	2.15E-04	6.25E-03	2.06E-04	2.46E-10	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		2.21E-01	2.21E-01	0.00E+00	2.21E-01	2.19E-01	2.21E-01	2.09E-01	0.00E+00	1.31E-04	1.31E-04
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		8.16E-06	8.16E-06	0.00E+00	8.87E-06	1.31E-03	8.20E-06	3.61E-13	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		3.49E-10	3.49E-10	0.00E+00	0.00E+00	0.00E+00	3.51E-10	6.16E-15	0.00E+00	0.00E+00	8.08E-31
Master Comp Mole Frac (H2O)		2.59E-04	2.59E-04	0.00E+00	0.00E+00	0.00E+00	2.60E-04	2.43E-03	0.00E+00	6.21E-02	6.21E-02
Master Comp Mole Frac (H2SO4)		1.24E-14	1.24E-14	0.00E+00	0.00E+00	0.00E+00	1.25E-14	6.16E-24	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		1.03E-15	1.03E-15	0.00E+00	0.00E+00	0.00E+00	1.04E-15	2.54E-27	0.00E+00	4.11E-09	4.11E-09
Master Comp Mole Frac (M-Oleate)		1.38E-07	1.38E-07	0.00E+00	1.83E-09	1.32E-07	1.39E-07	1.26E-14	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		1.29E-05	1.29E-05	0.00E+00	1.13E-06	1.29E-05	1.30E-05	3.77E-11	0.00E+00	9.28E-16	9.28E-16
Master Comp Mole Frac (Methanol)		4.04E-01	4.04E-01	0.00E+00	4.04E-01	4.01E-01	4.04E-01	4.26E-01	1.00E+00	9.38E-01	9.38E-01
Master Comp Mole Frac (n-Hexane)		3.75E-01	3.75E-01	1.00E+00	3.75E-01	3.72E-01	3.75E-01	3.63E-01	0.00E+00	4.62E-12	4.62E-12
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		4.97E-17	4.97E-17	0.00E+00	3.17E-17	7.31E-05	4.99E-17	3.49E-34	0.00E+00	0.00E+00	0.00E+00

		H2SO4	**S017**	**S018**	**S019***	**S011**	**KOH**	**S030***	**S030**	**S031***	**K2SO4 99%**
Vapour Fraction		0.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	0.00
Temperature	*C*	25.00	60.32	60.32	60.00	46.25	25.00	41.07	41.07	41.07	41.07
Pressure	*kPa*	101.32	101.00	110.00	101.00	70.00	101.32	101.00	101.00	101.00	101.00
Molar Flow	*kgmole/h*	0.09	12.71	12.71	0.00	308.89	0.18	0.00	40.05	0.00	0.09
Mass Flow	*kg/h*	8.74	401.92	401.92	0.00	17959.80	9.91	0.00	873.24	0.00	15.38
Std Ideal Liq Vol Flow	*m3/h*	0.00	0.50	0.50	0.00	25.12	0.01	0.00	0.94	0.00	0.01
Heat Flow	*kJ/h*	-84694.252	-3167749.9	-3167743.6	0	-68932833	-48980.916	0	-11070741	0	1033.74058
Molar Enthalpy	*kJ/kgmole*	-911341.69	-249325.77	-249325.27	-200206.15	-223160.15	-277396.26	-122565.63	-276439.75	-271184.51	11708.88
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.15E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		0.00E+00	1.30E-04	1.30E-04	2.43E-02	2.21E-01	0.00E+00	3.58E-02	4.10E-05	3.58E-02	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	0.00E+00	2.09E-08	8.87E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		0.00E+00	8.02E-31	8.02E-31	3.32E-09	0.00E+00	0.00E+00	1.61E-11	5.63E-04	1.61E-11	0.00E+00
Master Comp Mole Frac (H2O)		5.00E-02	6.20E-02	6.20E-02	5.45E-02	0.00E+00	0.00E+00	4.44E-02	7.55E-01	4.44E-02	0.00E+00
Master Comp Mole Frac (H2SO4)		9.50E-01	6.95E-03	6.95E-03	2.22E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.20E-03	0.00E+00	1.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	4.08E-09	4.08E-09	5.08E-19	0.00E+00	1.00E+00	8.77E-01	1.29E-09	8.77E-01	0.00E+00
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	7.75E-09	1.83E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		0.00E+00	9.22E-16	9.22E-16	5.32E-06	1.13E-06	0.00E+00	2.05E-07	3.02E-16	2.05E-07	0.00E+00
Master Comp Mole Frac (Methanol)		0.00E+00	9.31E-01	9.31E-01	8.60E-01	4.04E-01	0.00E+00	4.14E-02	2.43E-01	4.14E-02	0.00E+00
Master Comp Mole Frac (n-Hexane)		0.00E+00	4.58E-12	4.58E-12	6.08E-02	3.75E-01	0.00E+00	9.83E-04	1.45E-12	9.83E-04	0.00E+00
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	0.00E+00	8.37E-25	3.17E-17	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

		S031	**S032**	**S033**	**032***	**S008**	**HexaReco**	**Lipids**	**S009**	**S019**	**S020***
Vapour Fraction		0.00	0.00	0.00	0.00	0.99	1.00	0.00	0.99	0.00	1.00
Temperature	*C*	41.07	69.65	101.86	69.64	120.71	120.00	120.00	120.00	60.00	60.52
Pressure	*kPa*	101.00	101.00	110.00	101.00	102.50	70.00	70.00	70.00	101.00	101.00
Molar Flow	*kgmole/h*	39.96	10.18	29.78	10.18	311.55	308.89	2.66	311.55	15.36	0.00
Mass Flow	*kg/h*	857.85	315.20	542.66	315.18	18612.11	17959.80	652.31	18612.11	1054.22	0.00
Std Ideal Liq Vol Flow	*m3/h*	0.94	0.39	0.55	0.39	25.87	25.12	0.75	25.87	1.23	0.00
Heat Flow	*kJ/h*	-11071775	-2481076.6	-8336091	-2480783.7	-58384403	-56561864	-1822538.9	-58384402.5	-5137062.46	0
Molar Enthalpy	*kJ/kgmole*	-277076.39	-243741.85	-279920.87	-243736.40	-187398.04	-183110.92	-685448.43	-187398.04	-334353.51	-212836.06
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.25E-03	2.15E-04	7.08E-01	6.25E-03	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		4.10E-05	1.61E-04	1.00E-30	1.62E-04	2.19E-01	2.21E-01	2.69E-02	2.19E-01	4.76E-03	8.76E-02
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.31E-03	8.87E-06	1.53E-01	1.31E-03	2.64E-02	5.31E-08
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		5.64E-04	1.00E-30	7.57E-04	1.00E-30	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-03	5.81E-10
Master Comp Mole Frac (H2O)		7.56E-01	7.71E-02	9.88E-01	7.70E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-01	4.15E-01
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.75E-03	7.57E-16
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		1.30E-09	5.09E-09	1.88E-201	5.09E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.37E-09	1.35E-18
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.32E-07	1.83E-09	1.53E-05	1.32E-07	4.40E-03	2.00E-08
Master Comp Mole Frac (M-Palmitate)		3.03E-16	1.19E-15	1.00E-30	1.15E-15	1.29E-05	1.13E-06	1.38E-03	1.29E-05	1.23E-01	1.40E-05
Master Comp Mole Frac (Methanol)		2.43E-01	9.23E-01	1.08E-02	9.23E-01	4.01E-01	4.04E-01	3.52E-02	4.01E-01	6.49E-01	3.57E-01
Master Comp Mole Frac (n-Hexane)		1.45E-12	5.71E-12	1.00E-30	5.72E-12	3.72E-01	3.75E-01	6.76E-02	3.72E-01	1.17E-02	1.41E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.31E-05	3.17E-17	8.56E-03	7.31E-05	1.48E-05	7.02E-25

		S020	**S029**	**Vashing wate**	**S025**	**S026**	**S021**	**S023**	**S024**	**S027**	**S022**
Vapour Fraction		0.00	0.00	0.00	1.00	0.00	0.00	0.15	0.16	0.00	0.05
Temperature	*C*	60.52	60.52	25.00	169.28	169.28	60.52	170.00	169.28	114.00	117.00
Pressure	*kPa*	101.00	101.00	101.32	80.00	80.00	110.00	109.00	80.00	95.00	110.00
Molar Flow	*kgmole/h*	2.97	39.87	27.48	0.49	2.48	2.97	2.97	2.97	2.48	2.97
Mass Flow	*kg/h*	685.93	863.33	495.04	23.46	662.47	685.93	685.93	685.93	662.47	685.93
Std Ideal Liq Vol Flow	*m3/h*	0.79	0.94	0.50	0.03	0.76	0.79	0.79	0.79	0.76	0.79
Heat Flow	*kJ/h*	-1963215.4	-11021840	-7847992.9	-94247.653	-1691369.5	-1963205.7	-1785617.2	-1785617.18	-1775246.93	-1876668.95
Molar Enthalpy	*kJ/kgmole*	-660529.62	-276437.52	-285599.47	-193360.55	-680696.13	-660526.37	-600776.18	-600776.18	-714452.81	-631410.82
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		2.41E-02	4.11E-05	0.00E+00	1.12E-01	6.75E-03	2.41E-02	2.41E-02	2.41E-02	6.75E-03	2.41E-02
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		1.36E-01	4.89E-18	0.00E+00	2.38E-04	1.63E-01	1.36E-01	1.36E-01	1.36E-01	1.63E-01	1.36E-01
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		1.03E-06	5.65E-04	0.00E+00	2.14E-07	1.19E-06	1.03E-06	1.03E-06	1.03E-06	1.19E-06	1.03E-06
Master Comp Mole Frac (H2O)		3.49E-02	7.54E-01	1.00E+00	1.85E-01	5.49E-03	3.49E-02	3.49E-02	3.49E-02	5.49E-03	3.49E-02
Master Comp Mole Frac (H2SO4)		8.71E-09	2.21E-03	0.00E+00	7.56E-12	1.04E-08	8.71E-09	8.71E-09	8.71E-09	1.04E-08	8.71E-09
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		1.74E-08	5.83E-25	0.00E+00	5.36E-13	2.09E-08	1.74E-08	1.74E-08	1.74E-08	2.09E-08	1.74E-08
Master Comp Mole Frac (M-Oleate)		2.28E-02	6.12E-19	0.00E+00	7.53E-05	2.72E-02	2.28E-02	2.28E-02	2.28E-02	2.72E-02	2.28E-02
Master Comp Mole Frac (M-Palmitate)		6.34E-01	3.03E-16	0.00E+00	7.03E-03	7.57E-01	6.34E-01	6.34E-01	6.34E-01	7.57E-01	6.34E-01
Master Comp Mole Frac (Methanol)		8.68E-02	2.44E-01	0.00E+00	4.37E-01	1.81E-02	8.68E-02	8.68E-02	8.68E-02	1.81E-02	8.68E-02
Master Comp Mole Frac (n-Hexane)		6.05E-02	1.46E-12	0.00E+00	2.58E-01	2.17E-02	6.05E-02	6.05E-02	6.05E-02	2.17E-02	6.05E-02
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		7.66E-05	2.39E-21	0.00E+00	7.35E-15	9.16E-05	7.66E-05	7.66E-05	7.66E-05	9.16E-05	7.66E-05
		S028	**S015**	**Water 99%**	**S012**	**S013**	**S014**	**S014***	**FAME**	**Wax**	**v1**
Vapour Fraction		0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00
Temperature	*C*	114.00	35.00	35.00	46.61	119.87	5.00	5.00	5.00	4.77	50.00
Pressure	*kPa*	101.00	101.00	110.00	70.00	101.32	101.00	101.00	101.32	101.32	101.30
Molar Flow	*kgmole/h*	2.48	2.48	29.78	309.38	2.66	2.48	0.00	2.08	0.41	0.00
Mass Flow	*kg/h*	662.47	662.47	542.66	17983.26	652.31	662.47	0.00	536.58	125.89	0.00
Std Ideal Liq Vol Flow	*m3/h*	0.76	0.76	0.55	25.15	0.75	0.76	0.00	0.61	0.14	0.00
Heat Flow	*kJ/h*	-1775240.4	-1882467.8	-8485586.7	-69029740	-1822505	-1919180.9	0	-1596960.96	-322219.916	0
Molar Enthalpy	*kJ/kgmole*	-714450.20	-757604.15	-284940.85	-223121.80	-685435.67	-772379.41	-502307.30	-768015.56	-794760.29	-191835.13
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	2.15E-04	7.08E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.63E-09
Master Comp Mole Frac (Acetone)		6.75E-03	6.75E-03	1.00E-30	2.21E-01	2.69E-02	6.75E-03	3.73E-08	8.06E-03	0.00E+00	2.26E-01
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		1.63E-01	1.63E-01	0.00E+00	9.24E-06	1.53E-01	1.63E-01	3.83E-46	0.00E+00	1.00E+00	7.87E-11
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		1.19E-06	1.19E-06	7.57E-04	3.36E-10	0.00E+00	1.19E-06	5.96E-02	1.43E-06	0.00E+00	1.31E-15
Master Comp Mole Frac (H2O)		5.49E-03	5.49E-03	9.88E-01	2.92E-04	0.00E+00	5.49E-03	4.53E-01	6.56E-03	0.00E+00	2.24E-02
Master Comp Mole Frac (H2SO4)		1.04E-08	1.04E-08	0.00E+00	1.19E-14	0.00E+00	1.04E-08	4.82E-01	1.24E-08	0.00E+00	7.30E-26
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		2.09E-08	2.09E-08	1.88E-201	8.44E-16	0.00E+00	2.09E-08	5.03E-63	2.49E-08	0.00E+00	5.19E-27
Master Comp Mole Frac (M-Oleate)		2.72E-02	2.72E-02	0.00E+00	1.20E-07	1.53E-05	2.72E-02	1.23E-42	3.25E-02	0.00E+00	1.70E-14
Master Comp Mole Frac (M-Palmitate)		7.57E-01	7.57E-01	1.00E-30	1.22E-05	1.38E-03	7.57E-01	3.45E-31	9.05E-01	0.00E+00	4.86E-11
Master Comp Mole Frac (Methanol)		1.81E-02	1.81E-02	1.08E-02	4.04E-01	3.52E-02	1.81E-02	5.31E-03	2.17E-02	0.00E+00	3.96E-01
Master Comp Mole Frac (n-Hexane)		2.17E-02	2.17E-02	1.00E-30	3.75E-01	6.76E-02	2.17E-02	3.51E-15	2.59E-02	0.00E+00	3.56E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		9.16E-05	9.16E-05	0.00E+00	4.32E-17	8.56E-03	9.16E-05	8.79E-105	1.10E-04	0.00E+00	1.70E-22
		eq1	**E**	**R**	**Methanol**	**Acetone**	**rimary sludg**	**TG**	**OM***	**FFA**	**Salt**
Vapour Fraction		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Temperature	*C*	50.00	50.00	30.16	25.00	25.00	24.89	25.00	25.00	25.00	25.00
Pressure	*kPa*	101.30	105.00	105.00	101.32	101.32	101.30	101.32	101.30	101.30	101.30
Molar Flow	*kgmole/h*	336.68	311.55	25.12	0.53	0.36	25.80	0.02	7.58	1.97	8.79
Mass Flow	*kg/h*	20600.39	18612.11	1988.28	16.99	20.87	2526.00	21.00	1229.78	504.10	513.54
Std Ideal Liq Vol Flow	*m3/h*	27.18	25.87	1.31	0.02	0.03	1.90	0.02	0.82	0.57	0.21
Heat Flow	*kJ/h*	-73073037	-70645090	-2427947.6	-131216.83	-89550.323	-3951440.1	-3760.135	0	-1614677.22	0
Molar Enthalpy	*kJ/kgmole*	-217043.22	-226751.51	-96645.67	-247422.02	-249204.35	-153149.26	-158510.77	0.00	-821355.59	0.00
Master Comp Mole Frac (1C16oicAcid)		6.03E-03	6.25E-03	3.23E-03	0.00E+00	0.00E+00	7.62E-02	0.00E+00	0.00E+00	1.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		2.04E-01	2.19E-01	1.37E-02	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		2.25E-02	0.00E+00	3.02E-01	0.00E+00	0.00E+00	2.94E-01	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		1.26E-03	1.31E-03	6.77E-04	0.00E+00	0.00E+00	1.64E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		3.22E-10	0.00E+00	4.32E-09	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		2.11E-02	0.00E+00	2.82E-01	0.00E+00	0.00E+00	2.72E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2SO4)		1.15E-14	0.00E+00	1.54E-13	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		3.30E-40	0.00E+00	4.42E-39	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		9.52E-16	0.00E+00	1.28E-14	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		1.27E-07	1.32E-07	6.83E-08	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		1.19E-05	1.29E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Methanol)		3.73E-01	4.01E-01	2.50E-02	1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (n-Hexane)		3.46E-01	3.72E-01	2.32E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		2.61E-02	0.00E+00	3.50E-01	0.00E+00	0.00E+00	3.41E-01	0.00E+00	0.00E+00	0.00E+00	1.00E+00
Master Comp Mole Frac (Triolein*)		7.05E-05	7.31E-05	3.78E-05	0.00E+00	0.00E+00	9.19E-04	1.00E+00	0.00E+00	0.00E+00	0.00E+00



		H2O	Waxes	S002*	E*	S013*	ıry sewage sl	S026*	S025*
Vapour Fraction		0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.99
Temperature	*C*	25.00	25.00	24.89	51.75	52.00	24.89	112.17	116.78
Pressure	*kPa*	101.30	101.32	101.30	103.00	101.00	101.30	79.00	79.00
Molar Flow	*kgmole/h*	7.01	0.42	0.00	311.55	2.66	25.80	2.48	0.49
Mass Flow	*kg/h*	126.30	131.28	0.00	18612.11	652.31	2526.00	662.47	23.46
Std Ideal Liq Vol Flow	*m3/h*	0.13	0.15	0.00	25.87	0.75	1.90	0.76	0.03
Heat Flow	*kJ/h*	-2002276.5	-330726.19	0	-70555068	-1912526.4	-3951439.3	-1777906.3	-96907.0011
Molar Enthalpy	*kJ/kgmole*	-285599.47	-782295.48	-241913.85	-226462.56	-719292.32	-153149.23	-715523.07	-198816.52
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	1.85E-06	6.25E-03	7.08E-01	7.62E-02	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	2.19E-01	2.69E-02	0.00E+00	6.75E-03	1.12E-01
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.94E-01	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	1.00E+00	4.71E-09	1.31E-03	1.53E-01	1.64E-02	1.63E-01	2.38E-04
Master Comp Mole Frac (Ethane)		***	***	***	***	***	***	***	***
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.19E-06	2.14E-07
Master Comp Mole Frac (H2O)		1.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	2.72E-01	5.49E-03	1.85E-01
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.04E-08	7.56E-12
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.09E-08	5.36E-13
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	1.32E-07	1.53E-05	0.00E+00	2.72E-02	7.53E-05
Master Comp Mole Frac (M-Palmitate)		0.00E+00	0.00E+00	0.00E+00	1.29E-05	1.38E-03	0.00E+00	7.57E-01	7.03E-03
Master Comp Mole Frac (Methanol)		0.00E+00	0.00E+00	0.00E+00	4.01E-01	3.52E-02	0.00E+00	1.81E-02	4.37E-01
Master Comp Mole Frac (n-Hexane)		0.00E+00	0.00E+00	0.00E+00	3.72E-01	6.76E-02	0.00E+00	2.17E-02	2.58E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.41E-01	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	2.01E-29	7.31E-05	8.56E-03	9.19E-04	9.16E-05	7.35E-15

Figure S2(b): Mass balance of the DryA route flowsheet.

Figure S2: Base case flowsheet and mass balance of the DryA route with a mixture of hexane, methanol and acetone as a solvent.

The three simulated main parts of the DryB route appear in Figure S3. Although the number of the equipments in this route is lower, the profit and economic results are the worst option, by far. A conversion reactor for the in situ transesterification and a 10 stages-distillation tower for the methanol recovery were considered.

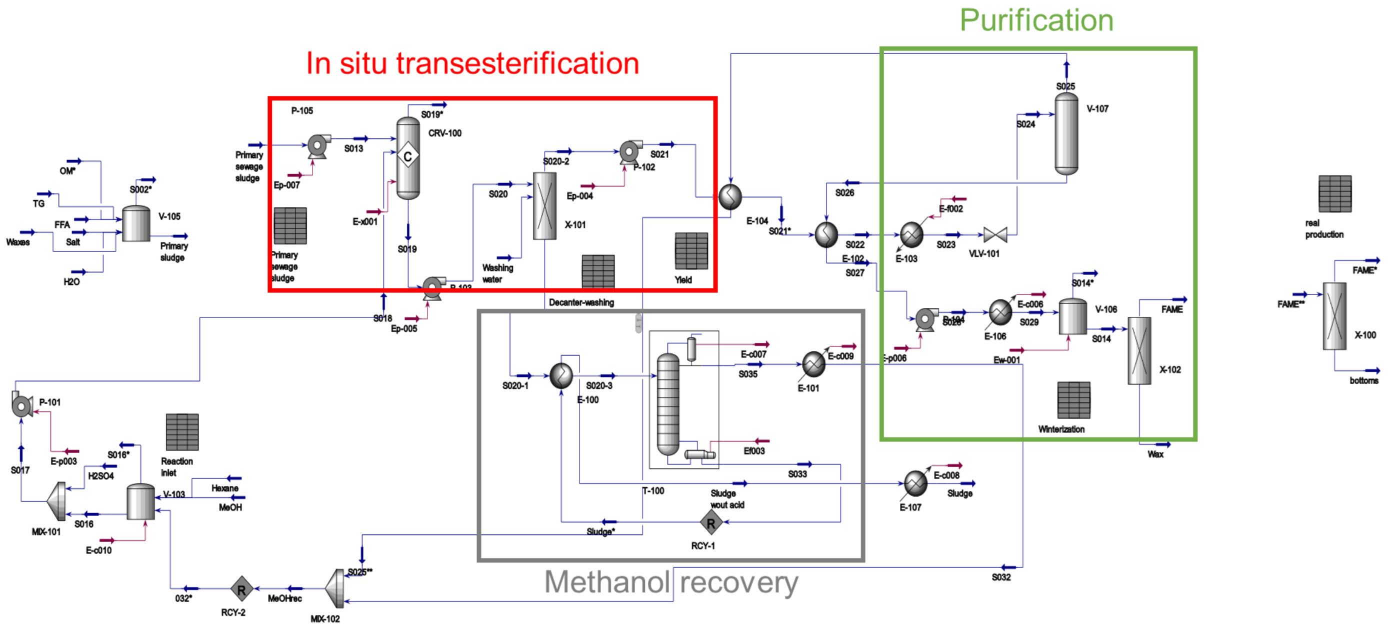
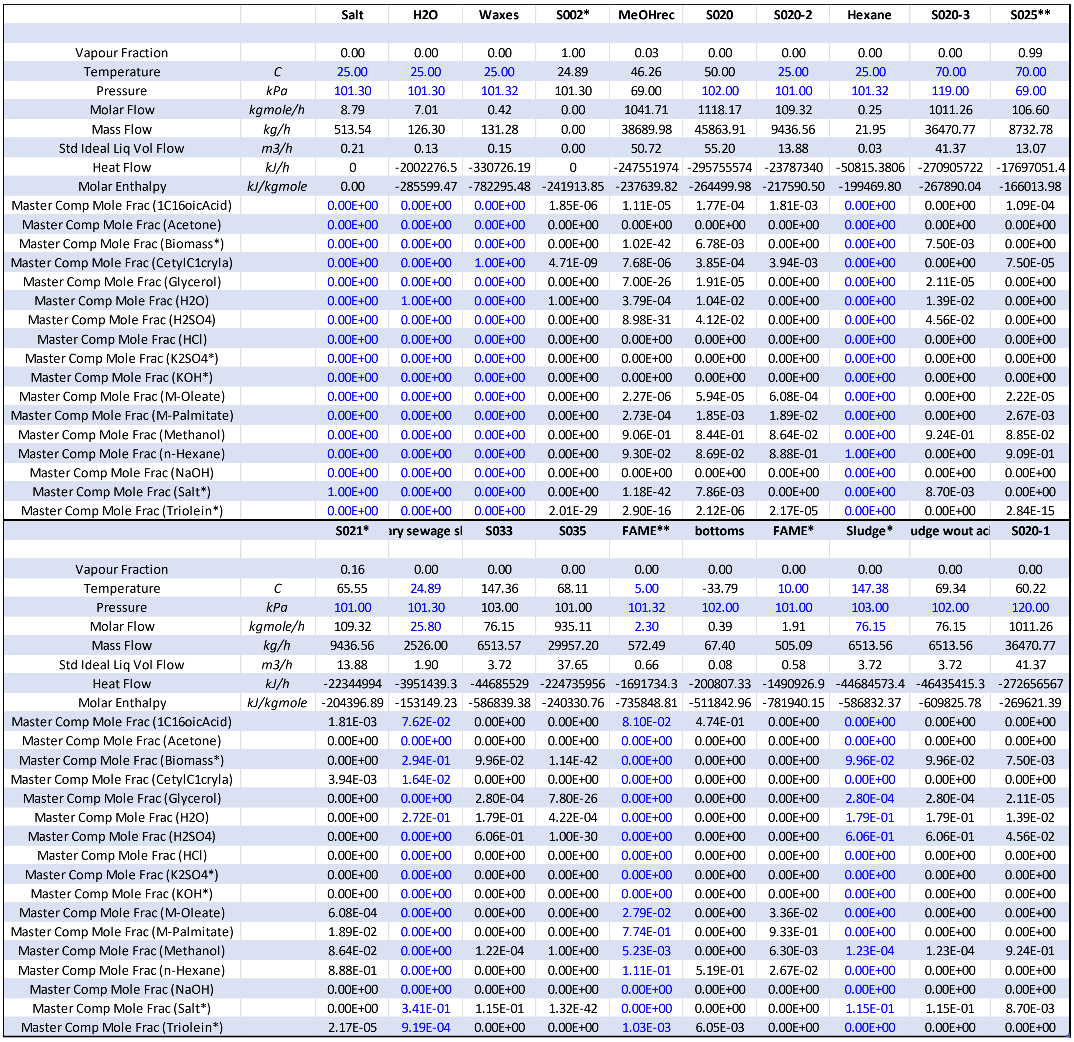


Figure S3(a): Aspen Hysys flowsheet of DryB route

	Unit	**MeOH**	**S016***	**S016**	**H2SO4**	**S017**	**S018**	**S019***	**S032**	**032***	**S019**
Vapour Fraction		0.00	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.03	0.00
Temperature	*C*	25.00	40.00	40.00	25.00	37.18	37.18	50.00	35.00	46.26	50.00
Pressure	*kPa*	101.32	69.00	69.00	101.32	69.00	110.00	101.32	101.00	69.00	101.32
Molar Flow	*kgmole/h*	1.87	0.00	1043.83	48.54	1092.37	1092.37	0.00	935.11	1041.71	1118.17
Mass Flow	*kg/h*	59.76	0.00	38771.69	4566.22	43337.91	43337.91	0.00	29957.20	38689.98	45863.91
Std Ideal Liq Vol Flow	*m3/h*	0.08	0.00	50.83	2.49	53.31	53.31	0.00	37.65	50.72	55.20
Heat Flow	*kJ/h*	-461471.19	0	-250299018	-44233936	-294532954	-294529984	0	-229854923	-247551993	-295755625
Molar Enthalpy	*kJ/kgmole*	-247422.02	-182414.30	-239789.01	-911341.69	-269628.11	-269625.39	-183498.70	-245804.94	-237639.94	-264500.02
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	5.30E-11	1.11E-05	0.00E+00	1.06E-05	1.06E-05	1.28E-09	0.00E+00	1.11E-05	1.77E-04
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	1.02E-42	0.00E+00	9.72E-43	9.72E-43	0.00E+00	1.14E-42	1.02E-42	6.78E-03
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	8.30E-13	7.66E-06	0.00E+00	7.32E-06	7.32E-06	9.40E-11	0.00E+00	7.68E-06	3.85E-04
Master Comp Mole Frac (Glycerol)		0.00E+00	1.93E-32	7.08E-26	0.00E+00	6.77E-26	6.77E-26	6.85E-12	7.80E-26	7.10E-26	1.91E-05
Master Comp Mole Frac (H2O)		0.00E+00	4.41E-05	3.78E-04	5.00E-02	2.58E-03	2.58E-03	1.11E-03	4.22E-04	3.78E-04	1.04E-02
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	5.68E-44	9.50E-01	4.22E-02	4.22E-02	9.79E-15	1.00E-30	5.69E-44	4.12E-02
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		0.00E+00	5.88E-13	2.27E-06	0.00E+00	2.17E-06	2.17E-06	3.34E-11	0.00E+00	2.27E-06	5.94E-05
Master Comp Mole Frac (M-Palmitate)		0.00E+00	3.62E-09	2.73E-04	0.00E+00	2.61E-04	2.61E-04	3.70E-08	0.00E+00	2.73E-04	1.85E-03
Master Comp Mole Frac (Methanol)		1.00E+00	4.82E-01	9.06E-01	0.00E+00	8.66E-01	8.66E-01	5.35E-01	1.00E+00	9.06E-01	8.44E-01
Master Comp Mole Frac (n-Hexane)		0.00E+00	5.18E-01	9.30E-02	0.00E+00	8.89E-02	8.89E-02	4.64E-01	0.00E+00	9.30E-02	8.69E-02
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	1.18E-42	0.00E+00	1.13E-42	1.13E-42	0.00E+00	1.32E-42	1.18E-42	7.86E-03
Master Comp Mole Frac (Triolein*)		0.00E+00	2.54E-35	2.90E-16	0.00E+00	2.77E-16	2.77E-16	3.13E-24	0.00E+00	2.90E-16	2.12E-06
		Washing wate	**S025**	**S026**	**S021**	**S023**	**S024**	**S027**	**S022**	**S028**	**S029**
Vapour Fraction		0.00	1.00	0.00	0.00	0.97	0.98	0.00	0.19	0.00	0.00
Temperature	*C*	25.00	149.16	149.16	25.00	150.00	149.16	95.00	66.01	95.01	35.00
Pressure	*kPa*	101.32	70.00	70.00	102.00	101.00	70.00	70.00	102.00	101.00	101.00
Molar Flow	*kgmole/h*	2.41	106.60	2.72	109.32	109.32	109.32	2.72	109.32	2.72	2.72
Mass Flow	*kg/h*	43.42	8732.78	703.77	9436.56	9436.56	9436.56	703.77	9436.56	703.77	703.77
Std Ideal Liq Vol Flow	*m3/h*	0.04	13.07	0.81	13.88	13.88	13.88	0.81	13.88	0.81	0.81
Heat Flow	*kJ/h*	-688333.11	-16254724	-1819081.2	-23787322	-18073805	-18073805	-1903790.7	-22260284.4	-1903755.31	-1988793.43
Molar Enthalpy	*kJ/kgmole*	-285599.47	-152483.67	-668331.72	-217590.33	-165326.95	-165326.95	-699454.02	-203622.03	-699441.03	-730684.09
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	1.09E-04	6.84E-02	1.81E-03	1.81E-03	1.81E-03	6.84E-02	1.81E-03	6.84E-02	6.84E-02
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	7.50E-05	1.55E-01	3.94E-03	3.94E-03	3.94E-03	1.55E-01	3.94E-03	1.55E-01	1.55E-01
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		0.00E+00	2.22E-05	2.35E-02	6.08E-04	6.08E-04	6.08E-04	2.35E-02	6.08E-04	2.35E-02	2.35E-02
Master Comp Mole Frac (M-Palmitate)		0.00E+00	2.67E-03	6.54E-01	1.89E-02	1.89E-02	1.89E-02	6.54E-01	1.89E-02	6.54E-01	6.54E-01
Master Comp Mole Frac (Methanol)		0.00E+00	8.85E-02	4.42E-03	8.64E-02	8.64E-02	8.64E-02	4.42E-03	8.64E-02	4.42E-03	4.42E-03
Master Comp Mole Frac (n-Hexane)		0.00E+00	9.09E-01	9.36E-02	8.88E-01	8.88E-01	8.88E-01	9.36E-02	8.88E-01	9.36E-02	9.36E-02
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	2.84E-15	8.72E-04	2.17E-05	2.17E-05	2.17E-05	8.72E-04	2.17E-05	8.72E-04	8.72E-04
		Sludge	**S013**	**S014**	**S014***	**FAME**	**Wax**	**rimary sludg**	**TG**	**OM***	**FFA**
Vapour Fraction		0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
Temperature	*C*	35.00	24.89	5.00	5.00	5.00	4.78	24.89	25.00	25.00	25.00
Pressure	*kPa*	102.00	101.32	101.00	101.00	101.32	101.32	101.30	101.32	101.30	101.30
Molar Flow	*kgmole/h*	76.15	25.80	2.72	0.00	2.30	0.42	25.80	0.02	7.58	1.97
Mass Flow	*kg/h*	6513.56	2526.00	703.77	0.00	572.50	131.28	2526.00	21.00	1229.78	504.10
Std Ideal Liq Vol Flow	*m3/h*	3.72	1.90	0.81	0.00	0.66	0.15	1.90	0.02	0.82	0.57
Heat Flow	*kJ/h*	-47219502	-3951438.5	-2027755.3	0	-1691762.5	-335992.82	-3951440.1	-3760.13502	0	-1614677.22
Molar Enthalpy	*kJ/kgmole*	-620123.00	-153149.20	-744998.71	-662450.59	-735849.62	-794753.00	-153149.26	-158510.77	0.00	-821355.59
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	7.62E-02	6.84E-02	6.84E-02	8.10E-02	0.00E+00	7.62E-02	0.00E+00	0.00E+00	1.00E+00
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		9.96E-02	2.94E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.94E-01	0.00E+00	1.00E+00	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	1.64E-02	1.55E-01	1.55E-01	0.00E+00	1.00E+00	1.64E-02	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		2.80E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2O)		1.79E-01	2.72E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.72E-01	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (H2SO4)		6.06E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	2.35E-02	2.35E-02	2.79E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		0.00E+00	0.00E+00	6.54E-01	6.54E-01	7.74E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Methanol)		1.23E-04	0.00E+00	4.42E-03	4.41E-03	5.23E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (n-Hexane)		0.00E+00	0.00E+00	9.36E-02	9.36E-02	1.11E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		1.15E-01	3.41E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.41E-01	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	9.19E-04	8.72E-04	8.66E-04	1.03E-03	0.00E+00	9.19E-04	1.00E+00	0.00E+00	0.00E+00



		Salt	H2O	Waxes	S002*	MeOHrec	S020	S020-2	Hexane	S020-3	S025**
Vapour Fraction		0.00	0.00	0.00	1.00	0.03	0.00	0.00	0.00	0.00	0.99
Temperature	*C*	25.00	25.00	25.00	24.89	46.26	50.00	25.00	25.00	70.00	70.00
Pressure	*kPa*	101.30	101.30	101.32	101.30	69.00	102.00	101.00	101.32	119.00	69.00
Molar Flow	*kgmole/h*	8.79	7.01	0.42	0.00	1041.71	1118.17	109.32	0.25	1011.26	106.60
Mass Flow	*kg/h*	513.54	126.30	131.28	0.00	38689.98	45863.91	9436.56	21.95	36470.77	8732.78
Std Ideal Liq Vol Flow	*m3/h*	0.21	0.13	0.15	0.00	50.72	55.20	13.88	0.03	41.37	13.07
Heat Flow	*kJ/h*	0	-2002276.5	-330726.19	0	-247551974	-295755574	-23787340	-50815.3806	-270905722	-17697051.4
Molar Enthalpy	*kJ/kgmole*	0.00	-285599.47	-782295.48	-241913.85	-237639.82	-264499.98	-217590.50	-199469.80	-267890.04	-166013.98
Master Comp Mole Frac (1C16oicAcid)		0.00E+00	0.00E+00	0.00E+00	1.85E-06	1.11E-05	1.77E-04	1.81E-03	0.00E+00	0.00E+00	1.09E-04
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E-42	6.78E-03	0.00E+00	0.00E+00	7.50E-03	0.00E+00
Master Comp Mole Frac (CetylC1cryla)		0.00E+00	0.00E+00	1.00E+00	4.71E-09	7.68E-06	3.85E-04	3.94E-03	0.00E+00	0.00E+00	7.50E-05
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.00E-26	1.91E-05	0.00E+00	0.00E+00	2.11E-05	0.00E+00
Master Comp Mole Frac (H2O)		0.00E+00	1.00E+00	0.00E+00	1.00E+00	3.79E-04	1.04E-02	0.00E+00	0.00E+00	1.39E-02	0.00E+00
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.98E-31	4.12E-02	0.00E+00	0.00E+00	4.56E-02	0.00E+00
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.27E-06	5.94E-05	6.08E-04	0.00E+00	0.00E+00	2.22E-05
Master Comp Mole Frac (M-Palmitate)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.73E-04	1.85E-03	1.89E-02	0.00E+00	0.00E+00	2.67E-03
Master Comp Mole Frac (Methanol)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.06E-01	8.44E-01	8.64E-02	0.00E+00	9.24E-01	8.85E-02
Master Comp Mole Frac (n-Hexane)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.30E-02	8.69E-02	8.88E-01	1.00E+00	0.00E+00	9.09E-01
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		1.00E+00	0.00E+00	0.00E+00	0.00E+00	1.18E-42	7.86E-03	0.00E+00	0.00E+00	8.70E-03	0.00E+00
Master Comp Mole Frac (Triolein*)		0.00E+00	0.00E+00	0.00E+00	2.01E-29	2.90E-16	2.12E-06	2.17E-05	0.00E+00	0.00E+00	2.84E-15

		S021*	ary sewage sl	S033	S035	FAME**	bottoms	FAME*	Sludge*	udge wout ac	S020-1
Vapour Fraction		0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Temperature	*C*	65.55	24.89	147.36	68.11	5.00	-33.79	10.00	147.38	69.34	60.22
Pressure	*kPa*	101.00	101.30	103.00	101.00	101.32	102.00	101.00	103.00	102.00	120.00
Molar Flow	*kgmole/h*	109.32	25.80	76.15	935.11	2.30	0.39	1.91	76.15	76.15	1011.26
Mass Flow	*kg/h*	9436.56	2526.00	6513.57	29957.20	572.49	67.40	505.09	6513.56	6513.56	36470.77
Std Ideal Liq Vol Flow	*m3/h*	13.88	1.90	3.72	37.65	0.66	0.08	0.58	3.72	3.72	41.37
Heat Flow	*kJ/h*	-22344994	-3951439.3	-44685529	-224735956	-1691734.3	-200807.33	-1490926.9	-44684573.4	-46435415.3	-272656567
Molar Enthalpy	*kJ/kgmole*	-204396.89	-153149.23	-586839.38	-240330.76	-735848.81	-511842.96	-781940.15	-586832.37	-609825.78	-269621.39
Master Comp Mole Frac (1C16oicAcid)		1.81E-03	7.62E-02	0.00E+00	0.00E+00	8.10E-02	4.74E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Acetone)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Biomass*)		0.00E+00	2.94E-01	9.96E-02	1.14E-42	0.00E+00	0.00E+00	0.00E+00	9.96E-02	9.96E-02	7.50E-03
Master Comp Mole Frac (CetylC1cryla)		3.94E-03	1.64E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Glycerol)		0.00E+00	0.00E+00	2.80E-04	7.80E-26	0.00E+00	0.00E+00	0.00E+00	2.80E-04	2.80E-04	2.11E-05
Master Comp Mole Frac (H2O)		0.00E+00	2.72E-01	1.79E-01	4.22E-04	0.00E+00	0.00E+00	0.00E+00	1.79E-01	1.79E-01	1.39E-02
Master Comp Mole Frac (H2SO4)		0.00E+00	0.00E+00	6.06E-01	1.00E-30	0.00E+00	0.00E+00	0.00E+00	6.06E-01	6.06E-01	4.56E-02
Master Comp Mole Frac (HCl)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (K2SO4*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (KOH*)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Oleate)		6.08E-04	0.00E+00	0.00E+00	0.00E+00	2.79E-02	0.00E+00	3.36E-02	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (M-Palmitate)		1.89E-02	0.00E+00	0.00E+00	0.00E+00	7.74E-01	0.00E+00	9.33E-01	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Methanol)		8.64E-02	0.00E+00	1.22E-04	1.00E+00	5.23E-03	0.00E+00	6.30E-03	1.23E-04	1.23E-04	9.24E-01
Master Comp Mole Frac (n-Hexane)		8.88E-01	0.00E+00	0.00E+00	0.00E+00	1.11E-01	5.19E-01	2.67E-02	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (NaOH)		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Master Comp Mole Frac (Salt*)		0.00E+00	3.41E-01	1.15E-01	1.32E-42	0.00E+00	0.00E+00	0.00E+00	1.15E-01	1.15E-01	8.70E-03
Master Comp Mole Frac (Triolein*)		2.17E-05	9.19E-04	0.00E+00	0.00E+00	1.03E-03	6.05E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Figure S2(b): Mass balance of the DryB route flowsheet.

Figure S3: Base case flowsheet and mass balance of the DryB route.

For the environmental assessment, the database was extracted from the ecoinvent v3.8 APOS. The LCA calculation was done in Matlab and the impact factor of each category was estimated based on the ReCiPe 2016 method. By multiplying the numbers in the ecoinvent database for selected inventories with the ReCiPe coefficient, the result is obtained in all the categories: GWHH: Global warming, Human Health, GWTE: Global warming, Terrestrial Ecosystems, GWFE: Global warming, Freshwater Ecosystems, SozD: Stratospheric ozone Depletion, Irad: Ionising radiation, OzFHH: Ozone Formation, Human Health, FPMF: Fine Particulate Matter Formation, OzFTE: Ozone Formation, Terrestrial Ecosystems, Tac: Terrestrial acidification, Feu: Freshwater eutrophication, Meu: Marine eutrophication, TEx: Terrestrial Ecotoxicity, Fex: Freshwater ecotoxicity, Mex: Marine ecotoxicity, HCTx: Human Carcinogenic Toxicity, HnCTx: Human non-Carcinogenic Toxicity, LU: Land Use, MRSc: Mineral Resource Scarcity, FRSc: Fossil Resource Scarcity, WCHH: Water Consumption, Human Health, WCTE: Water Consumption, Terrestrial Ecosystems, WCAE: Water Consumption, Aquatic Ecosystem.

Table S2: LCIA database for the base case.

		GWHH	GWTE	GWFE	SozD	Irad	OzFHH	FPMF	OzFTE	Tac	Feu	Meu
		DALY	species.yr	species.yr	DALY	DALY	DALY	DALY	species.yr	species.yr	species.yr	species.yr
Raw materials	Methanol	2.69E-07	8.11E-10	2.22E-14	1.28E-10	9.34E-10	1.43E-09	3.55E-07	2.21E-10	2.86E-10	1.21E-10	9.39E-14
Raw materials	Hexane	5.12E-07	1.55E-09	4.22E-14	3.67E-10	2.75E-10	2.83E-09	7.77E-07	4.99E-10	7.32E-10	7.12E-11	1.34E-14
Raw materials	Hydrochloride acid	5.49E-07	1.66E-09	4.53E-14	3.62E-10	1.49E-09	1.25E-09	8.41E-07	1.80E-10	7.50E-10	2.98E-10	7.66E-14
Raw materials	Potassium hydroxide	2.50E-06	7.53E-09	2.06E-13	5.75E-10	1.83E-09	6.62E-09	3.23E-06	9.51E-10	2.06E-09	7.25E-10	1.34E-13
Raw materials	Sulphuric acid	1.18E-07	3.55E-10	9.69E-15	2.82E-11	1.32E-10	3.63E-10	1.50E-06	5.36E-11	1.71E-09	3.79E-11	7.40E-15
Raw materials	Acetone	2.25E-06	6.80E-09	1.86E-13	6.43E-11	3.70E-10	5.16E-09	1.68E-06	8.25E-10	1.71E-09	1.74E-10	2.04E-14
Raw materials	Tap water	3.18E-10	9.61E-13	2.62E-17	8.71E-14	9.18E-13	7.42E-13	3.63E-10	1.08E-13	2.72E-13	1.68E-13	4.15E-17
Utilities	Electricity	3.58E-07	1.08E-09	2.95E-14	9.51E-11	1.82E-09	1.14E-09	5.65E-07	1.63E-10	4.86E-10	1.07E-10	2.40E-14
Utilities	Steam	9.68E-08	2.92E-10	7.98E-15	1.37E-11	2.11E-11	1.15E-10	5.01E-08	1.67E-11	5.01E-11	6.78E-12	1.22E-15
Utilities	Chilling	1.40E-07	4.22E-10	1.15E-14	2.38E-11	2.36E-11	1.19E-10	4.89E-08	1.75E-11	3.33E-11	1.07E-11	2.42E-15
Transport	Sewage Sludge (SS)	8.39E-08	2.53E-10	6.92E-15	3.59E-11	1.80E-11	2.82E-10	6.73E-08	4.13E-11	4.79E-11	3.93E-12	9.52E-16
Waste	Residual water	4.56E-07	1.38E-09	3.76E-14	7.59E-10	4.89E-10	1.68E-09	8.16E-07	2.41E-10	7.63E-10	7.50E-10	9.98E-12
By-product	Potassium sulfate	1.39E-06	4.19E-09	1.15E-13	4.90E-10	5.35E-10	4.36E-09	3.21E-06	6.28E-10	3.13E-09	4.65E-10	1.84E-13
Drying	SS drying	7.95E-09	2.40E-11	6.55E-16	8.19E-12	2.85E-11	1.57E-11	4.78E-09	2.29E-12	4.38E-12	1.46E-12	1.31E-14
Infraestructure	Infra.	2.42E+00	7.29E-03	1.99E-07	4.00E-04	8.96E-04	7.16E-03	2.98E+00	1.05E-03	2.81E-03	5.55E-04	2.11E-07

Table S2 (continue): LCIA database for the base case.

		Tex	Fex	Mex	HCTx	HnCTx	LU	MRSc	FRSc	WCHH	WCTE	WCAE
		species.yr	species.yr	species.yr	DALY	DALY	species.yr	USD2013	USD2013	DALY	species.yr	species.yr
Raw materials	Methanol	2.66E-11	2.56E-11	5.29E-12	2.44E-07	4.56E-07	2.16E-08	8.53E-04	3.01E-02	6.47E-09	4.73E-11	2.86E-15
Raw materials	Hexane	1.61E-11	2.01E-11	4.09E-12	1.70E-07	1.19E-07	3.66E-10	5.56E-04	3.85E-01	1.62E-08	1.02E-10	6.21E-15
Raw materials	Hydrochloride acid	2.47E-11	4.37E-11	8.60E-12	2.75E-07	2.70E-07	1.08E-09	9.61E-04	4.81E-02	4.03E-08	2.42E-10	1.21E-14
Raw materials	Potassium hydroxide	7.71E-11	1.08E-10	2.14E-11	7.98E-07	7.00E-07	1.99E-09	2.48E-03	1.83E-01	3.42E-08	2.22E-10	2.77E-14
Raw materials	Sulphuric acid	4.00E-11	1.47E-11	3.11E-12	7.70E-08	1.17E-07	2.14E-10	3.26E-04	4.17E-02	4.47E-08	2.72E-10	1.25E-14
Raw materials	Acetone	1.66E-11	1.75E-11	3.51E-12	1.99E-07	1.11E-07	3.23E-10	3.62E-04	5.53E-01	6.35E-08	3.85E-10	1.78E-14
Raw materials	Tap water	9.15E-15	1.31E-14	2.71E-15	9.03E-10	9.85E-11	3.98E-13	9.10E-07	1.87E-05	2.23E-09	1.35E-11	6.07E-16
Utilities	Electricity	5.48E-12	2.64E-11	4.98E-12	9.51E-08	9.40E-08	3.99E-10	2.32E-04	2.39E-02	5.68E-09	1.46E-11	2.12E-15
Utilities	Steam	1.74E-12	3.49E-13	9.07E-14	5.63E-09	4.19E-09	2.25E-11	6.00E-06	1.24E-02	1.15E-10	6.60E-13	4.86E-17
Utilities	Chilling	7.08E-13	3.13E-12	6.16E-13	2.00E-08	1.41E-08	1.68E-11	6.31E-05	1.73E-02	-1.93E-10	-7.48E-13	2.64E-15
Transport	SS	2.49E-11	9.77E-13	3.19E-13	1.58E-08	1.29E-08	6.73E-11	2.97E-05	1.39E-02	2.16E-10	1.42E-12	1.34E-16
Waste	Residual water	2.17E-11	3.28E-11	6.60E-12	7.89E-07	6.81E-07	4.73E-10	2.09E-03	2.93E-02	-1.99E-06	-1.21E-08	-5.40E-13
By-product	Potassium sulfate	1.73E-10	1.78E-10	3.49E-11	2.84E-07	9.84E-07	8.30E-09	9.81E-03	1.21E-01	6.67E-08	4.14E-10	2.34E-14
Drying	SS drying	2.09E-13	2.50E-13	5.00E-14	3.47E-09	2.60E-09	2.62E-11	2.56E-05	1.00E-03	5.23E-11	-1.85E-13	7.69E-17
Infraestructure	Infra.	9.87E-05	1.47E-04	3.09E-05	1.30E+01	9.14E-01	6.26E-03	1.13E+04	1.61E+05	3.53E-02	2.47E-04	2.69E-08

The LCA was done for all the cases. The normalized ReCipe points for each case study and the distribution between the different categories are available in Table S3. The final ReCiPe points are normalized based on default ReCiPe method recommendation.

Table S3: Distribution of the ReCiPe results for the alternatives.

	Stage	GWHH	GWTE	GWFE	SozD	Irad	OzFHH	FPMF	OzFTE	Tac	Feu	Meu
WET 400mL 20min pH2	1	1.13E-04	5.56E-06	1.52E-10	3.56E-08	1.32E-07	1.84E-07	9.67E-05	4.35E-07	1.41E-06	4.24E-07	1.14E-10
WET 400mL 20min pH2	2	1.07E-04	5.26E-06	1.44E-10	3.28E-08	1.31E-07	1.77E-07	9.13E-05	4.18E-07	1.33E-06	3.91E-07	1.06E-10
WET 400mL 20min pH2	3	1.08E-04	5.29E-06	1.45E-10	3.26E-08	1.39E-07	1.81E-07	9.30E-05	4.27E-07	1.35E-06	3.92E-07	1.06E-10
WET 400mL 20min pH2	4	1.08E-04	5.29E-06	1.45E-10	3.23E-08	1.47E-07	1.84E-07	9.41E-05	4.34E-07	1.37E-06	3.91E-07	1.05E-10
WET 400mL 20min pH2	5	1.10E-04	5.38E-06	1.47E-10	3.28E-08	1.58E-07	1.91E-07	9.75E-05	4.50E-07	1.41E-06	4.01E-07	1.07E-10
WET 200mL 60min pH2	1	9.28E-05	4.54E-06	1.24E-10	3.35E-08	1.27E-07	1.60E-07	8.67E-05	3.79E-07	1.25E-06	4.09E-07	1.13E-10
WET 200mL 60min pH2	2	8.47E-05	4.15E-06	1.13E-10	2.93E-08	1.17E-07	1.46E-07	7.78E-05	3.47E-07	1.12E-06	3.58E-07	9.95E-11
WET 200mL 60min pH2	3	8.52E-05	4.17E-06	1.14E-10	2.89E-08	1.21E-07	1.48E-07	7.81E-05	3.50E-07	1.12E-06	3.53E-07	9.80E-11
WET 200mL 60min pH2	4	8.48E-05	4.15E-06	1.13E-10	2.85E-08	1.25E-07	1.49E-07	7.83E-05	3.53E-07	1.12E-06	3.50E-07	9.70E-11
WET 200mL 60min pH2	5	8.60E-05	4.21E-06	1.15E-10	2.86E-08	1.32E-07	1.53E-07	8.02E-05	3.62E-07	1.15E-06	3.55E-07	9.78E-11
WET 100mL 60min pH2	1	9.73E-05	4.76E-06	1.30E-10	3.90E-08	1.51E-07	1.76E-07	9.88E-05	4.16E-07	1.42E-06	4.87E-07	1.34E-10
WET 100mL 60min pH2	2	8.23E-05	4.03E-06	1.10E-10	3.13E-08	1.26E-07	1.48E-07	8.07E-05	3.50E-07	1.15E-06	3.89E-07	1.09E-10
WET 100mL 60min pH2	3	7.81E-05	3.82E-06	1.04E-10	2.87E-08	1.19E-07	1.40E-07	7.54E-05	3.31E-07	1.08E-06	3.57E-07	9.98E-11
WET 100mL 60min pH2	4	7.67E-05	3.76E-06	1.03E-10	2.77E-08	1.19E-07	1.38E-07	7.39E-05	3.27E-07	1.05E-06	3.45E-07	9.66E-11
WET 100mL 60min pH2	5	7.67E-05	3.76E-06	1.03E-10	2.74E-08	1.22E-07	1.39E-07	7.40E-05	3.29E-07	1.05E-06	3.41E-07	9.56E-11
WET 200mL 20min pH4	1	9.58E-05	4.69E-06	1.28E-10	2.80E-08	1.03E-07	1.54E-07	7.77E-05	3.64E-07	1.13E-06	3.28E-07	9.08E-11
WET 200mL 20min pH4	2	8.90E-05	4.36E-06	1.19E-10	2.48E-08	9.83E-08	1.43E-07	7.12E-05	3.39E-07	1.03E-06	2.91E-07	8.11E-11
WET 200mL 20min pH4	3	8.87E-05	4.35E-06	1.19E-10	2.44E-08	1.04E-07	1.45E-07	7.16E-05	3.43E-07	1.04E-06	2.87E-07	8.00E-11
WET 200mL 20min pH4	4	8.88E-05	4.35E-06	1.19E-10	2.42E-08	1.11E-07	1.48E-07	7.27E-05	3.49E-07	1.05E-06	2.88E-07	7.97E-11
WET 200mL 20min pH4	5	8.99E-05	4.40E-06	1.20E-10	2.44E-08	1.19E-07	1.52E-07	7.48E-05	3.60E-07	1.08E-06	2.93E-07	8.09E-11
WET 100mL 20min pH4	1	8.83E-05	4.32E-06	1.18E-10	3.06E-08	1.18E-07	1.53E-07	8.14E-05	3.62E-07	1.17E-06	3.75E-07	1.05E-10
WET 100mL 20min pH4	2	7.88E-05	3.86E-06	1.05E-10	2.55E-08	1.04E-07	1.35E-07	6.97E-05	3.20E-07	1.00E-06	3.09E-07	8.74E-11
WET 100mL 20min pH4	3	7.58E-05	3.71E-06	1.01E-10	2.38E-08	1.03E-07	1.31E-07	6.67E-05	3.10E-07	9.53E-07	2.89E-07	8.19E-11
WET 100mL 20min pH4	4	7.50E-05	3.67E-06	1.00E-10	2.31E-08	1.06E-07	1.31E-07	6.62E-05	3.10E-07	9.45E-07	2.82E-07	8.00E-11
WET 100mL 20min pH4	5	7.59E-05	3.71E-06	1.01E-10	2.31E-08	1.12E-07	1.34E-07	6.75E-05	3.18E-07	9.63E-07	2.84E-07	8.02E-11
WET 100mL 60min pH4	1	7.58E-05	3.71E-06	1.01E-10	2.46E-08	9.20E-08	1.27E-07	6.55E-05	3.01E-07	9.41E-07	2.95E-07	8.39E-11
WET 100mL 60min pH4	2	6.58E-05	3.22E-06	8.80E-11	2.03E-08	8.06E-08	1.10E-07	5.53E-05	2.62E-07	7.87E-07	2.42E-07	7.07E-11
WET 100mL 60min pH4	3	6.40E-05	3.13E-06	8.56E-11	1.91E-08	8.02E-08	1.08E-07	5.33E-05	2.55E-07	7.57E-07	2.29E-07	6.69E-11
WET 100mL 60min pH4	4	6.38E-05	3.12E-06	8.53E-11	1.88E-08	8.29E-08	1.08E-07	5.33E-05	2.57E-07	7.55E-07	2.25E-07	6.58E-11
WET 100mL 60min pH4	5	6.35E-05	3.11E-06	8.49E-11	1.85E-08	8.59E-08	1.09E-07	5.35E-05	2.59E-07	7.57E-07	2.23E-07	6.50E-11
DryA	1	1.20E-04	5.86E-06	1.60E-10	1.87E-08	3.41E-08	1.58E-07	6.38E-05	3.82E-07	9.81E-07	1.56E-07	4.17E-11
Dry B	1	1.24E-03	6.08E-05	1.66E-09	2.00E-07	2.78E-07	1.33E-06	9.88E-04	3.15E-06	1.58E-05	1.65E-06	3.45E-10

Table S3 (continue): Distribution of the ReCiPe results for the alternatives.

	stage	Tex	Fex	Mex	HCTx	HnCTx	LU	MRSc	FRSc	WCHH	WCTE	WCAE	Normalized ReCipe
WET 400mL 20min pH2	1	4.55E-08	6.03E-08	1.21E-08	3.33E-05	2.50E-05	3.53E-06	6.59E-08	1.11E-05	2.69E-06	2.61E-07	1.90E-11	8.11E-04
WET 400mL 20min pH2	2	4.17E-08	5.69E-08	1.14E-08	3.05E-05	2.32E-05	3.46E-06	5.97E-08	1.05E-05	2.39E-06	2.30E-07	1.76E-11	8.75E-04
WET 400mL 20min pH2	3	4.12E-08	5.83E-08	1.16E-08	3.04E-05	2.32E-05	3.45E-06	5.92E-08	1.05E-05	2.35E-06	2.24E-07	1.75E-11	9.14E-04
WET 400mL 20min pH2	4	4.06E-08	5.93E-08	1.18E-08	3.01E-05	2.32E-05	3.41E-06	5.85E-08	1.04E-05	2.30E-06	2.18E-07	1.72E-11	9.51E-04
WET 400mL 20min pH2	5	4.11E-08	6.18E-08	1.23E-08	3.06E-05	2.37E-05	3.47E-06	5.95E-08	1.05E-05	2.33E-06	2.18E-07	1.73E-11	9.80E-04
WET 200mL 60min pH2	1	4.03E-08	6.01E-08	1.20E-08	3.30E-05	2.47E-05	3.54E-06	6.70E-08	8.87E-06	2.77E-06	2.70E-07	1.93E-11	6.85E-04
WET 200mL 60min pH2	2	3.53E-08	5.33E-08	1.06E-08	2.88E-05	2.18E-05	3.33E-06	5.73E-08	8.14E-06	2.34E-06	2.27E-07	1.70E-11	7.38E-04
WET 200mL 60min pH2	3	3.45E-08	5.35E-08	1.06E-08	2.82E-05	2.15E-05	3.29E-06	5.60E-08	8.17E-06	2.26E-06	2.18E-07	1.69E-11	7.74E-04
WET 200mL 60min pH2	4	3.40E-08	5.37E-08	1.07E-08	2.78E-05	2.13E-05	3.29E-06	5.51E-08	8.09E-06	2.21E-06	2.11E-07	1.66E-11	7.99E-04
WET 200mL 60min pH2	5	3.40E-08	5.51E-08	1.09E-08	2.80E-05	2.15E-05	3.26E-06	5.54E-08	8.15E-06	2.21E-06	2.10E-07	1.66E-11	8.21E-04
WET 100mL 60min pH2	1	4.59E-08	7.22E-08	1.44E-08	3.94E-05	2.92E-05	3.82E-06	8.23E-08	9.03E-06	3.46E-06	3.38E-07	2.27E-11	6.06E-04
WET 100mL 60min pH2	2	3.65E-08	5.87E-08	1.17E-08	3.16E-05	2.38E-05	3.49E-06	6.46E-08	7.73E-06	2.66E-06	2.59E-07	1.88E-11	6.57E-04
WET 100mL 60min pH2	3	3.34E-08	5.44E-08	1.08E-08	2.89E-05	2.19E-05	3.32E-06	5.83E-08	7.37E-06	2.38E-06	2.31E-07	1.74E-11	6.95E-04
WET 100mL 60min pH2	4	3.22E-08	5.31E-08	1.05E-08	2.78E-05	2.12E-05	3.29E-06	5.59E-08	7.23E-06	2.26E-06	2.18E-07	1.68E-11	7.22E-04
WET 100mL 60min pH2	5	3.17E-08	5.31E-08	1.05E-08	2.74E-05	2.10E-05	3.28E-06	5.49E-08	7.22E-06	2.21E-06	2.12E-07	1.66E-11	7.45E-04
WET 200mL 20min pH4	1	3.62E-08	4.73E-08	9.53E-09	3.10E-05	1.99E-05	3.24E-06	5.29E-08	9.54E-06	1.96E-06	1.90E-07	1.55E-11	4.76E-04
WET 200mL 20min pH4	2	3.20E-08	4.29E-08	8.62E-09	2.70E-05	1.78E-05	3.10E-06	4.53E-08	8.87E-06	1.64E-06	1.57E-07	1.39E-11	5.34E-04
WET 200mL 20min pH4	3	3.12E-08	4.34E-08	8.69E-09	2.62E-05	1.76E-05	3.09E-06	4.40E-08	8.80E-06	1.57E-06	1.49E-07	1.36E-11	5.68E-04
WET 200mL 20min pH4	4	3.08E-08	4.44E-08	8.86E-09	2.59E-05	1.76E-05	3.07E-06	4.35E-08	8.74E-06	1.54E-06	1.44E-07	1.35E-11	5.95E-04
WET 200mL 20min pH4	5	3.09E-08	4.60E-08	9.17E-09	2.60E-05	1.79E-05	3.11E-06	4.38E-08	8.78E-06	1.54E-06	1.43E-07	1.35E-11	6.18E-04
WET 100mL 20min pH4	1	3.74E-08	5.61E-08	1.12E-08	3.67E-05	2.29E-05	3.42E-06	6.49E-08	8.44E-06	2.47E-06	2.40E-07	1.79E-11	3.77E-04
WET 100mL 20min pH4	2	3.09E-08	4.72E-08	9.41E-09	2.98E-05	1.92E-05	3.16E-06	5.17E-08	7.63E-06	1.92E-06	1.85E-07	1.53E-11	4.28E-04
WET 100mL 20min pH4	3	2.87E-08	4.48E-08	8.93E-09	2.75E-05	1.80E-05	3.09E-06	4.73E-08	7.34E-06	1.73E-06	1.66E-07	1.43E-11	4.60E-04
WET 100mL 20min pH4	4	2.78E-08	4.45E-08	8.85E-09	2.65E-05	1.77E-05	3.07E-06	4.55E-08	7.23E-06	1.65E-06	1.56E-07	1.39E-11	4.85E-04
WET 100mL 20min pH4	5	2.77E-08	4.55E-08	9.03E-09	2.64E-05	1.77E-05	3.08E-06	4.53E-08	7.27E-06	1.63E-06	1.53E-07	1.38E-11	5.05E-04
WET 100mL 60min pH4	1	3.00E-08	4.40E-08	8.80E-09	2.88E-05	1.84E-05	3.08E-06	4.97E-08	7.42E-06	1.85E-06	1.81E-07	1.48E-11	4.15E-04
WET 100mL 60min pH4	2	2.44E-08	3.72E-08	7.43E-09	2.35E-05	1.55E-05	2.96E-06	3.97E-08	6.50E-06	1.44E-06	1.39E-07	1.28E-11	4.66E-04
WET 100mL 60min pH4	3	2.28E-08	3.56E-08	7.11E-09	2.19E-05	1.47E-05	2.87E-06	3.66E-08	6.32E-06	1.30E-06	1.25E-07	1.22E-11	5.03E-04
WET 100mL 60min pH4	4	2.23E-08	3.56E-08	7.10E-09	2.13E-05	1.45E-05	2.88E-06	3.55E-08	6.28E-06	1.25E-06	1.19E-07	1.20E-11	5.32E-04
WET 100mL 60min pH4	5	2.19E-08	3.58E-08	7.11E-09	2.09E-05	1.44E-05	2.85E-06	3.47E-08	6.22E-06	1.21E-06	1.15E-07	1.17E-11	5.53E-04
DryA	1	3.20E-08	1.59E-08	3.54E-09	1.62E-05	9.44E-06	2.66E-06	1.57E-08	1.43E-05	2.83E-07	2.91E-08	7.54E-12	9.08E-04
Dry B	1	4.15E-07	3.60E-07	7.39E-08	1.60E-04	1.31E-04	5.89E-06	3.90E-07	1.41E-04	1.39E-05	1.41E-06	2.80E-10	1.08E-02

II.7 References

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Chapter III

Exploring the environmental and economic benefits of hybrid natural gas and biomass conversion to liquid fuels

III. APPENDIX

III.1 List of publications

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III.1.1 Research articles

[1]. Mostafa Zarandi, Carmen Torres, Josep M. Mateo-Sanz, and Laureano Jiménez. "Multicriteria analysis of sewage sludge-based biodiesel production." *Journal of Environmental Management* 348 (2023): 119269. DOI: 10.1016/j.jenvman.2023.119269. Impact factor: 8.0. Area: ENVIRONMENTAL SCIENCES. Position: 34/358. 1st decile. Sustainable Development Goals mapped to this document (Scopus): Goal 6: Clean water and sanitation; Goal 7: Affordable and clean energy; Goal 8: Decent work and economic growth; Goal 9: Industry, innovation and infrastructure; Goal 12: Responsible consumption and production. Prominence percentile: 84.079 in Biodiesel; Transesterification; Wastewater Treatment (SciVal).

[2]. Mostafa Zarandi, Mehdi Panahi, Ahmad Rafiee, Sajad Namazi Rad, Ángel Galán-Martín, Josep M. Mateo-Sanz and Laureano Jiménez. "Exploring the environmental and economic benefits of hybrid natural gas and biomass conversion to liquid fuels." *International Journal of Hydrogen Energy*. Area: Fuel Technology (#12 of 128/Q1) / Renewable Energy, Sustainability and the Environment (#38 of 270/Q1) / Energy Engineering and Power Technology (#19 of 272/Q1). Impact Factor: 8.1. Status: revision requested.

III.2 Scientific conferences participations

[1]. Mostafa Zarandi, Carmen Torres, Magdalena Olkiewicz Magda, Josep Maria Mateo, Laureano Jiménez, "Multicriteria analysis of sewage sludge-based biodiesel production", *URV doctoral day*, May 2022.

[2]. Mostafa Zarandi, Mehdi Panahi, Ahmad Rafiee, Josep Maria Mateo, Laureano Jiménez, "Techno-economic assessment of hybrid natural gas and biomass conversion to liquid fuels", *URV doctoral day*, May 2023.

[3]. Mostafa Zarandi, Mehdi Panahi, Ahmad Rafiee, Josep Maria Mateo, Laureano Jiménez, “Comparing liquid fuels from residues or conventional sources”, *Tecnatox*, February 2024.