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MODELAGEM TÉCNICO-ECONÔMICA DA APLICAÇÃO DE BIORREATORES HETEROTRÓFICOS MICROALGAIS NO TRATAMENTO DE EFLUENTES AGROINDUSTRIAIS

DISSERTAÇÃO DE MESTRADO

Gabriela Rigo Roso

Santa Maria, RS, Brasil
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Gabriela Rigo Roso

Dissertação apresentada ao curso de Mestrado do Programa de Pós Graduação em Ciência e Tecnologia dos Alimentos, Área de Concentração em Qualidade dos Alimentos, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para obtenção do grau de
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Orientador: Prof. Dr. Eduardo Jacob-Lopes

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elaborada por
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como requisito para obtenção do grau de
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COMISSÃO EXAMINADORA

Prof. Dr. Eduardo Jacob-Lopes (UFSM)
(Presidente/Orientador)

Prof^{a}. Dr^{a}. Leila Queiroz Zepka (UFSM)

Prof. Dr. Alexandre Swarowsky (UNIFRA)

Prof. Dr. Cristiano Ragagnin de Menezes (UFSM)
(Membro suplente)

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RESUMO

Dissertação de Mestrado
Programa de Pós-Graduação em Ciência e Tecnologia dos Alimentos
Universidade Federal de Santa Maria

MODELAGEM TÉCNICO-ECONÔMICA DA APLICAÇÃO DE BIORREATORES HETEROTRÓFICOS MICROALGAIS NO TRATAMENTO DE EFLUENTES AGROINDUSTRIAIS

AUTORA: GABRIELA RIGO ROSO
ORIENTADOR: EDUARDO JACOB LOPES
Data e Local da Defesa: Santa Maria, 10 de março de 2015.

O projeto teve por objetivo realizar a modelagem técnico-econômica da aplicação de biorreatores heterotróficos microalgais no tratamento de efluentes provenientes do abate e processamento de aves e suínos e possível exploração dos bioprodutos provenientes da biomassa gerada no processo. O foco do projeto foi direcionado à modelagem técnico-econômica dos seguintes bioprocessos: (i) tratamento do efluente agroindustrial e produção de biomassa integral (ii) obtenção de óleo a granel e farelo microalgal desengordurado, como matéria-prima para o processo de conversão de biodiesel microalgal e produção de proteína (iii) obtenção de oleorresina de carotenóides mistos solubilizada em óleo de soja a partir de microalgas. Os resultados indicaram que os custos de tratamento do efluente agroindustrial e produção de biomassa microalgal foram US$ 2,66 por m³ de efluente e US$ 30 por tonelada de biomassa seca respectivamente. A obtenção de óleo a granel e farelo de microalgas obtiveram um custo de produção de US$ 386,5 e 70,4 por tonelada de óleo e farelo, respectivamente. Por fim, a oleorresina produzida teve um custo de produção estimado em US$ 146,9 por quilograma. Os resultados evidenciaram que a modelagem técnico-econômica da aplicação do biorreator heterotrófico microalgal, são uma alternativa para minimizar substancialmente os custos de produção, dando sustentabilidade econômica às agroindústrias de processamento de aves e suínos.

Palavras-chave: biorreator heterotrófico microalgal, efluente agroindustrial, modelagem econômica

ABSTRACT

Master Dissertation
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TECHNO-ECONOMIC MODELING OF THE MICROLGAE HETEROTROPHIC BIOREACTORS APPLICATION IN AGROINDUSTRIAL WASTEWATER TREATMENT

AUTHOR: GABRIELA RIGO ROSO
ADVISOR: EDUARDO JACOB LOPES
Place and Date: Santa Maria, March 10, 2015.

The project aimed to carry out the techno-economic modeling of the heterotrophic microalgae bioreactors application in the poultry and swine abattoirs and processing wastewater treatment and possible exploitation of bioproducts from biomass generated in the process. The project focus was directed to the techno-economic modeling of bioprocesses following: (i) agroindustrial wastewater treatment and integral biomass production (ii) obtaining of bulk oil and lipid extracted algal (LEA) as feedstock for biodiesel conversion process and protein production (iii) obtaining of microalgal carotenoid-rich oleoresin solubilized in soybean oil. The results indicated that the agroindustrial wastewater treatment costs and production of microalgal biomass were USD 2.66 per cubic meter and USD 30 per ton of dried biomass respectively. The obtaining of bulk oil and LEA had a production cost of approx. USD 386.5 and 70.4 per ton. Finally, the oleoresin produced had an estimated production cost in USD 146.9 per kilogram. The results evidenced that the techno-economic modeling of the heterotrophic microalgae bioreactors application are an alternative to substantially minimize the production costs, giving economic sustainability to the agroindustry of poultry and swine processing.

Keywords: heterotrophic microalgae bioreactors, agroindustrial wastewater, economic modeling

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NOMENCLATURA

μ_{max} - maximum specific growth rate
AOAC - Association of Official Analytical Chemistry
APCI- analyzer and atmospheric pressure chemical ionization
C/N - carbon/nitrogen ratio
COD - chemical oxygen demand
COL - cost of operational labor
CRM - cost of raw materials
CT – custo total
CUT - cost of utilities
DTDC - desolventizer–toaster-dryer-cooler
EE - economic equilibrium
F - flow
FAMEs - fatty acid methyl esters
FC - fixed capital
FCI - fixed capital investment
FOB - free on board
FS - fixed solids
HDT - hydraulic detention time
HPLC-PDA-MS/MS - high performance liquid chromatography
ICM - index contribution margin
KL_a - constant volumetric mass transfer coeficiente
KOH - potassium hydroxide
LEA - lipid extracted algae
MEC - major equipment costs
MeOH - methanol
MTBE - methyl tert-butyl ether
N/P - nitrogen/phosphorous ratio
N-TKN - total nitrogen Kjeldahl
P - profitability
$P\text{-}PO_4^{-3}$ - total phosphorus
RC - recursos de capital
RF - recursos financeiros
RH - recursos humanos
RM - recursos materiais
PRI - period of return on investment
P_X - average cellular productivity
R - rentability
RE - removal efficiency
r_S – substrate consumption rate
SS - suspended solids
TBHQ - tert-butylhydroquinone
TCI - total capital investment
TOC - total operating capital
TS - total solids
VS - volatile solids
VVM - volume of air per volume of wastewater per minute

WC - working capital
$Y_{X/COD}$ - biomass yield coefficient

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INTRODUÇÃO

A exigência de um desenvolvimento industrial sustentável, responsabilidade ambiental e a utilização de energias renováveis com menor impacto ambiental por parte da sociedade, têm feito as indústrias de base química investirem na intensificação de processos, que segundo Fischer et al. (2009) é uma abordagem tecnológica que oferece melhorias no processo de industrialização de produtos utilizando tecnologias mais baratas, seguras e sustentáveis.

O atual estágio de desenvolvimento tecnológico para tratamento de efluentes agroindustriais ainda utiliza configurações de reatores que operam em múltiplas operações unitárias de natureza química, física e biológica, impactando economicamente toda a cadeia de produção. Além disso, esses sistemas estão vinculados a processos onerosos, com custos elevados, além da geração massiva de lodos biológicos resultantes dos processos, o que requer a disposição em aterros sanitários controlados (BONINI, 2012).

Os biorreatores heterotróficos microalgais possuem capacidades de bioconversão de material orgânico e nutrientes presentes em águas residuárias, de forma relativamente rápida e ecologicamente segura, além de proporcionar quantidades substanciais de biomassa, atuando como uma alternativa para a diminuição dos custos elevados de processos convencionais de tratamento (KUMAR et al., 2014; QUEIROZ et al., 2007; QUEIROZ et al., 2013).

Como principais vantagens da tecnologia do biorreator heterotrófico microalgal, estão a redução do número de operações unitárias do processo, menor demanda de potência e menor gasto energético, sendo caracterizado como biorreator multifuncional. Essas vantagens, fazem do biorreator uma potencial tecnologia da intensificação de processos, uma vez que possui características de eficiência do processo produtivo, além de possibilitar o reaproveitamento e potencial exploração de bioprodutos formados durante o processo (JACOB-LOPES; FRANCO, 2013).

O fornecimento energético para as microalgas no processo heterotrófico, decorre da assimilação de uma fonte de carbono exógena, como por exemplo, mono e polissacarídeos (FRANCISCO et al., 2014). Porém, o emprego de substratos desta natureza traria um alto custo à produção (DUCAT et al., 2011) e novas fontes de carbono de menor custo são requeridas, como por exemplo, os resíduos agroindustriais de alta carga orgânica e nutrientes, podendo representar um significativo avanço na direção de reduzir os custos de produção, bem como a grande importância destas fontes de carbono de baixo custo para a produção em modo heterotrófico (GUPTA et al., 2013).

O interesse biotecnológico pelos metabólitos presentes na biomassa microalgal, faz com que se torne ainda mais interessante ser estudada a produção comercial destes compostos, sendo necessárias pesquisas visando o desenvolvimento e o aperfeiçoamento dos sistemas de produção, a fim de torná-los viáveis economicamente. Sistemas baseados em fontes renováveis podem ser alternativas à produção de compostos de interesse industrial, entretanto, para a consolidação do conceito de biorrefinaria microalgal, é necessário um estudo aprofundado acerca do processo econômico e produção destes metabólitos (WIJFFELS et al., 2013).

A maximização dos processos baseados em microalgas em escala industrial, ressalta a importância da realização de uma modelagem técnico-econômica, no sentido de minimizar os custos de produção e aumentar a sustentabilidade econômica do processo. Paralelamente, a realização do estudo da viabilidade, auxilia o processo a fim de se obter com maior precisão quais os pontos a serem focados, melhorando a economia do processo até que este se torne rentável (TERCERO et al., 2014).

1 REVISÃO BIBLIOGRÁFICA

1.1 Intensificação de processos

A sociedade tem exigido uma exploração industrial sustentável, delineada por responsabilidade ambiental, o uso de energia renovável e maior eficiência energética. Estes requisitos estão expressos em uma legislação mais rigorosa em relação à produção de resíduos, emissões de CO_2, poluição do ar e da água. As demandas econômicas estão forçando a indústria a ser mais flexível a fim de alterar as capacidades de rápida produção. Além disso, variações frequentes nas composições, juntamente com os preços e às vezes, imprevisíveis oscilações dão bastante ênfase na dinâmica do processo (NIKAČEVIĆ et al., 2012).

Acredita-se que é possível haver uma transformação no setor químico industrial com menor impacto ao meio ambiente. Nesse sentido, as indústrias de base química têm investido na intensificação de processos, que pode ser definido segundo Stankiewicz e Moulijn (2000), como qualquer desenvolvimento de tecnologia que leva a um processo substancialmente menor, mais limpo e mais eficiente em termos energéticos, além da conservação dos recursos naturais. É importante desenvolver um quadro eficaz para gerar e buscar oportunidades válidas para a intensificação de processos (PONCE-ORTEGA et al., 2012).

Adicionalmente, outros autores caracterizam a intensificação de processo como qualquer atividade baseada em uma ou mais das seguintes características: (i) equipamentos menores para determinado rendimento (produção de uma atividade ao longo do tempo, utilizando um equipamento pequeno ou de menor volume); (ii) maior produção para determinado tamanho de equipamento ou determinado processo (produção de maior rendimento, utilizando o mesmo equipamento ou processo); (iii) menor utilização de materiais e matéria-prima para um determinado rendimento, levando-se em conta o tamanho do equipamento (em menor uso de materiais utilitários como aquecimento, resfriamento, solventes, etc e/ou matéria-prima).

A intensificação de processos, de acordo com Stankiewicz (2003) leva a um processo mais barato, especialmente em termos de custos (maior capacidade de produção), os custos de investimento, de materiais, os custos dos serviços públicos (energia, em particular), e os custos de processamento de resíduos de fluxo (exceto os resíduos em geral). Esse autor também relata que, para muitas indústrias químicas e farmacêuticas, a intensificação de processos pode oferecer uma redução do tempo de mercado, por exemplo, através do desenvolvimento de um processo contínuo à escala laboratorial, o que poderia ser utilizada diretamente como o processo em escala comercial.

Ainda baseado nessas definições, Stankiewicz e Moulijn (2000), dividiram a intensificação de processo em duas classes: equipamentos e métodos. A classe de equipamentos incluem reatores e equipamentos para operações não-reativas. Por outro lado, a classe de métodos incluem reatores multifuncionais, separadores híbridos, recursos energéticos alternativos. Um dos componentes básicos da intensificação de processos são os chamados reatores multifuncionais, que podem ser descritos como reatores que combinam mais de uma função, geralmente uma operação unitária.

De acordo com Fischer et al. (2009), o principal interesse na intensificação de processos era, principalmente a redução de custos, porém, rapidamente se tornou evidente que existem outros importantes benefícios potenciais, em matéria de melhoria da segurança intrínseca. Atualmente, as oportunidades que a abordagem de intensificação de processos oferecem para uma indústria de base química baseiam-se principalmente em seis áreas: custos, segurança, solidez, condições controladas bem definidas, tempo no mercado e imagem da empresa (STANKIEWICZ, 2003).

1.2 Processos baseados em microalgas

As microalgas são microrganismos heterogêneos, usualmente microscópicos, unicelulares, coloniais ou filamentosos, coloridos e fotoautotróficos. Filogeneticamente, podem ser procarióticos ou eucarióticos (OLAIZOLA, 2003). Elas são classificadas em múltiplos grandes grupos, como: cianobactérias (Cyanophyceae), algas verdes (Chlorophyceae), diatomáceas (Bacillariophyceae), algas verde-amareladas (Xanthophyceae), algas douradas (Chrysophyceae), algas vermelhas (Rhodophyceae), algas marrons (Phaeophyceae), dinoflagelados (Dinophyceae) e picoplâncton (Prasinophyceae e Eustigmatophyceae) (QIANG et al., 2008).

De acordo com o que foi relatado por Tran et al. (2010), as microalgas, particularmente as cianobactérias têm sido consideradas como potenciais biocatalisadores para aplicação em processos biológicos de tratamento de efluentes industriais. Elas são robustas, têm necessidades nutricionais simples, e podem utilizar até três vias metabólicas para obtenção de energia, ou seja, fotossíntese, respiração e a fixação de nitrogênio. A fotossíntese é a forma de obtenção de energia mais utilizada pelas microalgas, e em casos onde não haja contato com a luz, algumas obtêm energia através da respiração. Há microalgas que desenvolvem organelas capazes de fixar nitrogênio da atmosfera quando este se encontra escasso no meio (LOURENÇO, 2006; TRAN et al., 2010).

Durante a respiração, ao contrário da fotossíntese, o oxigênio é consumido, com paralela produção de CO_2, sendo que a taxa respiratória dos substratos orgânicos está intimamente orientada para o crescimento e divisões celulares. O metabolismo respiratório em microalgas desempenha duas funções principais: serve como fonte exclusiva de energia para manutenção e biossíntese e fornece os blocos construtores de carbono para a biossíntese (JACOB-LOPES et al., 2010), muito embora alguns autores tenham relatado que o único objetivo da respiração de cianobactérias é gerar energia mínima para o crescimento na ausência de luz (FAY, 1983; SCHMETTERER, 1994).

A fonte de carbono orgânico pode ser obtida a partir de resíduos agroindustriais. Além disso, a produção de biomassa a partir de águas residuais tem mostrado efeito positivo, uma vez que indica alto nível de concentração em nutrientes, favoráveis ao crescimento microalgal. Este tipo de substrato proporciona uma fonte economicamente viável de nutrientes para as culturas de microalgas. Muitas espécies de microalgas têm sido utilizadas para converter diversos resíduos industriais em biomassa (QUEIROZ et al., 2007; VOLTOLINA et al., 1999). Nesse contexto, Demirbas (2001) e Duong et al. (2012) relataram que as microalgas possuem bom potencial biotecnológico, uma vez que elas produzem substâncias naturais e biomateriais que podem encontrar aplicação industrial diversificada, além de ser uma fonte alternativa para aqueles derivados de fontes não renováveis.

Nestas condições, as fontes orgânicas exógenas de carbono podem ser obtidas através de águas residuais industriais. Nesse caso específico é possível direcionar a conversão de matéria orgânica como nitrogênio e fósforo em biomoléculas de valor agregado. Por outro lado, se considerarmos apenas as características de tratamento de resíduos industriais, a principal vantagem do uso de biorreatores heterotróficos com microalgas está relacionada com a conversão simultânea de matéria orgânica e nutrientes, em uma única etapa, reduzindo custos capitais e operacionais comumente associados às formas convencionais de tratamento (QUEIROZ et al., 2007).

Sistemas baseados em microalgas para a produção de produtos químicos são uma área emergente, o que representa uma grande promessa para aplicação industrial. Vários processos têm demonstrado potencial, principalmente para as indústrias de alimentos e rações, produção de pigmentos e aditivos, como também para as indústrias de cosméticos (RODRIGUES et al., 2014). Esses microorganismos têm uma versatilidade metabólica de suporte com possibilidade de produção de biomassa com base em fontes orgânicas sem valor comercial, tais como resíduos industriais (PEREZ-GARCIA et al., 2011).

1.3 Microalgas no tratamento de resíduos

Os resíduos agroindustriais são compostos por consideráveis quantidades de carbono orgânico, nitrogênio, fósforo, metais e sólidos. Além disso, carboidratos, gorduras, proteínas, aminoácidos e ácidos voláteis também fazem parte dessa composição (HORAN, 1989; LIM et al., 2010; TEBBUTT, 1997). Essa composição rica, faz com que esses resíduos se tornem uma fonte de matéria-prima adequada para apoiar o crescimento de microorganismos, em particular as microalgas (LIM et al., 2003).

Recentemente, as microalgas passaram a ser vistas como biocatalisadores potencialmente úteis no tratamento de águas residuais, uma vez que possuem habilidade de remover matéria orgânica e nutrientes de efluentes, incorporando-os à biomassa. Esta aplicação, entretanto, encontra limitações principalmente devido ao custo e operação dos sistemas autotróficos, além do fato de as águas residuárias, de maneira geral, apresentarem turbidez elevada, dificultando a penetração de luz solar (BONINI, 2012).

Por essa razão, o tratamento biológico de águas residuais por cianobactérias foi proposto, motivado pelo metabolismo heterotrófico destes microorganismos, com o consumo de simples moléculas orgânicas e nutrientes inorgânicos na ausência de luz (ARDELEAN; ZARNEA, 1998; TAM; WONG, 2000). A utilização de cianobactérias no tratamento de águas residuárias é uma alternativa técnico-econômica potencial em relação aos sistemas convencionais de tratamento secundário e terciário de efluentes.

Esses processos são baseados nas rotas metabólicas respiratórias que algumas espécies de cianobactérias apresentam, no qual fontes exógenas de carbono orgânico e nutrientes inorgânicos são bioconvertidos em produtos do metabolismo heterotrófico, particularmente em uma biomassa com elevados teores de proteínas, carboidratos, lipídeos e pigmentos (ZEPKA et al., 2010). Estudos restritos, no entanto, têm sido direcionados para elucidar o potencial do metabolismo heterotrófico de microalgas para esta finalidade (DEVI et al., 2012).

Os processos convencionais de remoção de carbono, nitrogênio e fósforo de águas residuárias são focados na volatilização dos compostos nitrogenados, na forma de gás nitrogênio. Essa estratégia, embora eficiente do ponto de vista de disposição de resíduos, não permite o uso sustentável desses compostos, que servem como blocos construtores de inúmeras substâncias de valor comercial (QUEIROZ et al., 2007). Assim, Devi et al. (2012), afirmam que em meio heterotrófico, tanto o crescimento celular quanto à biossíntese dos produtos são significativamente influenciados pelos nutrientes presentes no meio e por fatores ambientais. A seleção de nutrientes adequada para estirpes de microalgas também fornece um modo econômico de produção de insumos a partir do tratamento de águas residuais.

Os biorreatores heterotróficos microalgais aplicáveis ao tratamento de efluentes estão associados a melhorias de processamento, uma vez que cumprem com as diretrizes gerais dos processos intensivos, reduzindo o número de operações unitárias do processo, o que demanda menores densidades de potência durante a operação, além de não gerarem poluição secundária e permitirem o reaproveitamento/valorização dos bioprodutos formados durante o processo (JACOB-LOPES; FRANCO, 2013; PARK et al., 2010).

O cultivo de microalgas em águas residuárias é biotecnologicamente viável, uma vez que oferece vantagens combinadas de tratamento das águas residuais e simultaneamente a produção de biomassa microalgal. Além disso, adquire a possibilidade de valorização dos resíduos por biotransformação em produtos de valor agregado (QUEIROZ et al., 2007; MALLICK, 2002).

1.4 Sistemas de biorrefinarias industriais

Recursos renováveis têm ganhado atenção como insumos para a indústria e tem estimulado o desenvolvimento de novas formas integradas de produção (BOUAID et al., 2010). Denomina-se biorrefinaria, esta nova abordagem, que oferece uma alternativa barata para as rotas tecnológicas convencionais de produção para obtenção de matérias-primas e produtos renováveis em um processo integrado, de forma sustentável (CHERUBINI, 2010; OCTAVE; THOMAS, 2009). As biorrefinarias apostam em sistemas que combinam as tecnologias necessárias entre a concepção, exploração das matérias-primas biológicas (biomassa) e a produção de uma ampla gama de insumos intermediários no processo integrado, através de um processamento sustentável, isto é, usando uma combinação sinérgica entre conversões biológicas e químicas.

Uma vez produzidos, os novos produtos e subprodutos obtidos podem ser comercializados ou destinados às indústrias alimentares convencionais (KAMM; KAMM, 2004; IEA BIOENERGY, 2009). Embora o conceito de biorrefinaria seja bem estruturado, a maior barreira para uma aplicação em grande escala é a ausência de tecnologias de processamento de baixo custo. Dentro deste contexto, as microalgas, particularmente as cianobactérias vêm sendo utilizadas na conversão de resíduos industriais, utilizando os diferentes constituintes dos efluentes para o seu crescimento, o que leva, consequentemente, a uma produção massiva de biomassa.

A biomassa resultante destas conversões é uma fonte renovável potencialmente rica em produtos de valor agregado. Tanto a biomassa microalgal quanto os demais produtos do seu metabolismo apresentam elevado potencial de reutilização em diversos segmentos industriais. Esta cogeração de insumos é atrativa, uma vez que os custos de produção podem ser reduzidos com créditos para tratamento de águas residuais, bem como com a redução da emissão de gases (FENG et al., 2011; WU et al., 2012), limitando o impacto ambiental das produções.

De acordo com Jones e Mayfield (2012), a concretização da exploração de processos microalgais dependerá da criação de sistemas com aproveitamento global, completamente otimizado e eficiente, que use todos os componentes da biomassa microalgal, o que somente poderá ser obtido sob o escopo de uma biorrefinaria. Ao produzir múltiplos produtos, uma biorrefinaria pode tirar vantagem das diferenças de componentes da biomassa e intermediários, e maximizar o valor derivado da matéria-prima de biomassa de acordo com a situação do mercado e disponibilidade da biomassa (LUO et al., 2011; SUBHADRA, 2011; GRINSON-GEORGE, 2011).

Através da produção de vários produtos, a biorrefinaria de microalgas utiliza todos os componentes da biomassa e intermediários, maximizando assim o valor da matéria-prima derivada de biomassa (QUEIROZ et al., 2013), de uma forma que integre a conversão de biomassa e a separação, no qual o objetivo é a obtenção de várias frações usando separações leves, a fim de obter diferentes tipos de produtos a partir de uma única fonte (VANTHOOR-KOOPMANS et al., 2013).

1.5 Produtos obtidos da biomassa de microalgas

As cianobactérias são consideradas fábricas celulares naturais capazes de sintetizar uma série de compostos úteis (GERSHWIN; BELAY, 2008). Elas contêm quantidades elevadas de lipídeos, proteínas, carboidratos, pigmentos, os quais todos podem ser utilizados para diferentes mercados (WIJFFELS; BARBOSA, 2010).

Nos últimos anos, microalgas foram identificadas como um dos grupos mais promissores de organismos para isolar produtos naturais e ativos bioquímicos de valor agregado (PRASANNA et al., 2008). Elas podem sintetizar, metabolizar, acumular e secretar uma grande diversidade de compostos orgânicos com potencial de aplicação no mercado industrial. (YAMAGUCHI, 1996). Quando explorado todo o potencial dos componentes da biomassa microalgal, muitos produtos diferentes podem ser obtidos e, simultaneamente, o valor de mercado será maior do que os custos de produção (WIJFFELS et al., 2010).

Geralmente, não é assumida uma combinação de produtos de altos valores, como produtos de química fina em nichos de mercado, uma vez que o volume de mercado desses produtos têm se tornado incompatível. Nesse sentido, uma biorrefinaria de biomassa microalgal de produtos que podem ser considerados como “a granel” vêm fazendo uso de sua funcionalidade no mercado de produção desses produtos (WIJFFELS et al., 2010).

1.5.1 Proteínas

A exploração comercial em larga escala das microalgas, segundo Spolaore et al. (2006) é motivada pelo elevado teor de proteínas da biomassa para utilização como recurso alimentar alternativo, tendo um alto valor de qualidade protéica comparado com fontes vegetais, como por exemplo, trigo, arroz e leguminosas, mas inferiores a fontes animais, como leite e carne (MATA et al., 2010). Em virtude das características da biomassa, processos baseados em cianobactérias têm sido considerados nos últimos anos potenciais tecnologias para converter resíduos industriais em insumos proteicos usados na formulação de rações animais (JACOB-LOPES et al., 2010).

A produção de proteína unicelular, através da biomassa residual fornece uma fonte economicamente viável de proteína, conhecida como farelo, para utilização em ração animal, uma vez que muitas vezes atende aos requisitos nutricionais para a proteína (KUHAD et al., 1997; VOLTOLINA et al., 2005). Além disso, Raposo et al. (2013) afirmam que algumas microalgas, devido à sua riqueza em proteína e o seu perfil de aminoácidos, podem ser utilizadas como produtos nutracêuticos ou ser incluídas em alimentos funcionais para prevenir algumas doenças e danos nas células ou tecidos.

A população mundial e demanda de alimentos está crescendo com uma necessidade simultânea para sistemas adicionais de produção de proteína animal (SUBHADRA, 2011). O farelo de microalgas têm se apresentado como uma alternativa para o farelo de peixes, uma vez que este, não pode ser considerado como fonte de proteína sustentável para atender à crescente demanda da indústria de alimentação animal (SUBHADRA; EDWARDS, 2011).

As proteínas têm um importante valor como “commodities” na alimentação animal. Efeitos econômicos positivos, têm conduzido a um aumento significativo na utilização da biomassa de microalgas como aditivos, não só na alimentação animais terrestres, como também na aquicultura (WILLIANS; LAURENS, 2010).

1.5.2 Lipídeos

As microalgas sintetizam e acumulam quantidades substanciais de lipídeos que podem ser moduladas por fatores bióticos e abióticos, e por essa razão, atraem bastante atenção para a produção de biodiesel, como também um potencial recurso renovável para ácidos graxos essenciais (RATHA et al., 2013). Os lipídeos podem ser usado como blocos construtores da indústria química e óleos comestíveis no segmento alimentar, para a produção de óleo bruto como fonte de biocombustíveis (SONG et al., 2008).

Os produtos lipídicos de microalgas incluem principalmente na sua composição óleo/hidrocarbonetos e triacilgliceróis, com uma concentração que varia entre 20 e 60% (WIJFFELS et al., 2010). Paralelo à isso, devido às altas taxas de produtividade, estes lipídeos caracterizam-se como matéria-prima para grande produção de biocombustíveis, de uma forma sustentável e rentável (HARWATI et al., 2012). O biodiesel a partir de biotecnologia de microalgas, segundo Chisti (2008) é uma alternativa ao diesel de petróleo e biodiesel obtido por oleaginosas, no entanto, barreiras técnico-econômicas ainda limitam sua implementação em escala comercial.

Após o processo de extração, o oléo bruto de microalgas pode ser convertido em biodiesel por meio de um processo chamado transesterificação. A transesterificação é uma reação química entre triglicerídeos e álcool, na presença de um catalisador para produzir os monoésteres que são denominados como biodiesel (SHARMA; SINGH, 2009).

Nesse sentindo, Wijffels e Barbosa (2010) têm proposto que comercialmente, a produção de biocombustível viável só pode ser possível se outros constituintes da biomassa de microalgas forem explorados como coprodutos em conjunto com a utilização dos triglicerídeos para a produção de biodiesel, uma vez se torna impossível para o biodiesel de algas competir com os combustíveis fósseis sem a gestão de coprodutos (LARDON et al., 2009; KHOO et al., 2011).

1.5.3 Carotenóides

Os carotenóides têm propriedades que os fazem importantes tanto na qualidade de alimentos quanto na saúde humana, e segundo Perez-Garcia et al. (2011) são um dos principais campos de exploração da biotecnologia de microalgas, com uma vasta gama de aplicações.

Exemplos clássicos da produção de pigmentos por microalgas são o β-caroteno, astaxantina, luteína e a ficocianina.

Os extratos de pigmentos oleosos oriundos de diferentes fontes, tem uma composição de carotenóides muito variada, sendo capazes de proporcionar diferentes tonalidades, do amarelo ao vermelho e suficientemente concentradas, para permitir a sua utilização comercial em grande escala (baixas doses são suficientes para alcançar o cor desejada em uma grande quantidade de produtos) (RIOS et al., 2008).

Os carotenoides extraídos de uma fonte natural, com formulação básica é uma suspensão oleosa ou oleorresina, denominada assim, quando se tem o solvente evaporado no processo de extração, constituída de carotenóides juntamente com outros materiais solúveis em óleo como os triacilgliceróis, esteróis, ceras, etc. As oleorresinas podem ser produzidas e comercializadas como suspensões em óleos (BRITTON; KHACHIK, 2009).

O processo de síntese e purificação de carotenóides, atualmente ainda requer a utilização de técnicas que tornariam a produção em larga escala muito difícil e extremamente cara (GARNETT et al., 2010), uma vez que é altamente complicado, envolvendo diferentes solventes orgânicos e múltiplos passos para a purificação (JOSEPH; ANANDANE, 2011).

Nesse sentido, fontes alternativas do formato de produção de carotenóides são necessárias, embora estas ainda apresentem um desafio para a indústria, no sentido de competir em preço ou diferenciar-se da fonte alternativa no mercado (BOROWITZKA, 2013). A produção de uma olerresina, apresenta-se como uma forma acessível de comercialização de carotenoides naturais, na qual é composta por frações de diferentes carotenoides mistos na forma oleosa, em um mesmo extrato.

1.6 Análise econômica de bioprocessos

A análise técnico-econômica de um processo está focada em tecnologias projetadas para serem viáveis dentro de um prazo. Com base neste prazo e depois de considerar o tempo para o delineamento, construção e colocação em funcionamento, o processo provavelmente tem como base, dados experimentais disponíveis. Nesse sentido, deve ser considerado para esse tipo de processo a economia, maturidade tecnológica, aspectos ambientais, o desempenho de processos e os riscos técnicos e econômicos (WRIGHT et al., 2010).

A necessidade de monitorar trabalhos de pesquisa com o objetivo de concentrar os esforços nas etapas mais influentes dos processos, auxilia no requerimento de um delineamento de processo em nível adequado de detalhamento e modelagem do custo de produção, utilizando conjuntos de suposições relevantes e consistentes. Nesse sentido, as questões metodológicas são discutidas em particular no que diz respeito a como lidar com as cadeias de valores de biomassa ao realizar uma análise técnico-econômica (GNANSOUNOU; DAURIAT, 2010).

A função da produção de um determinado produto ou serviço associa, para cada unidade produzida, a quantidade de insumos necessários à realização daquela produção. Os insumos os quais são referidos são basicamente representados por: recursos humanos (RH), recursos materiais (RM), recursos de capital (RC) e recursos financeiros (RF). Assim a produção de um determinado produto, em termos técnicos, estaria representada como:

$$Pa = RHa + RMa + RCa + RFa \quad (I)$$

Ao mesmo tempo, existe uma relação técnica que associa a quantidade de insumos de produção (recursos humanos, recursos materiais, recursos financeiros e recursos de capital) à quantidade do produto. Esta relação técnica se transformará em uma relação ou medida econômica, ao associarmos à quantidade do insumo ao seu custo, o que resultará no custo total de produção do produto.

$$CT\ (Pa) = C\ (RHa) + C\ (RMa) + C\ (RCa) + C\ (RFa) \quad (II)$$

A equação acima, expressa o custo total para a produção de um produto, a partir de uma relação técnica envolvendo os recursos necessários para a sua produção. Esses recursos poderão ser fixos ou variáveis. Os recursos fixos são aqueles que se associam à capacidade de produção, isto é, definem a capacidade de produção para o produto considerado, e só podem ser modificados com um custo elevado e com considerável dispêndio de tempo. Já os recursos variáveis, possuem a liberdade de se modificar em uma relação direta com a quantidade produzida do produto (BARRETO, 1996).

De acordo com Gnansounou e Dauriat (2010), a avaliação econômica consiste na estimativa de custos de um processo de produção, sendo estes custos referenciados no custo líquido de produção, que é dividido em: (1) custos de investimento (2) custos operacionais fixos (incluindo salários, despesas gerais, seguro, impostos e manutenção), (3) custos operacionais variáveis (incluindo a compra de materiais de consumo, consumo de energia elétrica, demanda de água e vapor, e tratamento de resíduos).

Antes de uma planta industrial ser colocada em operação, um orçamento precisa ser investigado para a compra e instalação dos equipamentos e maquinários necessários. O capital necessário para a fabricação e instalações de uma planta é chamado de capital fixo, enquanto que o funcionamento da instalação é denominado como o capital de giro. A soma do capital fixo e capital de giro é conhecido como o capital de investimento total (XIANG et al., 2014).

Para uma modelagem de custos, dados do projetos e outras informações do processo são obtidos durante a fase de desenvolvimento. Estas informações são utilizadas como base para a realização de fases adicionais do projeto. Uma análise completa do mercado é feita e retornos prováveis em investimentos necessários são determinados e, adicionalmente, uma análise de viabilidade completa do processo é desenvolvida (PETERS; TIMMERHAUS, 2003).

A importância de analisar a viabilidade do processo produtivo, permite identificar com maior precisão quais seriam as seções do processo, para focar em futuras atividades de investigação e desenvolvimento, melhorando a economia do processo até que o mesmo se torne rentável (TERCERO et al., 2014), sendo assim, o processo excede seu total de custos e, mostra-se positivo do ponto de vista econômico. Além disso, esta análise pode ser utilizada para identificar os principais fatores que determinam os custos de produção, auxiliando na identificação dos principais problemas técnicos a serem resolvidos a fim de alcançar a viabilidade econômica (RICHARDSON et al., 2010).

ARTIGO 1 – TECHNO-ECONOMIC MODELING OF MICROALGAL HETEROTROPHIC BIOREACTORS APPLIED TO AGROINDUSTRIAL WASTEWATER TREATMENT

Techno-economic modeling of microalgal heterotrophic bioreactors applied to agroindustrial wastewater treatment

Gabriela Rigo Roso[1] and Eduardo Jacob-Lopes[1*]

[1] Department of Food Science and Technology, Federal University of Santa Maria, Roraima Avenue, 1000, 97105-900, Santa Maria, RS, Brazil. Phone: +55 55 32208822. Email: jacoblopes@pq.cnpq.br
*corresponding author

ABSTRACT

The techno-economic analysis of the microalgal heterotrophic bioreactors applied to the treatment of the poultry and swine slaughterhouse wastewater is presented. The process is based on a multifunctional bioreactor used to simultaneously convert organic matter (COD), nitrogen (N-TKN) and phosphorus ($P\text{-}PO_4^{-3}$) into microalgal biomass. The experimental data, obtained from a bench scale facility, were used to estimate the costs of an industrial scale (16,000 m^3/day). The results obtained indicate removal efficiencies of 97.6, 85.5 and 92.4% for COD, N-TKN and $P\text{-}PO_4^{-3}$, respectively, in parallel to a microalgal sludge productivity of 0.27 $kg/m^3/d$. The economic analysis demonstrated a cost of USD 2.66 per cubic meter of industrial wastewater treated, and as consequence of this process, the production cost of microalgal sludge was USD 0.03 per kilogram of biomass dehydrated.

Keywords: microalgae/cyanobacteria, industrial effluent, heterotrophic cultivation, cost analysis

1 Introduction

Society has been demanding a sustainable industrial development outlined by environmental responsibility, renewable energy use and higher energy efficiency. [1] It is believed that there can be a transformation in the industrial sector with less impact on the environment and, therefore, industries have invested in process intensification, through the development of innovative apparatuses and techniques that offer drastic improvements in manufacturing and processing, substantially decreasing equipment volume, energy consumption, or waste formation, and ultimately leading to cheaper, safer, sustainable technologies. [2] One of the basic components of process intensification is the so-called multifunctional reactors, that are described as reactors combining at least one more function, usually a unit operation. [3]

Currently, Brazil has high competence and competitiveness in the production and productivity of poultry and swine meat, being the third largest producer and the largest exporter of poultry meat and the fourth largest producer and exporter of swine. [4] The industry of poultry and swine abattoirs generates a large volume of wastewater with a high pollutant load. It is estimated that this industrial process demands an average water volume of 10 m^3 per ton of final product, leading to a high volumes of wastewater to be treated. [5]

In the wastewater treatment facilities, although conventional methods can be used, the high energy consumption and the generation of secondary pollution limit the techno-economic feasibility of the main wastewater treatment systems, such as activated sludge, nitrification-denitrification, and phosphorus precipitation. In this sense, processes with high efficiency, cost effectiveness, and environmental friendliness should be developed to make the global production chain sustainable. [6-9]

Heterotrophic microalgal bioreactors are a potential technology to be applied in industrial wastewater treatment facilities. The heterotrophic microalgae metabolism has as its characteristic, the simultaneous conversion of the pollutants present in wastewater in a single step, thereby reducing capital and operational costs. In addition, substantial amounts of microalgae biomass with a high potential of exploitation as industrial feedstocks are formed that are inherent in the process of treatment. [10,11]

The techno-economic studies of the microalgae-based processes have been shown to be economically infeasible scenarios. [12-14] This infeasibility is related mainly with the reduced scalability of the photosynthetic and the high operational costs of the heterotrophic processes. According to Wijffels et al. [15] the technological routes are immature and need to be fully developed, implying the need for a large effort in research and development (R&D). These authors reported that microalgal biotechnology will be competitive and commercially attractive by 2020.

In the analysis and cost estimate for designing a new process, almost all the decisions are impacted by the economic factors and, therefore, it is critical to study process economics. The major criteria to judge feasibility are preliminary design and economic potential estimation to be attained, and knowing the price of the final product is necessary for covering the costs involved. The feasibility of these processes has been determined based on the techno-economic analysis of the simultaneous process of wastewater treatment and biomass production, which is conducted based on a relationship of a benefit-cost ratio. Feasibility indicators such as the economic equilibrium, profitability, rentability, and period of return on investment are the main parameters utilized. [16]

In this regard, the aim of this study is to evaluate the techno-economic modeling of microalgal heterotrophic bioreactors when applied to poultry and swine slaughterhouse wastewater treatment.

2 Material and methods

2.1 Microorganism and culture conditions

The microalgae used was *Phormidium* sp., originally isolated from the Cuatro Cienegas desert (26º59'N, 102º03'W-Mexico). [17] Stock cultures were propagated and maintained in solidified agar-agar (20g/L) containing synthetic BG11 medium. [18] The incubation conditions used were 25ºC, a photon flux density of 15 $\mu molm^{-2}\ s^{-1}$ and a photoperiod of 12h. To obtain the inoculums in liquid form, 1 mL of sterile synthetic medium was transferred to slants, the colonies were scraped and then homogenized with the aid of mixer tubes. The entire procedure was performed aseptically.

2.2 Wastewater

The poultry and swine slaughterhouse wastewater used in the experiments was obtained from an industry located in Santa Catarina, Brazil (27º14’02”S, 52º01’40”W). It was collected from the discharge point of an equalization tank over a period of one year, and analyzed for pH, chemical oxygen demand (COD), total nitrogen (N-TKN), total phosphorus ($P\text{-}PO_4^{-3}$), total solids (TS), suspended solids (SS), volatile solids (VS), and fixed solids (FS) following the total solids Standard Methods for the Examination of Water and Wastewater. [19] The average composition of the wastewater, in a one year of sampling, has the following composition (mg/L): pH of 5.9±0.05, COD of 4100±874, N-TKN of 128.5±12.1, $P\text{-}PO_4^{-3}$ of 2.84±0.2, TS of 3.8±2.7, SS of 1.9±0.8, VS of 2.9±1.4 and FS of 0.9±0.3, C/N ratio of 31.9 and N/P ratio of 45.2. The carbon/nitrogen ratio (C/N) and nitrogen/phosphorous ratio (N/P) were calculated through COD, N-TKN, and $P\text{-}PO_4^{-3}$.

2.3 Process description

The unit operations of the process were based on a patent application developed by Jacob-Lopes et al. [20] Figure 1 shows the flow diagram of the process. The core of the process is one heterotrophic microalgal bioreactor that is, used to convert simultaneously COD, N-TKN and $P\text{-}PO_4^{-3}$ into microalgal biomass. The bioreactor has a height/diameter (h/D) ratio equal to 1.3 and a nominal working volume of 5 L. The dispersion system of the reactor consisted of a 1.5 cm diameter air diffuser located inside the bioreactor. In addition to the bioreactor, the bench scale facility is equipped with all the necessary ancillaries to convert the pollutants of the agroindustrial wastewater into dried microalgal biomass.

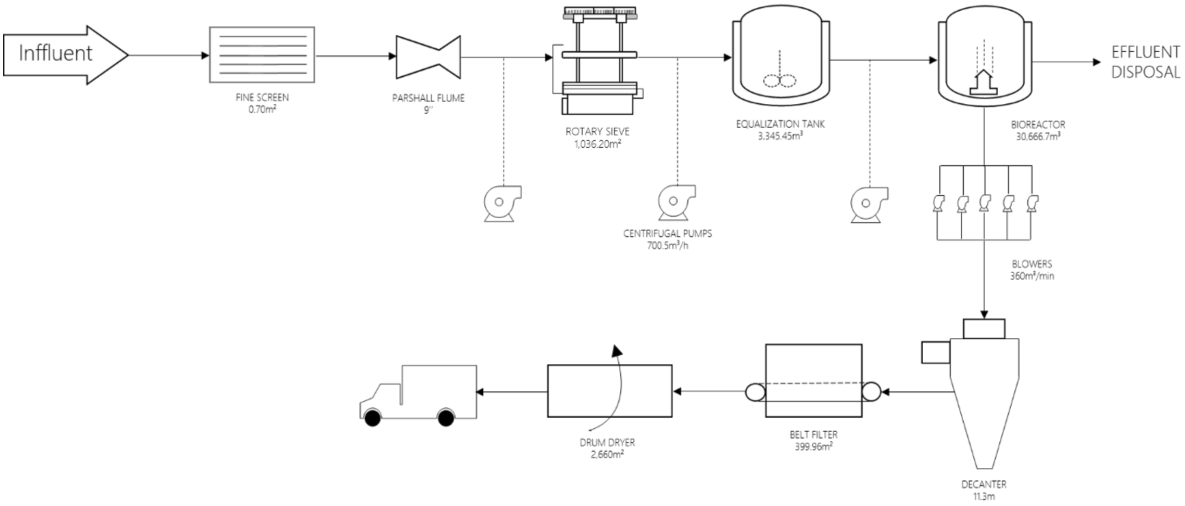

Figure 1 – Process flow diagram of the agroindustrial wastewater treatment and biomass production.

The operational conditions of the continuous process were previously optimized in order to define a pH adjusted to 7.6, temperature of 20ºC, volumetric airflow rate per volume unit of 1 VVM (volume of air per volume of wastewater per minute), absence of light and a dilution rate of 0.6/d. [21]

2.4 Sampling and analytical methods

Samples were collected aseptically in a laminar flow hood. The cell biomass, the pH dynamics, the consumption of organic carbon, total nitrogen and total phosphorus and the dissolved oxygen concentration were monitored every 24 hours during the growth phase of microorganism. The analysis were performed in triplicate and data refer to the average of six repetitions.

The photon flux density was determined using a digital photometer (Spectronics, Westbury-NY, USA), measuring the light incident on the external surface of the cultures.

The cell biomass was gravimetrically evaluated by filtering a known volume of culture medium through a 0.45µm membrane filter (Millex FG®, Billerica-MA, USA), drying at 60ºC for 24h.

The organic carbon concentration was expressed in terms of chemical oxygen demand (COD) and analyzed according to the closed reflux colorimetric method. Total nitrogen was determined by Kjeldahl method and the total phosphorus was determined by the spectrophotometric molybdovanadate method. [19]

2.5 Scale-up and sensitivity analysis of the wastewater treatment process

The dissolved oxygen concentration in the wastewater was determined by polarographic oxygen sensor (Mettler-Toledo, Zurich, Switzerland).

The theoretical scale-up of the process was performed using the criteria of constant oxygen transfer rate, through of the constant volumetric mass transfer coefficient (KL_a) method. [22]

The estimation of large-scale process was based on an industrial plant operating at a wastewater flow rate of 16,000 m^3/day, working 24 h/day and 336 days/year.

2.6 Cost analysis methodology

To assess the wastewater treatment cost and the production cost of microalgal sludge in the described facility it was necessary describe the flowchart of the process in detail, including a list of equipment, its size, and the consumables of the process.

The used methodology to determine the total capital investment is presented in Figure 2. [23] The total capital investment was based on the somatory of the fixed capital (FC) and the working capital (WC). Manufacturing fixed-capital investment represents the capital necessary for the installed process equipment with all auxiliaries that are needed for complete process operation. Fixed capital required for construction overhead and for all plant componentes that are not directly related to the process operation.

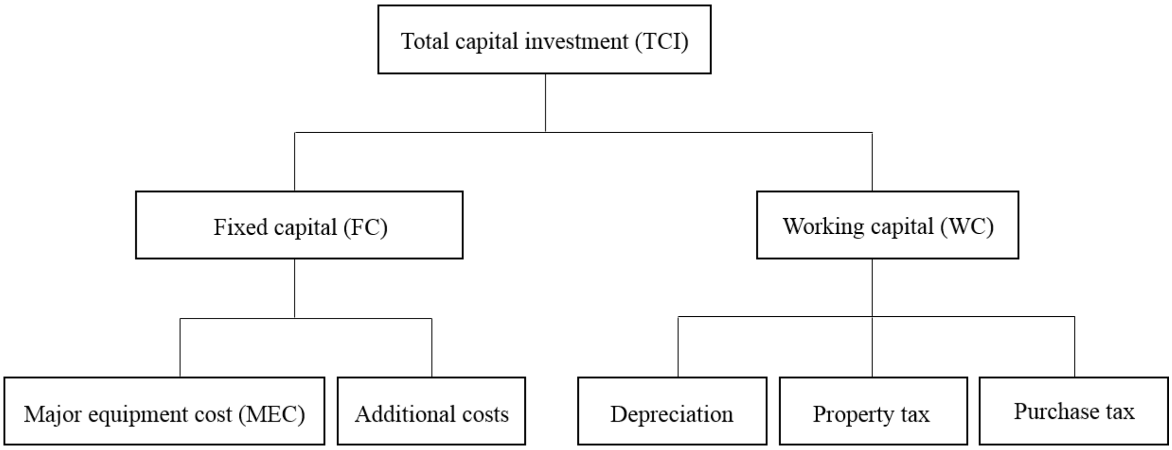

Figure 2 - Representation of the cost methodology.

In keeping with standard bioprocess engineering practice, the fixed costs was estimated as factors of the major equipment costs (MEC). The total fixed capital was calculated after the MEC determination, using appropriate factors (Lang factors), by multiplying the corresponding factor according to the nature of the item. The estimate cost for each piece of equipment was obtained from a website that estimates engineering the prices in 2014 FOB in USD. [24] The working capital estimated to industrial plant proposed, consisted of the total amount of money needed to for operation of the facilities. Are included depreciation, property tax and purchase tax.

Another equally important part is the estimation of costs for operating the plant is total operating capital (TOC), in which form part the costs with raw materials and supplies, utilities, labor costs and others (supervision, payroll charges, maintenance, operating supplies, general plant overheads, tax, and contingency). A percentage method was employed to calculate the different items. The amount of the raw materials was supplied per unit of product and determined from process material balances according to the direct quotations from market prices whereas the consumption of utilities was estimated from the power consumption of the process, which considered a value of 2% of the plant's capital for an overall utility cost. [14,25]

The direct labor costs were calculated estimating five workers, three shifts a day, working 8 h/day and earning USD 8.50 per hour. This value was multiplied by two to include labor charges, totaling the costs.

2.7 Feasibility analysis of process

To determine the techno-economic feasibility of the process, an overall economic analysis was conducted based on a relationship of benefit/cost ratios, represented by feasibility indicators such as the economic equilibrium (EE=total fixed cost/index contribution margin), index contribution margin (ICM=total revenue – [total variable cost/total revenue]), profitability (P=net profit/total investment), rentability (R=net profit/total revenue) and period of return on investment (PRI=total investment/net profit). [16]

3 Results and discussion

3.1 Wastewater treatment and microalgal sludge production

The bioreactor performance parameters are presented in Table 1. A simultaneous conversion at high rates of organic matter (0.75 kg/m^3/d), total nitrogen (0.02 kg/m^3/d), and total phosphorus (0.001 kg/m^3/d) was evidenced, resulting in removal efficiencies of 97.6, 85.5, and 92.4% for COD, N-TKN and P-PO$_4^{-3}$, respectively. In terms of microalgal growth, maximum specific growth rates of 0.6 d^{-1} and average microalgal sludge productivity of 0.27 kg/m^3/d were obtained. Moreover, this wastewater treatment process showed a biomass yield coefficient of 0.34 kg$_{sludge}$/kg$_{COD}$ and a hydraulic detention time of 1.9 h. In terms of oxygen transfer, a volumetric mass transfer coefficient (KL$_a$) of 0.002 min^{-1} was evidenced in the biorreator, in parallel to a power density demand of 9.7 W/m^3.

Table 1 - Bioreactor performance parameters

Parameter	**Value**
$r_{S\ (COD)}$ (kg/m^3/d)	0.75 ± 0.01
$r_{S\ (N\text{-}TKN)}$ (kg/m^3/d)	0.02 ± 0.00
$r_{S\ (P\text{-}PO4\text{-}3)}$ (kg/m^3/d)	0.001 ± 0.00
$RE_{(COD)}$ (%)	97.6 ± 1.64
$RE_{(N\text{-}TKN)}$ (%)	85.5 ± 2.37
$RE_{(P\text{-}PO4\text{-}3)}$ (%)	92.4 ± 0.22
μ_{max} (d^{-1})	0.60 ± 0.00
P_X (kg/m^3/d)	0.27 ± 0.03
$Y_{X/COD}$ (kg_{sludge}/kg_{COD})	0.34 ± 0.00
HDT (h)	1.91 ± 0.00
KL_a (min^{-1})	0.002 ± 0.00

$r_{S\ (COD)}$: COD consumption rate; $r_{S\ (N\text{-}TKN)}$: N-TKN consumption rate; $r_{S\ (P\text{-}PO4\text{-}3)}$: $P\text{-}PO_4^{-3}$ consumption rate; $RE_{(COD)}$: COD removal efficiency; $RE_{(N\text{-}TKN)}$: N-TKN removal efficiency; $RE_{(P\text{-}PO4\text{-}3)}$: $P\text{-}PO_4^{-3}$ removal efficiency; μ_{max}: maximum specific growth rate; P_X: average cellular productivity; $Y_{X/COD}$: biomass yield coefficient; HDT: hydraulic detention time, KL_a: volumetric mass transfer coefficient.

The system performance complies with the main wastewater discharge standards [26] and could be an alternative to conventional wastewater treatment processes such as activated sludge, nitrification-denitrification, and chemical phosphorus precipitation, usually employed in the meat processing industry. Besides the wastewater treatment occurring in a single step, in a multifunctional reactor, the partial conversion of the pollutants in a microalgal biomass with a large potential of commercial exploitation is the differential of this technology.

Based on scale-up of the process (16,000 m^3/d), an air flow rate of 360 m^3/min was theoretically estimated. In these conditions, this process has the potential to generate 503,967.7 tons of microalgal biomass per year from the treatment of 5,376,000 m^3 of wastewater.

3.2 Determination of the cost analysis

The cost estimate of wastewater treatment facility was determined using the basis description of the equipment utilized, including their size and type (Table 2). The most costly equipment was the bioreactor, followed by the drum-dryer and then by the belt filter used to dry the microalgae sludge. The total cost of MEC sums up to USD 25,968,800.00.

Table 2 - Major equipment costs used in the process

Item	**Capacity**	**Cost (USD)**	**Nº of units**	**Total cost (USD)**
1. Fine screen	(0.70m², carbon steel)	261,000.00	1	261,000.00
2. Rotary sieve	(1,036.20m², stainless steel)	325,600.00	1	325,600.00
3. Equalization tank	(3,345.45m³, carbon steel)	583,100.00	1	583,100.00
4. Parshall flume	(9", stainless steel)	19,000.00	1	19,000.00
5. Bioreactor	(30,666.7m³, stainless steel)	12,944,200.00	1	12,944,200.00

6. Decanter	(11.29m, carbon steel)	1,114,700.00	2	2,229,400.00
7. Centrifugal pump	(700.5m^3/h, stainless steel)	39,900.00	3	119,700.00
8. Drum dryer	(2,660m^2, stainless steel)	5,258,400.00	1	5,258,400.00
9. Blowers	(360m^3/min, carbon steel)	133,400.00	5	667,000.00
10. Belt filter	(399.96m^2, carbon steel)	3,561,400.00	1	3,561,400.00
Total MEC (USD)				**25,968,800.00**

In Table 3, the installation costs are shown, including the deployment, instrumentation, piping, and other elements necessary that resulted in a total fixed capital investment of USD 70,894,824.00. Considering a lifetime of 10 years, the annual fixed capital per year, required to keep the facility in operation, was estimated in USD 8,112,393.40.

Table 3 - Fixed capital investment of the process

Item	**Factor**	**Cost (USD)**
1. Major equipment cost (MEC)	1	25,968,800.00
2. Installations	0.2	5,193,760.00
3. Instrumentation and control	0.4	10,387,520.00
4. Piping	0.4	10,387,520.00
5. Eletrical	0.09	2,337,192.00
6. Buildings	0.11	2,856,568.00
7. Services	0.14	3,635,632.00
8. Land	0.06	1,558,128.00
9. Engineering and supervision	0.13	3,375,944.00
10. Contractor's fee (0.05 Σ items 1-8)	0.05	3,116,256.00
11. Contingency	0.08	2,077,504.00
Total fixed capital, *A* (USD)		**70,894,824.00**
Item		**Cost (USD)**
Depreciation (Σ items 1-7, 9-11)/10 years		6,933,669.60
Property tax (0.01 depreciation)	0.01	69,336.70
Purchase tax (0.16 items 1-10/10)	0.16	1,109,387.10
Total fixed capital per year, *B* (USD)		**8,112,393.40**

Within the total operating capital, the direct production costs such as raw materials, the utilities and labor were the main entries. Table 4 shows that the total of the raw materials was summarized as USD 1,017,676.80, wherein the consumption of caustic soda was the main cost. The utilities costs, based only on power consumption, were estimated as USD 1,417,896.40. Finally, other costs (labor, supervision, payroll charges, maintenance, operating supplies, overheads, taxes and contingencies) reached USD 3,773,008.70. In this sense, the total operating capital was estimated as USD 14,320,974.00 per year.

Table 4 - Total operating capital of the process

Raw materials	**Total quantity**	**Cost (USD)**
1. Caustic soda (USD 0.348/kg)	0.464 kg/m³	867,686.40
2. Flocculants (USD 2.79/kg)	160 kg/day	149,990.40
Total raw materials, *C* (USD)		1,017,676.80
Utilities	**Total quantity**	**Cost (USD)**
3. Power consumption (0.02 FCI)	kWh	1,417,896.40
Total, *D* (USD)		1,417,896.40
Others	**Total quantity**	**Cost (USD)**
4. Labor (USD 8.50/h, 3 shifts)	5 workers	685,440.00
5. Supervision (0.2 labor)		137,088.00
6. Payroll charges (0.25 labor + supervision)		205,632.00
7. Maintenance (0.04 MEC)		1,038,752.00
8. Operating supplies (0.004 *C*)		4,070.70
9. General plant overheads (0.55 labor + supervision + maintenance)		1,023,704.00
10. Tax (0.16 items 1-3, 7 and 8)		556,543.34
11. Contingency (0.05 items 1-3)		121,778.66
Total, *E* (USD)		3,773,008.70
Total production cost, *F* (*B* (Table 3) + *C*+ *D* + *E*) (USD)		**14,320,974.00**

Regarding the analysis of the major costs of the process, the MEC showed that the bioreactor represents a cost close to 50% of the total facility, followed by the drum-dryer and the belt filter, showing the relationship of this equipments with their high power consumption. The fixed capital investment, depreciation over 10 years, contributed to approximately 56% to the cost of the process. The remaining 44% of the production cost originated in the direct production of total operating capital. Depreciation charges contributed an approx. 48% to the annual production cost and raw materials, utilities and labor contributed 7%, 9%, and 5%, respectively, to the production cost.

Based on the determination of cost analysis and the calculation basis of the industry in analysis (16,000 m^3 per day), the wastewater treatment cost was estimated as USD 2.66 per cubic meter (USD 0.70/m³ considering only operational costs). Additionally, through the microalgae sludge formation it is possible to predict a cost of USD 0.03 cents per kilogram of the dried biomass.

Comparatively, Figure 3 shows the operational costs of conventional wastewater treatment processes and the costs of the main processes for microalgal biomass production. The conventional technologies for wastewater treatment have operational costs estimated between

USD 1.06/m^3 to USD 2.58/m^3. [27,28] In particular, for the meat processing wastewater, the chemical treatment followed by activated sludge with extended aeration are the most usual treatments, with operational costs superior to estimated in this study. The application of microalgal heterotrophic bioreactors could represent substantial savings per cubic meter of wastewater treated and, furthermore, generates a sludge with commercial value, viable to the exploitation of bioproducts. The low production cost of this biomass (USD 0.03/kg) makes it viable to exploit low added value products, which is currently an infeasible scenario. The production costs of the microalgal biomasses are estimated as USD 5.71/kg to tubular photobioreactor and USD 8.18/kg to flat panel photobioreactor. [13] Additionally, the production cost of the heterotrophic fermenters is close to USD 12.00/kg. [12] According to Wijffels et al. [15] the production cost of microalgae biomass may not be higher than USD 0.55 cents/kg (ideal theoretical price) aiming to manufacture bulk products such as biofuels, which makes this process highly attractive in a commercial point of view.

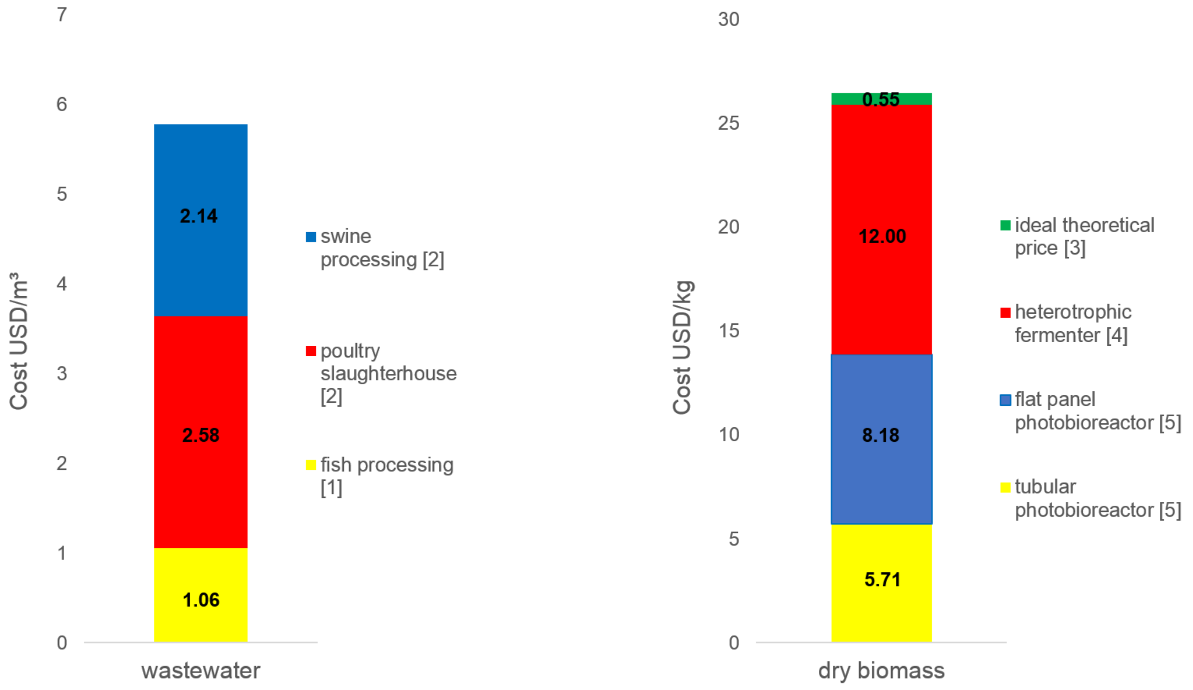

Figure 3 - Comparative costs of the wastewater treatment processes and dried microalgal biomass. [1] Cristóvão et al. [27]; [2] Asselin et al. [28]; [4] Wijffels et al. [15]; [5] Lee, [12]; [6] Norske et al. [13].

3.3 Applicability of the process

The feasibility of the process was determined based on the estimated of the economic equilibrium, profitability, rentability, and period of return on investment (Table 5).

Table 5 - Economical feasibility indicators of the process

Parameter	Value
Economic equilibrium (USD)	71,610,933.30
Profitability (% per year)	94.00
Rentability (% per year)	321.00
Period of return on investment (year)	0.29

The wastewater treatment generates a substantial amount of microalgal biomass of rich composition, similar to commodity products such as soybeans. Soybeans have an international price in the market average estimated at USD 0.48 cents/kg. [29] and, therefore, the commercial value of microalgal biomass was compared with the price of soybeans, resulting in USD 480/ton.

The net profit was estimated as USD 227,583,522.00 with a profit margin of 94%. The profitability of the process reports that, each year, the industry recovers approx. 321% of the amount invested and when the revenue reaches the value of USD 71,610,933.30 the payment of the total costs is made. The time of return on investment was estimated as 0.29 years, which means when this period of operation is achieved, the industry recovers the invested capital. These values are highly attractive, since the most companies use a value of 12% as minimum acceptable rate of return. [30] This rate is usually determined by evaluating existing opportunities in operations expansion, rate of return for investments, and other factors deemed relevant by management. However, companies operating in industries with more volatile markets might use a slightly higher rate in order to offset risk and attract investors. [31] In this sense, the feasibility analysis of the process demonstrated that the heterotrophic microalgal bioreactors applied to poultry and swine slaughterhouse wastewater treatment has a wide economic margin to explore industrial and commercially.

Additionally, the feasibility of the process demonstrates that this microalgal biomass produced in the agroindustrial wastewater has an economic margin that allows for working with fine chemical products but also commodities from microalgae, clearly showing the relationship benefit-cost for both.

The heterotrophic microalgal bioreactor is associated with improvements in the productive process, since it complies with the general guidelines intensive processes, combining more than one function. It requires lower power densities during operation, confirming the high performance of bioreactor, snapping it into the category of multifunctional reactors. [3] The cultivation of microalgae in wastewater offers combined advantages for the wastewater treatment and simultaneously the production of a valuable biomass. This bioreactor serves as an alternative to reducing the high costs of conventional secondary and tertiary treatment. Inherent to the treatment process, microalgal sludge is generated with a minimum cost of production, since it is a resultant product of an intensive process based in inputs of negligible cost (agroindustrial wastewater).

The current agroindustrial wastewater treatment systems utilize processes operating in multiple unit operations, which require high energetic demand, impacting finances throughout the production chain. Furthermore, these systems are still linked to expensive processes, with high capital and operation costs, besides the massive generation of biological sludge, with a low potential of reuse. The heterotrophic microalgal bioreactor, in addition to acting as an alternative for the decreased costs of conventional processes of wastewater treatment, biomass that is susceptible to the exploitation of bioproducts of commercial value is still generated at the end of the process. The process conducted from the use of heterotrophic microalgae bioreactor contributes to the maturation of the technology, in order to possibly explore these technological routes.

4 Conclusion

The emerging microalgae industry continues its march toward industrial application. The agroindustrial wastewater treatment with the parallel production of microalgal biomass could contribute to technology consolidation.

The multifunctional heterotrophic microalgal bioreactor simultaneously converts the three main pollutant of the poultry and swine slaughterhouse wastewater, reaching removal efficiencies of 97.6% (COD), 85.5% (N-TKN) and 92.4% ($P\text{-}PO_4^{-3}$). In addition, a microalgal sludge productivity of 0.27 $kg/m^3/d$ is obtained, potentializing the reuse in multiple production platforms.

The economic analysis demonstrated a cost of USD 2.66 per cubic meter of industrial wastewater treated, and as a consequence of this process, the production cost of microalgal sludge was USD 0.03 per kilogram of biomass dehydrated.

The feasibility analysis for the industrial applicability of the technology proposed shows that if the commercial value of microalgal biomass is estimated in USD 480/ton, it is possible to obtain a profit margin of 94%.

5 Acknowledgments

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ARTIGO 2 –THE ECONOMETRICS OF PRODUCTION OF BULK OIL AND LIPID EXTRACTED ALGAE IN AN AGROINDUSTRIAL BIOREFINERY

The econometrics of production of bulk oil and lipid extracted algae in an agroindustrial biorefinery

Gabriela Rigo Roso[a] and Eduardo Jacob-Lopes[a*]

[a] Department of Food Science and Technology, Federal University of Santa Maria, Roraima Avenue, 1000, 97105-900, Santa Maria, RS, Brazil. Phone: +55 55 32208822. Email: jacoblopes@pq.cnpq.br
*corresponding author

ABSTRACT

This article highlights the techno-economic analysis of a large-scale process to produce bulk oiland lipid extracted algae (LEA) in an agroindustrial biorefinery. The microalgal biorefinery hascapacity to produce 503,677.70 tons of biomass per year resulting in a bulk oil and lipid extracted algae production of 77,611.10 and 425,859.5 tons/year, respectively. The economic analysisforesees an estimated cost of USD 386.5 per ton of bulk oil and USD 70.4 per ton of LEA, demonstrating that this technological route has potential to provide feedstocks to both energy and feed industries.

Keywords: techno-economic analysis, biodiesel, animal feed

1 Introduction

Microalgae have been rediscovered as promising candidates for biotechnological applications in energy production systems, may be exploited specifically due to relatively high biomass productivity and oil content. [1,2] However for a sustainable lipids and biofuels production from microalgae, the concept of biorefinery must be applied. As in an oil refinery, a biorefinery uses all biomass components for obtaining biofuels and value added products. [3] The biorefinery for the nascent microalgal industry, is accelerating its maturation into a vital business sector, and this approach has the potential of contributing to a favourable techno-economic status when evaluating the production of bulk oil. [4,5]

Although there are still a number of technological market and policy barriers to the economic feasibility and competitiveness for the microalgae oil production, conversely, there are also a number of business opportunities if the production of such alternative oil becomes part of a larger integrated system, following the biorefinery strategy. In this case, the concurrent extraction of other added value products in addition to lipids from algal biomass may result in an economically beneficial technology, with an important objective of integrated algal biorefinery, contributing to an overall enhancement of the economic viability of the whole system and enabling the future commercialization of bulk products. [6,7]

Some estrategies has become relevant to overcome the economic constraints of microalgae production on a large scale. Among suggestions are: i) to recover the nutrients found in wastewater to cultivate the microalgae at a low cost with the additional benefit of eliminating pollutants from the environment. [8,9]; ii) to combine the production of microalgae lipid and biofuels with the production of chemicals and feed ingredientes. [10]; iii) to use a biorefinery-based production strategies. [11,12] and iv) to significantly improve the efficiency, cost structure and ability to scale-up algal biomass production, lipid extraction, and biofuel production. [13] Such strategies offer new opportunities for the cost-effective and competitive production of lipids based on microalgae technology along with valuable non-fuel products, produced at a competitive cost. [14]

The data of production costs from bulk oil vary widely from study to study, with conclusions stating that it is economically feasible or impossible to be competitive. The prices shown are not normalized for today prices, as they represent what authors found at that point of time, with values reaching until USD 28,439.3/ton [15,16], depending of the technology employed. However, according to Wijffels et al. [17] with the technology development, the production capacity will gradually increase and the production cost will reduce, reaching a cost compatible with the current market.

For it to be possible to decrease the production cost, econometric analysis of microalgal biorefineries should be carried out. [18-22] A tool set such as techno-economic analysis and economic feasibility of commercial production have been leveraged to evaluate alternative processing technologies, identify the most critical drivers and to focusing research and development, to understand and achieving the commercial viability of the bulk products from de microalgae. [23] In this sense, the aim of this work was to evaluate the techno-economic analysis of a large-scale process to production of bulk oil and lipid extracted algae (LEA) in an agroindustrial biorefinery. The study focused on definition of the production capacities, in determination of cost analysis and in the feasibility analysis of the process.

2 Material and methods

2.1 Microorganism and culture conditions

The microalgae used was *Phormidium autumnale,* originally isolated from the Cuatro Cienegas desert (26º59'N, 102º03'W-Mexico). Stock cultures were propagated and maintained in solidified agar-agar (20g/L) containing synthetic BG11 medium. [24] The incubation conditions used were 25ºC, a photon flux density of 15 μmolm^{-2} s^{-1} and a photoperiod of 12h. To obtain the inoculums in liquid form, 1 mL of sterile synthetic medium was transferred to slants, the colonies were scraped and then homogenized with the aid of mixer tubes. The entire procedure was performed aseptically.

2.2 Wastewater

The slaughterhouse wastewater was used in the experiments as culture medium. It was collected from the discharge point of an equalization tank over a period of one year, and analyzed for pH, chemical oxygen demand (COD), total nitrogen (N-TKN), total phosphorus (P-PO_4^{-3}), total solids (TS), suspended solids (SS), volatile solids (VS), and fixed solids (FS) following the Standard Methods for the Examination of Water and Wastewater. [25] The average composition of the wastewater, in a one year of sampling, has the following composition (mg/L): pH of 5.9±0.05, COD of 4100±874, N-TKN of 128.5±12.1, P-PO_4^{-3} of 2.84±0.2, TS of 3.8±2.7, SS of 1.9±0.8, VS of 2.9±1.4 and FS of 0.9±0.3, C/N ratio of 31.9 and N/P ratio of 45.2. The carbon/nitrogen ratio (C/N) and nitrogen/phosphorous ratio (N/P) were calculated through COD, N-TKN, and P-PO_4^{-3}.

2.3 Process description

2.3.1 The microalgal biorefinery

The unit operations of the process were based on a patent application developed by Jacob-Lopes et al. [26] The core of the process is one heterotrophic microalgal bioreactor that is, used to convert simultaneously COD, N-TKN and P-PO_4^{-3} into microalgal biomass. The bioreactor has a height/diameter (h/D) ratio equal to 1.3 and a nominal working volume of 5 L. The dispersion system of the reactor consisted of a 1.5 cm diameter air diffuser located inside the bioreactor. In addition to the bioreactor, the bench scale facility is equipped with all the necessary ancillaries to convert the pollutants of the agroindustrial wastewater into dried microalgal biomass and the fractionation of biomass into bulk oil and lipid extracted algae. The operational conditions of the continuous process were previously optimized in order to define a pH adjusted to 7.6, temperature of 20ºC, volumetric airflow rate per volume unit of 1 VVM (volume of air per volume of wastewater per minute), absence of light and a dilution rate of 0.6/d.

2.3.2 Obtaining of bulk oil and lipid extracted algae

The modified Bligh and Dyer [27] method was used to extract the lipid content of the biomass. The biomass that is left over from the extraction, the lipid extracted algae, was dried in a tray dryer at 60ºC.

With basis in laboratory experiments, an industrial process was proposed to oil extraction of the dried biomass (Figure 1). The hexane extraction was defined as the most suitable method to industrial application. [28] The extraction of this process generates a liquid stream, composed of microalgae oil and hexane, and the solid stream, that is composed of lipid extracted algae, hexane, residual oil and water. The solvent separation and is performed by distillation, in a stripping column, and recycled to the process, leaving a 99% pure solvent stream. The hexane separation and drying of the lipid extracted algae is done by a desolventizer–toaster-dryer-cooler (DTDC).

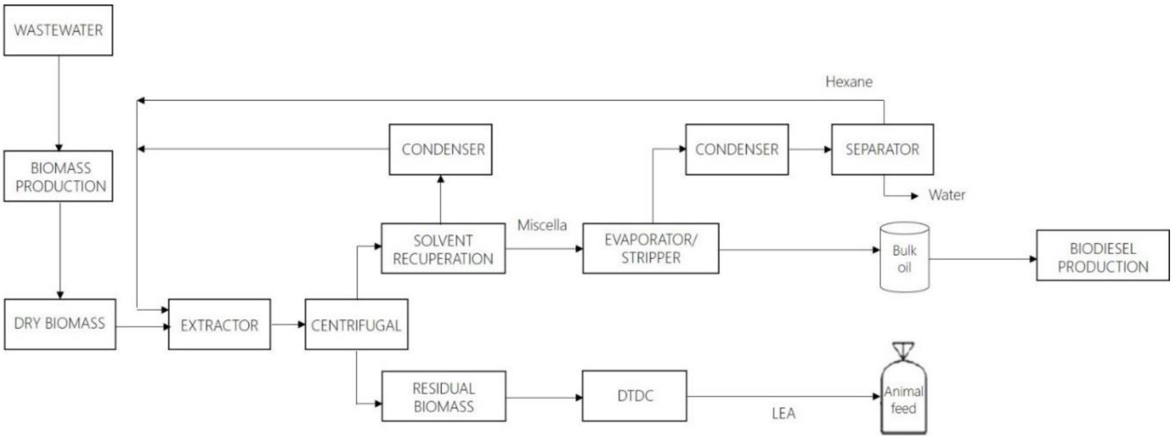

Figure 1 - Flowchart diagram of the bulk oil extraction and LEA.

2.4 Sampling and analytical methods

Samples were collected aseptically in a laminar flow hood. The cell biomass and the dissolved oxygen concentration were monitored every 24 hours during the growth phase of microorganism. The analysis were performed in triplicate and data refer to the average of six repetitions.

The cell biomass was gravimetrically evaluated by filtering a known volume of culture medium through a 0.45µm membrane filter (Millex FG®, Billerica-MA, USA), drying at 60ºC for 24h.

The dissolved oxygen concentration in the wastewater was determined by polarographic oxygen sensor (Mettler-Toledo, Zurich, Switzerland).

The centesimal composition of lipid extracted algae was determined in accordance with. [29]

The method of Hartman and Lago [30] was used to saponify and esterify the dried lipid extract to obtain the fatty acid methyl esters (FAMEs). The fatty acid composition was determined using a VARIAN 3400CX gas chromatograph (Varian, Palo Alto-CA, USA). The FAMEs were identified by comparison of the retention times with those of the standard (Supelco, Louis-MO, USA) and quantified by area normalization.

2.5 Scale-up of the process

The theoretical scale-up of the process was performed using the criteria of constant oxygen transfer rate, through of the constant volumetric mass transfer coefficient (KL_a) method. [31] The estimation of large-scale process was based on an industrial plant operating at a wastewater flow rate of 16,000 m^3/day, working 24 h/day and 336 days/year.

2.6 Cost analysis methodology

A techno-economic analysis of microalgal biorefinery was conducted based on technical and economics parameters of the experimental data, being necessary describe the flowchart of the process in detail, including a list of equipment, its size, and the consumables of the process.

The investment costs were annualized to create a common basis within the different lifetimes of production and supporting equipment. Annualizing costs is also necessary to set them in relation to the use-related costs and yields, which are both calculated on an annual basis. [32]

The capital investment was based on estimation of the total capital investment (TCI), that is the somatory of the fixed capital investment (FCI) and the working capital (WC). [33] The FCI includes the major equipment cost (MEC), and all the required additional costs necessary to build the plant (e.g. installation of the equipment). These additional costs are related to the MEC through certain factors taken from the literature (Lang factors). [34] The estimate cost for each piece of equipment was obtained from a website that estimates engineering the prices in 2014 FOB in USD [35] and of suppliers. The working capital estimated to industrial plant proposed, consisted of the total amount of money needed to for operation of the facilities, including the depreciation, property tax and purchase tax.

To estimate the total operating capital (TOC) we take into account the cost of raw materials, the utility costs and others costs (supervision, payroll charges, maintenance, operating supplies, general plant overheads, tax, and contingency) that are essential to plant operation on an annual basis. The raw materials was supplied per unit of product and determined from process material balances according to the direct quotations from market prices. The costs of consumption of utilities was estimated from the power consumption of the process, which considered a value of 2% of the plant’s capital for an overall utility cost [36], solid-waste disposal, steam, water consumption and wastewater treatment. The direct labor costs were calculated estimating five workers, three shifts a day, working 8 h/day and earning USD 8.50 per hour. This value was multiplied by two to include labor charges, totaling the costs.

2.7 Feasibility analysis

To determine the techno-economic feasibility of the process, an overall economic analysis was conducted based on a relationship of benefit/cost ratios, represented by feasibility indicators such as the economic equilibrium (EE=total fixed cost/index contribution margin), index contribution margin (ICM=total revenue–[total variable cost/total revenue]), profitability (P=net profit/total investment), rentability (R=net profit/total revenue) and period of return on investment (PRI=total investment/net profit). [37]

3 Results and discussion

The microalgae biomass is the primary bioproduct of a microalgal biorefinery and, considering that the oil is an intracellular product, the biomass productivity is a key performance indicator of the bulk oil production by microalgae (Figure 2). Thus, the microalgal biomass productivity in cultivation on wastewater was 0.64 $kg/m^3/d$, which enables predict an annual industrial biomass production of 503,677.70 tons. This biomass has an intracellular oil content of 15.5% (w/w), possibiliting an oil productivity of 0.1 $kg/m^3/d$ and an annual production of 77,611.10 tons. The microalgal oil has a composition predominantly saturated (93.1%) and monounsaturated (6.9%), suitable to biodiesel synthesis. [38] In parallel is estimated a lipid extracted algae (LEA) production of 425,859.5 ton/year with a composition of 34.6% of proteins, 15.9% of carbohydrates, 21.7% of minerals and 13.0% of moisture. The high protein content, similar to soybean meal, boosts usage of LEA in animal feed. [39]

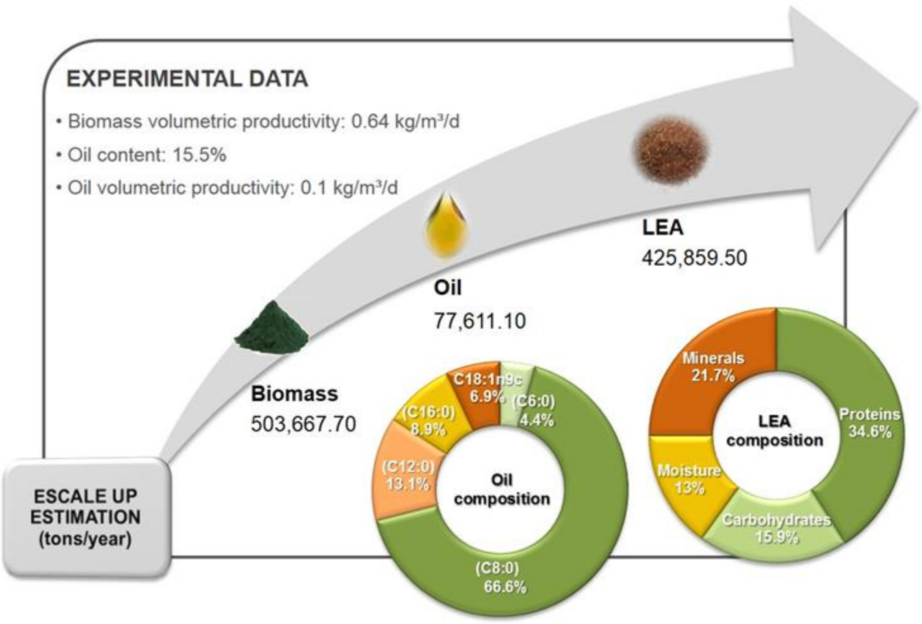

Figure 2 - Experimental data, composition and scale-up estimates of bulk oil and LEA production in a microalgal biorefinery.

Based on these experimental and theoretical data, the techno-economic modeling was performed. The costs for biorefinery process were estimated based on vendor quotes, prior literature studies, or standard engineering estimates. [40,41] In order to develop the estimate economic analysis, all equipment utilized, including their size and type are showed, followed by its costs (Table 1). The total cost of the MEC is totaled in USD 14,250,000.00. The most costly equipment was the evaporator/stripper, followed by the extractor and then by the DTDC. The MEC showed that the evaporator/stripper represented a cost close to 52.4% of the total facility, showing the relationship of this equipment with their high energy demand for to recovery of solvent.

Table 1 - Major equipment costs

Items	**Units**	**Cost USD**
Extractor (958.33 m³)	1	3,000,100.00
Centrifuge (13.50 m)	1	1,368,500.00
Evaporator/Stripper (200.78 m²)	1	7,487,100.00
Decanter (13.50 m)	1	190,000.00
Desolventizer-Toaster-Dryer-Cooler (DTDC) (10.20 ton/h)	1	2,000,000.00
Storage tank hexane (958.33 m³)	1	67,100.00
Storage tank oil (265.65 m³)	1	57,400.00
Centrifugal pump (416.66 m³/h)	2	79,800.00
Total MEC (USD)		**14,250,000.00**

The FCI varies almost linearly as a function of the production capacity, especially for larger capacities. [42] In Table 2 are presented the FCI values and detailed calculations such as installation costs, including the deployment, instrumentation, piping, and other elements necessary, that resulted in a total fixed capital investment of USD 63,555,000.00. Considering a lifetime of 10 years, the annual fixed capital per year, required to keep the facility in operation was estimated in USD 7,331,340.00.

To calculate the TOC, the direct production costs such as raw materials, the utilities and labor were the main entries. The raw materials were summarized as USD 4,529,010.00. The major costs of the utilities are associated with the solid-waste disposal and wastewater treatment, followed by high-pressure steam, used to vaporize the solvent in separator and stripping column. The utilities costs was estimated in USD 12,161,670.43. Other costs (labor, supervision, payroll charges, maintenance, operating supplies, overheads, taxes and contingencies) reached USD 5,981,307.90. Finally, the total capital production was summarized as USD 30,003,328.33 (Table 2).

The FCI contributed to approximately 24.4% to the total cost of the process. The remaining 75.6% originated of the TOC. The raw materials, utilities and other costs represented 15, 40.5 and 20% of the total production cost, respectively.

Based on these results, and considering the biomass microalgae formation by a cost of USD 0.03 cents per kilogram of the dried biomass [43], the unit production costs of output was estimated in USD 386.5 per ton for bulk oil (it did not include the costs of converting to biodiesel) and USD 70.4 per ton for the LEA (Table 2).

Table 2 - Economic parameters of the process

Fixed capital investment	**Factor**	**Cost (USD)**
1. MEC	1.0	14,250,000.00
2. Instalattions	0.2	2,850,000.00
3. Instrumentation and control	0.4	5,700,000.00
4. Piping	0.4	5,700,000.00
5. Eletrical	0.09	1,282,500.00
6. Buildings	0.11	1,567,500.00
7. Services	0.14	1,995,000.00
8. Land	0.06	855,000.00
9. Engineering and supervision	0.13	1,852,500.00
10. Contractor's fee (0.05 Σ items 1-8)	0.05	26,362,500.00
11. Contingency	0.08	1,140,000.00

Total fixed capital, *A* (USD)		**63,555,000.00**
Depreciation (Σ items 1-7, 9-11)/10 years		6,270,000.00
Property tax (0.01 depreciation)	0.01	62,700.00
Purchase tax (0.16 items 1-10/10)	0.16	998,640.00
Total fixed capital per year, *B* (USD)		**7,331,340.00**
Total operating capital		
Raw materials	Total quantity	Cost (USD)
12. Hexane (USD 0.75/kg)[a]	6,038.68 m^3	4,529,010.00
Total, *C* (USD)		**4,529,010.00**
Utilities		
13. Power consumption (0.02 TFC)[b]	kWh	1,271,100.00
14. Solid-waste disposal (USD 31.81/ton)[c]	266,308.90 tons	7,198,886.11
15. Steam (USD 10/GJ)[d]	108,655.54 GJ	1,086,555.40
16. Water (USD 0.0003/kg)[e]	31,044.30 m^3	9,313.32
17. Wastewater treatment (USD 0.07/kg chemical)[c]	37,083.08 m^3	595,815.60
Total, *D* (USD)		**12,161,670.43**
Others		
18. Labor (USD 8.50/h, 3 shifts)	5 workers	685,440.00
19. Supervision (0.2 labor)		137,088.00
20. Payroll charges (0.25 labor + supervision)		205,632.00
21. Maintenance (0.04 MEC)		570,000.00
22. Operating supplies (0.004 *C*)		18,116.04
23. General plant overheads (0.55 labor + supervision + maintenance)		765,890.40
24. Tax (0.16 items 12-17, 21 and 22)		2,764,607.44
25. Contingency (0.05 items 12-17)		834,534.02
Total, *E* (USD)		**5,981,307.90**
Total production cost, *F* (*B* + *C*+ *D* + *E*) (USD)		**30,003,328.33**
Unit cost production		
Bulk oil	USD/ton	386.5
LEA	USD/ton	70.4

[a]Labib et al., 2013; [b]Anderson, 2009; [c]Meyers, 2004; [d]Apostolakou et al., 2009; [e]Qureshi et al., 2013.

Comparatively, we perform a literature survey and identified that, depending on the technological route used, the production costs have a range of values ranging from USD 497.1 to 28,439.3 per ton of microalgae bulk oil. [6,15,16,44-48] Conversely, Borowitzka [49] affirmed that algae oil would need to cost less than USD 450/ton to be commercially produced aiming to biodiesel production. Based on this, the technological route developed, if scalable, has potential to provide financial gains to industrial operator.

Through of the definition of unit selling prices, the annual revenues were estimated, aiming to ensuring a return or profit. The feasibility of the process was based on a relationship of a benefit-cost ratio. In the present study, the main feasibility indicators such as the economic equilibrium, profitability, rentability, and period of return on investment were related (Table 3).

Table 3 - Economical feasibility indicators

Parameters	USD 735/ton	USD 829/ton	USD 400/ton
Economic equilibrium (USD)	94,858,209.00	89,514,084.50	70,616,666.70
Profitability (% per year)	41.5	48	82.3
Rentability (% per year)	33.5	44	220.8
Period of return on investiment (year)	2.9	2.2	0.45

The selling price of microalgae bulk oil considered for feasibility analysis was based in the selling prices of main feedstocks worldwide used for biodiesel synthesis, that is soybean oil and canola oil, currently quoted in USD 735.00/ton and USD 829.00/ton, respectively. [50]

In a simulation market scenarios (Table 3), considering a selling price of USD 735/ton (equivalent to soybean oil), the net profit was estimated as USD 21,336,414.30 with a profit margin of 41.5%. The profitability of the process reported that, each year, the industry recovers approx. 33.5% of the amount invested and when the revenue reaches the value of USD 94,858,209.00 the payment of the total costs is made. The time of return on investment was estimated as 2.9 years, which means when this period of operation is achieved, the industry recovers the invested capital. At the same time, if the bulk oil is sold at a price of USD 829/ton (equivalent to canola oil), the net profit is estimated in USD 27,902,313.40 with a profit margin of 48%, profitability of 44% and when the revenue reaches the value of USD 89,514,084.50 the payment of the total costs is made. The time of return on investment is thus, estimated as 2.2 years.

These values can be converted into biodiesel selling price increasing it by 15% as suggested by Davis et al. [43] According to these authors, this value is a rule-of-thumb which includes all processing costs from bulk oil to biodiesel. In this way, the microalgal biodiesel selling price can be estimated between 845.2 to 953.3 USD/ton, resulting in a probable value between 0.73 to 0.82 USD per liter in the diesel pump. These values are compatible with the prices of biodiesel (B100) available in the US, Europe and Brazil, currently quoted in a range of USD 0.71 to 0.96 per liter. [51-53]

Finally, considering the LEA marketing in USD 400/ton (equivalent to soybean meal prices) [54], is possible to obtain a net profit of USD 140,340,472.00 (Table 3). This additional revenue substantially improve the econometrics of the process, demonstrating that the process integration is one of main strategies to be adopted to commercial consolidation of microalgal biofuels.

4 Conclusion

The development of renewable energy carriers and fuels that can be incorporated into existing infrastructures is underway worldwide. The heterotrophic bulk oil production by microalgae based on wastes of the meat processing showed to be a potential technological route to production of energy feedstocks and feed ingredients.

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ARTIGO 3 - THE BIOECONOMY OF MICROALGAL CAROTENOID-RICH OLEORESINS PRODUCED IN AGROINDUSTRIAL BIOREFINERIES

The bioeconomy of microalgal carotenoid-rich oleoresins produced in agroindustrial biorefineries

Gabriela Rigo Roso[a], Cristiano Ragagnin de Menezes[a], Maria Isabel Queiroz[b], Leila Queiroz Zepka[a], Eduardo Jacob-Lopes[a*]

[a] Department of Food Science and Technology, Federal University of Santa Maria, Roraima Avenue, 1000, 97105-900, Santa Maria, RS, Brazil. Phone: +55 55 32208822. Email: jacoblopes@pq.cnpq.br
[b] School of Chemistry and Food, Federal University of Rio Grande , Itália Avenue, 96201-900, Rio Grande, RS, Brazil. Phone: +55 55 3232 5069.
*corresponding author

ABSTRACT

The techno-economic evaluation of the obtaining process of a natural mixed carotenoid-rich oleoresin from microalgae dried biomass is presented in this paper. The process is based on solvent extraction on industrial scale, and the oleoresin obtained is suspended in soybean oil at a concentration of 20%. The oleoresin is compound of a mix of *trans* and *cis* isomers of carotenoids, having as the major carotenoid the all-*trans*-β-carotene, in amounts close to 37%. The experimental data were used to estimate the costs of an industrial plant that has the potential to generate 569,016 tons of microalgal biomass per year, in which 107,902.5 kilograms per year are represented by total carotenoids. Based on the determination of the cost analysis, it was demonstrated that the natural mixed carotenoid-rich oleoresin in soybean oil has a production cost estimated as USD 146.9 per kilogram.

Keywords: cost analysis, microalgae, oleoresin, wastewater

1 Introduction

Microalgae-based systems for the production of chemicals are an emergent area, representing, therefore, great promise for industrial application. Several processes have primarily demonstrated capabilities for the food and feed industries, pigments and additives production, and the cosmetics industries. [1] These microorganisms have a metabolic versatility that enables the biomass production based on organic sources without commercial value, such as industrial wastes. [2]

Such possibilities become attractive for bioprospecting and exploitation as commercial sources in a wide range natural pigments primarily when their feedstock comes from biorefinery systems. [3-9] The biorefinery approach consists of a sustainable processing of biomass into a wide range of valuable bioproducts in an integrated process. The use of these strategies may provide an inexpensive alternative to the conventional technological routes of natural pigments production, e.g. carotenoids. [10]

Commercially, carotenoids are used as food colorants and nutritional supplements, with an estimated global market of USD 935 million in 2005. [11] The growing worldwide market value of carotenoids is projected to reach over USD 1 billion by the end of the decade. [12] This market was predicted to achieve USD 1.2 billion by 2009, and is expected to approach USD 919 million by 2015. Increased competition is the reason for a lower market value than previously predicted. [13]

The process of synthesis and purification of carotenoids requires the use of techniques that would make production on a commercial scale very difficult and extremely expensive. [14] This process is highly complicated and involves different organic solvents and multiple steps for the purification. [15] Consequently, the purified form of carotenoids is not easily scaled up to an efficient commercial scale, wherein disposal considerations of various solvents play an important role in the overall feasibility of the process. [16] It is necessary, therefore, to find a more affordable way for commercializing this product, for instance fractions of different carotenoids in oily form in the same extract.

The oily extracts of pigments from different sources have a rather varied carotenoid composition, and according to Rios et al. [17] they are able to provide different tonalities from yellow to red, which are sufficiently concentrated to enable their large-scale commercial use (low doses are sufficient to achieve the desired color in a large amount of foodstuff). When carotenoids are extracted from natural sources and the solvent is evaporated, the residue is called oleoresin. According to these authors, the oleoresins are commercially available as food grade, and the natural carotenoids may also be manufactured as oil suspensions. Palm oil carotenes and carotenoids from *Dunaliella salina* and *Blakeslea trispora* are traded as 20-30% suspensions in vegetable oil. In the oil suspensions, the esters may be hydrolyzed, and the free carotenoids may be suspended in vegetable oil to give a less viscous product than the isolated oleoresin. [18]

A key issue on the viable production of the natural carotenoids is the general absence of low-cost processing technology. The biotechnological production of carotenoids originated of microalgae can circumvent the majority of these limitations, since the biomass carotenoid-rich production can be supported in agroindustrial wastes. These bioresources have low chemical risks, are potentially available on a large scale, and can generate feedstocks at a competitive cost. [6,19] Moreover, the utilization of these substrates might reduce the environmental and energetic problems related to their disposal. [20]

In this regard, the aim of this study was to perform a techno-economic evaluation of a natural mixed carotenoid-rich oleoresin extracted from microalgae biomass produced in an agroindustrial biorefinery. The study focused on the carotenoid-rich biomass production, in the determination of the cost analysis and in the evaluation of the applicability of the process.

2 Material and methods

2.1 Standards

The standards of all-*trans*-violaxanthin, all-*trans*-lutein, all-*trans*-zeaxanthin, all-*trans*-zeinoxanthin, all-*trans*-lutein, all-*trans*-α-carotene, all-*trans*-β-carotene were donated by DMS Nutritional Products (BASEL, Switzerland) with purities ranging from 95.0% to 99.9%, as determined by HPLC-PDA. Methanol (MeOH), methyl tert-butyl ether (MTBE), hexane and potassium hydroxide (KOH) were obtained from Sigma Aldrich (St. Louis, MO, USA).

2.2 Microorganisms and culture media

Axenic cultures of *Phormidium autumnale* were originally isolated from the Cuatro Cienegas desert (26°59′N, 102°03′W-Mexico). Stock cultures were propagated and maintained in solidified agar–agar (20 g/L), containing synthetic BG11 medium. [21] The incubation conditions used were 25°C, a photon flux density of 15 μmol/m^2/s and a photoperiod of 12/12 hour light/dark.

2.3 Microalgal biomass production in a biorefinery

The biomass production was made in heterotrophic conditions, using the slaughterhouse wastewater as the culture medium. The cultivations were performed in a bubble column bioreactor (height/diameter (h/D) ratio equal to 1.3 and a nominal working volume of 5 L). The dispersion system of the reactor consisted of a 1.5 cm diameter air diffuser located inside the bioreactor.

The average composition of the wastewater, during one year of sampling, has the following composition (mg/L): pH of 5.9 ± 0.05, chemical oxygen demand of 4100 ± 874, total nitrogen of 128.5 ± 12.1, total phosphorus of 2.84 ± 0.2, total solids of 3.8 ± 2.7, suspended solids of 1.9 ± 0.8, volatile solids of 2.9 ± 1.4 and fixed solids of 0.9 ± 0.3. The operational conditions of the continuous process were previously optimized in order to define a pH adjusted to 7.6, temperature of 20ºC, volumetric airflow rate per volume unit of 1 VVM (volume of air per volume of wastewater per minute), absence of light, and a dilution rate of 0.6/d. The wet biomass was separated from the wastewater by centrifugation and then dried on a tray dryer at 60ºC. The cultivations were performed twice, and in duplicate.

2.4 Carotenoid extraction and carotenoid-rich oleoresin production

The carotenoids were extracted from the dried biomass based on an extraction phase composed by hexane/potassium hydroxide/methanol, which simultaneously affects an alkaline treatment to saponify susceptible lipids and extract the intended carotenoids. [22-23] The carotenoids extract was solubilized in soybean oil, at a concentration of 20%, and stabilized with antioxidant tert-butylhydroquinone (TBHQ) at a concentration of 0.02% (v/v). The final product obtained was a natural mixed carotenoid-rich oleoresin in soybean oil.

2.5 Sampling and analytical methods

Samples were collected aseptically in a laminar flow hood; the cell biomass was monitored every 24 hours during the growth phase of microorganism; the analyses were performed in triplicate and the data refer to the average of six repetitions.

The cell biomass was gravimetrically evaluated by filtering an established volume of culture medium through a 0.45μm membrane filter (Millex FG®, Billerica-MA, USA), drying at 60ºC for 24 h.

The dissolved oxygen concentration in the wastewater was determined by a polarographic oxygen sensor (Mettler-Toledo, Zurich, Switzerland).

The carotenoid extract was analyzed by a high performance liquid chromatography HPLC-PDA-MS/MS (Shimadzu, Kyoto, Japan) equipped with quaternary pumps (model LC-20AD), online degasser, and injection valve with a 20 μL loop (Rheodyne, Rohnert Park, CA, USA). The equipment was connected in series to a PDA detector (model SPD-M20A) and a mass spectrometer with an ion-trap analyzer and atmospheric pressure chemical ionization (APCI) source (model Esquire 4000, Bruker Daltonics, Bremen, Germany). The carotenoid separation was performed on a C_{30} YMC column (5 μm, 250 × 4.6 mm) (Waters, Wilmington, DE, USA). HPLC-PDA-MS/MS parameters were set as previously described by De Rosso and Mercadante. [24] The mobile phase consisted in a mixture of methanol and MTBE. A linear gradient was applied from 95:5 to 70:30 in 30 min, to 50:50 in 20 min. The flow rate was 0.9 $mL.min^{-1}$. The identification was performed according to the following combined information: elution order on C_{30} HPLC column, co-chromatography with authentic standards, UV-visible spectrum (λ max, spectral fine structure, peak *cis* intensity), and mass spectra characteristics (protonated molecule ($[M+H]^+$) and MS/MS fragments), compared with data available in the literature. [1,24-27] The carotenoids were also quantified by HPLC-PDA, using five-point analytical curves of all-*trans*-violaxanthin, all-*trans*-zeaxanthin, all-*trans*-zeinoxanthin, all-*trans*-lutein, all-*trans*-β-carotene and all-*trans*-α-carotene. All other xanthophyll and carotene contents were estimated using the curve of all-*trans*-lutein and all-*trans*-β-carotene, respectively. The *cis*-isomers were estimated by using the curve of the corresponding all-*trans*-carotenoid. The total carotenoid content was calculated as the sum of the contents of each individual carotenoid separated on the C_{30} column.

2.6 Scale-up of the microalgal biorefinery

The theoretical scale-up of the process was performed using the criteria of a constant oxygen transfer rate through the constant volumetric mass transfer coefficient (KL_a) method. [28] The estimation of large-scale process was based on an industrial plant operating at a wastewater flow rate of 10,000 m^3/day, working 24 h/day and 336 days/year, and performing one extraction of carotenoids per day.

2.7 Cost analysis methodology

The production cost of the mixed carotenoids-rich oleoresin was initially based on the description of the flowchart of the process (Figure 1). A list of the equipment used, its size, and the consumables of the process has also been given.

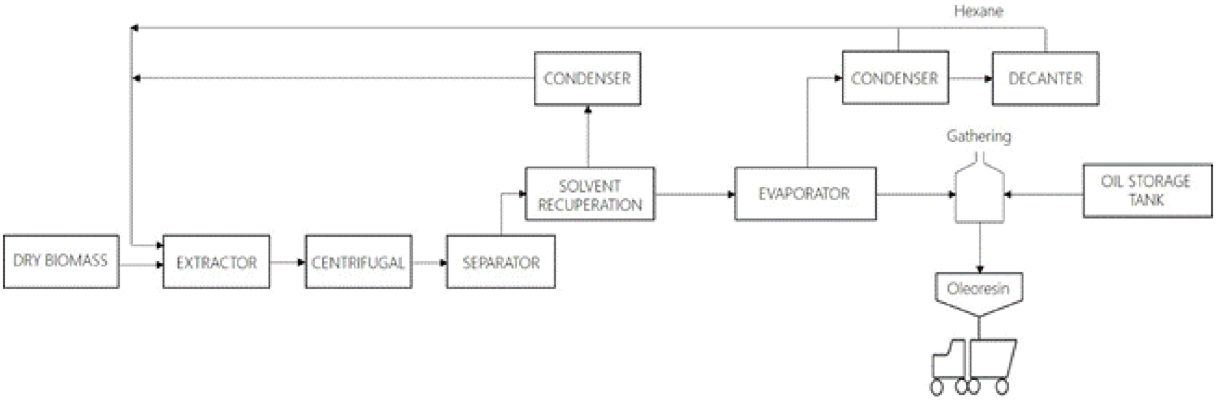

Figure 1 - Flowchart diagram of the mixed carotenoid-rich oleoresin in soybean oil extraction process.

The methodology applied to determine the total capital investment was established based on an estimation of the total capital investment (TCI), which is the somatory of the fixed capital investment (FCI) and the working capital (WC). [29]

The fixed costs were estimated through the factors of the major equipment costs (MEC) and all the required additional costs necessary to build the plant (e.g. installation of the equipment). These additional costs are related to the MEC through certain factors taken from the literature (Lang factors).

The different items were estimated as a percentage of the MEC, multiplying the corresponding Lang factors according to the nature of the item. The estimated cost for each piece of equipment was obtained from a website that estimates engineering prices in 2014 FOB in USD. [30]

The total of the operating capital represents the costs that are directly dependent on the production rate. It consists of the cost of raw materials (CRM) as well the cost of the solvent lost during the process, known as the cost of utilities (CUT), which represents the demand for water that is required for the evaporator and condenser, electricity, waste treatment, and the cost of operational labor (COL). Within operating capital, the direct production costs included raw materials, utilities, labor costs and others (supervision, payroll charges, maintenance, operating supplies, general plant overheads, tax, and contingency). A percentage method was employed to calculate the different items. [31] The amount of the required raw materials was calculated from mass balances, whereas the consumption of utilities was estimated from the power consumption of the process that considered a value of 2% of the plant's capital for an overall utility cost. [32-33] The costs of raw materials were obtained through the selling prices of the market.

The direct labor costs were calculated estimating five workers, during three shifts a day, working 8 h/day and earning USD 8.50 per hour. This value was multiplied by two to include labor charges and then the costs were totaled.

3. Results and discussion

3.1 Carotenoid-rich biomass production

The microalgae biomass is the primary bioproduct of a microalgal biorefinery and, considering that, the carotenoids are intracellular products, and the biomass productivity is a key performance indicator of the pigments production by microalgae (Table 1). Thus, the microalgal biomass productivity in cultivation on wastewater was 0.63 kg/m^3/d, which enables the prediction of an annual production of 569,016 tons on an industrial scale (F=10.000 m^3/d). This biomass has a total carotenoids concentration of 183.03 mg/kg with the possibility of an annual production of 107,902.5 kg/year.

Table 1 - Kinect parameters and massa balance for microalgal biomass carotenoids production in a microalgal biorefinery

Parameter	**Value**
Biomass volumetric productivity (g/m^3/d)	630
Biomass production (ton/year)	569,016
Total carotenoids concentration (μg$_{\text{carotenoids}}$/g$_{\text{biomass}}$)	183.03
Total carotenoids production (kg/year)	107,902.5

Qualitatively, Figure 2 shows the carotenoids profile of the microalgal biomass. Twenty carotenoids were found, the majority of which were the isomers of β-carotene (42.7%), followed by the isomers of echinenone (19.4%), isomers of zeaxanthin (14.6%) and the isomers of lutein (13.1%). Others minority carotenoids comprised by 10.1% of the total.

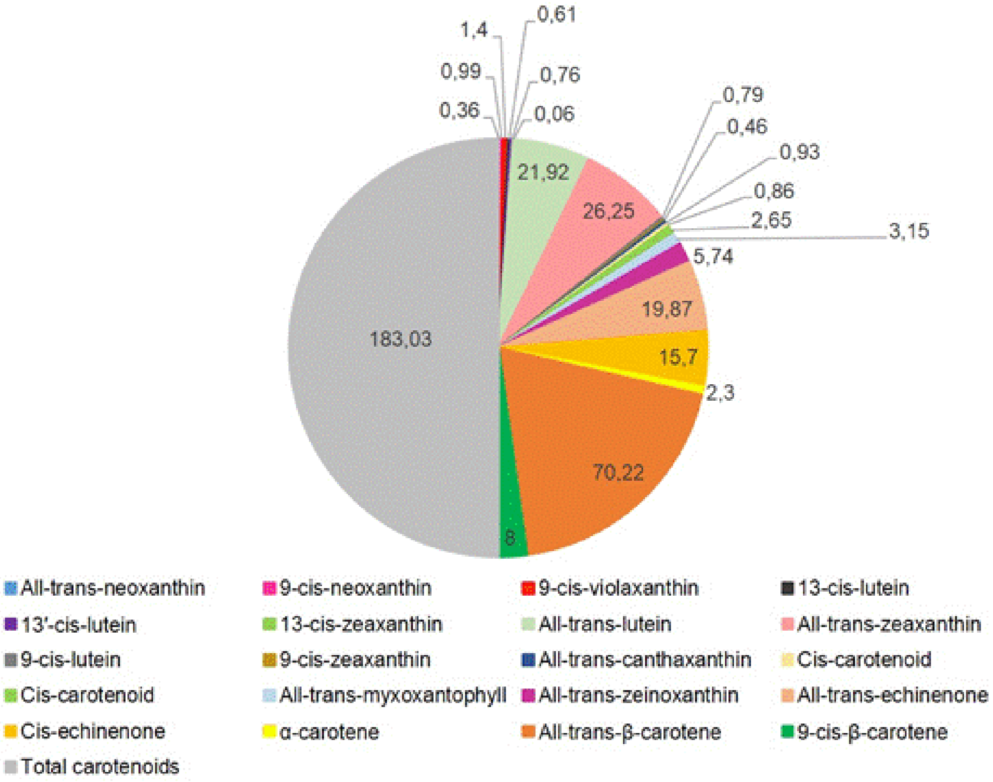

Figure 2 - Identification of the carotenoids obtained by HPLC–PDA–MS/MS and their contents in µg/g.

Moreover, *Phormidium autumnale* biosynthesized some unique types of ketocarotenoids and glycosylated carotenoids (Figure 3), wherein all-*trans*-canthaxanthin and all-*trans*-myxoxanthophyll are exclusively present in the microalgal, besides the already reported isomers of echinenone. The potential bioactivity of these carotenoids should be considered in addition to the coloring capacity.

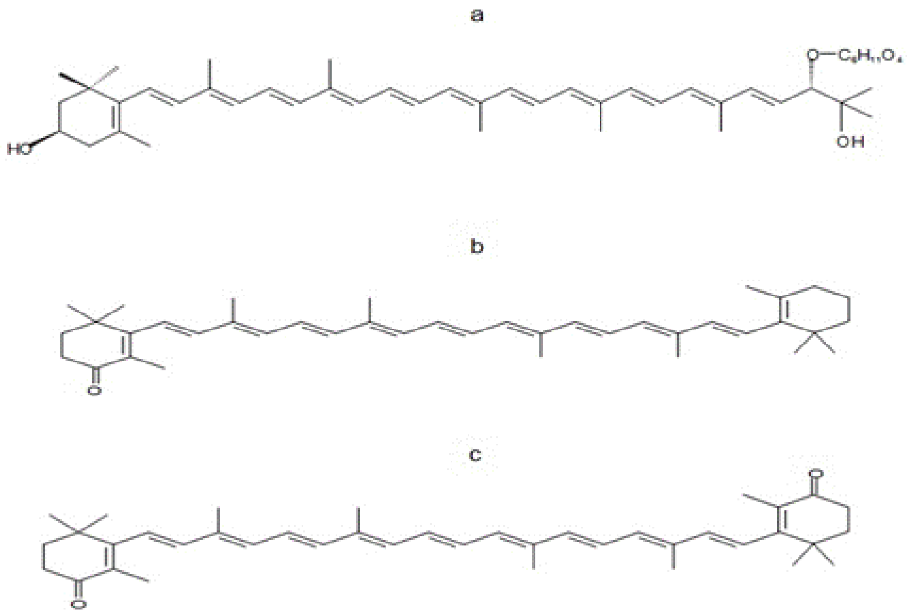

Figure 3 - Ketocarotenoids and glycosylated carotenoids presente in *Phormidium autumnale*. (a) all-*trans*-myxoxantophyll (b) all-*trans*-echinenone (c) all-*trans*-canthaxanthin.

3.2 Determination of the cost analysis

The cost estimate of a natural mixed carotenoids-rich oleoresin production facility was determined using the description of the process proposed. The equipment that was utilized, including its size and type, is described in Table 2. The most costly of the MEC was the evaporator, followed by the extractor. The total amount of the MEC totals USD 25,796,500.00.

Table 2 - Major equipment costs in the extraction process of the oleoresin

Items	**Units**	**Cost USD**
Extractor (7,790.1 m³)	1	9,108,600.00
Centrifuge (13.5 m)	1	1,368,500.00
Separator (13.5 m)	1	190,000.00
Evaporator (6,397.6 m²)	1	13,946,800.00
Condenser (887.1 m²)	1	850,500.00
Storage tank hexane (6,774 m³)	1	85,000.00
Storage tank methanol (25.4 m³)	1	43,200.00
Storage tank oil (1.6 m³)	1	33,700.00
Storage tank water (11,290 m³)	1	90,400.00
Centrifugal pump (416.6 m³/h)	2	79,800.00
Total MEC (USD)		**25,796,500.00**

The installation expenses are shown, including the deployment, instrumentation, piping, and other elements necessary, resulting in a total fixed capital investment of USD

70,424,445.00. Considering a lifetime of 10 years, the annual fixed capital, required to keep the facility in operation, was estimated as USD 7,977,116.23 per year (Table 3).

Table 3 - Economic parameters used in the process

Fixed capital investment		
Items	**Factor**	**Cost (USD)**
1. MEC	1.0	25,796,500.00
2. Instalattions	0.2	5,159,300.00
3. Instrumentation and control	0.4	10,318,600.00
4. Piping	0.4	10,318,600.00
5. Eletrical	0.09	2,321,685.00
6. Buildings	0.11	2,837,615.00
7. Services	0.14	3,611,510.00
8. Land	0.06	1,547,790.00
9. Engineering and supervision	0.13	3,353,545.00
10. Contractor's fee (0.05 Σ items 1-8)	0.05	3,095,580.00
11. Contingency	0.08	2,063,720.00
Total fixed capital, *A* (USD)		**70,424,445.00**
Depreciation (Σ items 1-7, 9-11)/10 years		6,825,103.50
Property tax (0.01 depreciation)	0.01	68,251.03
Purchase tax (0.16 items 1-10/10)	0.16	1,083,761.70
Total fixed capital per year, *B* (USD)		**7,977,116.23**
Total operating capital		
Raw materials	Total quantity	Cost (USD)
12. Hexane (USD 0.41/kg)[a]	29,466.9 m^3	12,081,429.00
13. Methanol (USD 0.42/kg)[a]	25.4 m^3	3,584,448.00
14. KOH (USD 0.40/kg)[b]	2,133,801.6 kg	853,520.60
15. Antioxidant (USD 28.66/kg)[c]	113,803.2 kg	3,261,599.70
16. Soybean oil (USD 0.54/kg)[d]	539.5 m^3	291,338.20
Total, *C* (USD)		**19,218,814.90**
Utilities		
17. Power consumption (0.02 FCI)[e]	kWh	1,408,488.90
18. Water (USD 0.0003/kg)[f]	3.8x10^9 m^3	1,138,032.00
19. Wastewater treatment (USD 2.99/m^3)[g]	11,315.4 m^3	11,367,903.50
20. Solid-waste disposal (USD 31.81/ton)[h]	558,601.2 tons	17,769,104.20
Total, *D* (USD)		**31,683,528.60**
Others		
21. Labor (USD 8.50/h, 3 shifts)	5 workers	685,440.00
22. Supervision (0.2 labor)		137,088.00
23. Payroll charges (0.25 labor + supervision)		205,632.00
24. Maintenance (0.04 MEC)		1,031,860.00
25. Operating supplies (0.004 *C*)		768,752.60
26. General plant overheads		1,019,913.40

(0.55 labor + supervision + maintenance)	
27. Tax (0.16 items 12-20, 24 and 25)	8,432,472.98
28. Contingency (0.05 items 12-20)	2,545,117.18
Total, *E* (USD)	**14,826,276.16**
Total production cost, *F* (*B* + *C*+ *D* + *E*) (USD)	**73,705,735.90**

[a](Koutinas et al., 2014); [b](Tabernero et al., 2012); [c](Almeida-Doria and Regitano-D'arce, 2000); [d](Glisic and Orlović, 2014); [e](Anderson, 2009); [f](Qureshi et al., 2013); [g](Buyukkamaci and Koken, 2010); [h](Meyers, 2004).

Within the total operating capital, the direct production costs such as raw materials, utilities and labor were the main entries. Table 3 shows that the total of the raw materials was summarized as USD 19,218,814.90, wherein the consumption of hexane utilized for extraction was the major cost. The utilities expenses, based on water demand, power consumption and wastes treatment, were estimated as USD 31,683,528.60. In addition, other costs (labor, supervision, payroll charges, maintenance, operating supplies, overheads, taxes and contingencies) reached USD 14,826,276.16. In this sense, the total operating capital was estimated as USD 73,705,735.90 per year.

Regarding the analysis of the major costs of the process, the MEC showed that the evaporator represents an amount close to 54% of the total facility, followed by the extractor with 35%. The fixed capital investment, over 10 years of depreciation, contributed to approximately 10.8% to the cost of the process. The remaining 89.2% of the production cost originated the total operating capital. Depreciation charges contributed an approx. 9.2% to the annual production cost, and raw materials and utilities 26% and 43%, respectively, to the production cost.

Based on the determination of cost analysis, the calculation basis of the industry in analysis (1,693,500 kg per day of biomass), and considering the biomass microalgae formation, it is possible to predict a cost of USD 0.03 cents per kilogram of the dried biomass. [34] The natural mixed carotenoid-rich oleoresin in soybean oil cost production was estimated as USD 146.9 per kilogram.

Comparatively, the products commercially sold today, characterized as natural mixed carotenoid, are Betatene®, Betanat®, Caromin® and Tocomin®. All of these products are a mixed suspension of natural carotenoids (preferentially *trans* and *cis* isomers of carotenes and xanthophylls) in vegetable oil, marketed in different concentrations. These products are isolated from different matrices as the alga *Dunaliella salina* (Betatene®), fungal *Blakeslea trispora* (Betanat®), palm fruit *Elaeis guineenses* (Caromin®), and crude palm oil (Tocomin®). Two of these products described herein above are more specifically similar with the product developed and presented in this study (Betatene® and Caromin®). The selling prices of these products are USD 12,774 and USD 12,642 per kilogram [35], respectively. Therefore, the new technological route presented in this paper could represent substantial savings per kilogram of natural mixed carotenoids-rich oleoresin produced, potentiating the economic viability of the process.

3.3 Applicability of the process

The major criteria for judging the feasibility of the process are the preliminary design and economic potential estimation, which are to be attained, and knowing the price of the final product is necessary for covering the costs involved. [36] The feasibility of the process was determined based on the techno-economic analysis a in a global scenario of the mixed carotenoid-rich oleoresin production, conducted based on a relationship of a benefit-cost ratio. In the present study, the main feasibility indicators were related, such as the economic equilibrium, profitability, rentability, and period of return on investment (Table 4).

Table 4 - Economical feasibility indicators of the process

Parameter	Value
Economic equilibrium (USD)	89,144,867.10
Profitability (% per year)	70.62
Rentability (% per year)	251.50
Period of return on investment (year)	0.39

Taking into account that the commercial products sold in the market as natural mixed carotenoids reach USD 12,800 per kilogram, the production cost of mixed carotenoid-rich oleoresin demonstrated in this study (USD 146.9 per kilogram) is shown to be extremely low. This occurs because the sources that are commercially available today are extracted of matrices that are highly expensive and difficult to obtain, handle, and extract. However, the oleoresin extracted in our process, is a product supported in a feedstock of negligible costs.

In addition, if our natural mixed carotenoid-rich oleoresin was sold at a value of USD 12,000/kg, the annual revenue would be more than USD 6 billion/year and with a profit margin of 98%. On the other hand, taking into consideration that the feedstock utilized has a negligible cost (USD 0.03 cents/kg of the dried biomass), the oleoresin may be quietly sold at a price of USD 500/kg, and yet, have a net profit estimated as USD 177,164,564.00 with a profit margin of 70.6%. The profitability of the process reports that, each year, the industry recovers approximately 251.5% of the amount invested, and when the revenue reaches the value of USD

89,144,867.10 the payment of the total costs is made. The time of return on investment was estimated as 0.39 years, which means when this period of operation is achieved the industry recovers the invested capital. These values are highly attractive, since the most companies use a value of 12% as minimum acceptable rate of return. [37] This rate is usually determined by evaluating existing opportunities in operations expansion, rate of return for investments, and other factors deemed relevant by management. However, companies operating in industries with more volatile markets might use a slightly higher rate in order to offset risk and attract investors. [38] In this sense, the feasibility of the process demonstrated that the natural mixed carotenoid-rich oleoresin obtained from the microalgae biomass of low production cost has a wide economic margin to explore industrial and commercially.

4 Conclusion

The techno-economic modeling of the process demonstrated that the production cost of natural mixed carotenoid-rich oleoresin in soybean oil was USD 146.9/kg.

The feasibility analysis for the industrial applicability of the technology proposed showed that if the commercial value of mixed carotenoid-rich oleoresin is estimated as USD 500/kg, it is possible to obtain a 70.6% profit margin.

Accordingly, the oleoresin production in biorefinery systems can contribute to the technology consolidation of waste-pigment-utilization.

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CONCLUSÃO GERAL

A modelagem técnico-econômica da aplicação de biorreatores heterotróficos microalgais no tratamento de efluentes agroindustriais apresentou potencialidade para utilização industrial e exploração comercial da tecnologia;

Em nível de tratamento das águas residuárias do processamento de aves e suínos, é possível converter simultaneamente matéria orgânica, nitrogênio total e fósforo total, em etapa única, a um custo de US$ 2,66 por metro cúbico de efluente tratado. Paralelamente o lodo microalgal tem um custo estimado em US$ 30,0 por tonelada;

A integração do processo através de uma biorrefinaria agroindustrial indicou a possibilidade de utilizar o lodo microalgal para extração de óleo a granel e farelo microalgal desengordurado. O preço de custo destes produtos foi estimado em US$ 386,5 e 70,4 por tonelada de óleo e farelo, respectivamente;

A integração do processo através de um biorrefinaria agroindustrial indicou a possibilidade de produzir oleorresinas ricas em carotenóides mistos a um custo de produção estimado em US$ 146,9 por quilograma de produto.

Independente do produto considerado, as análises de viabilidade econômica demostraram elevado potencial de ganhos financeiros associados a exploração comercial destas rotas tecnológicas, com lucratividades superiores a 70,6% ao ano.

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