UNIVERSIDADE ESTADUAL DO CEARÁ
CENTRO DE CIÊNCIAS E TECNOLOGIA
PROGRAMA DE PÓS - GRADUAÇÃO EM CIÊNCIAS NATURAIS
DOUTORADO EM CIÊNCIAS NATURAIS

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FRAMEWORK TEEC: INTELIGÊNCIA DECISÓRIA PARA O ESCALONAMENTO SUSTENTÁVEL DE TECNOLOGIAS ALIMENTÍCIAS

FORTALEZA - CEARÁ
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Tese apresentada ao Programa de Pós-Graduação em Ciências Naturais, do Centro de Ciências e Tecnologia, da Universidade Estadual do Ceará, como parte dos requisitos para a obtenção do título de Doutor em Ciências Naturais. Área de concentração: Aproveitamento de Recursos Naturais.

Orientadora: Profa. Dra. Maria Cléa Brito de Figueirêdo.

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FOLHA DE APROVAÇÃO – DEFESA DE TESE

ALUNO: Moacir Jean Rodrigues

Título: FRAMEWORK TEEC: INTELIGÊNCIA DECISÓRIA PARA O ESCALONAMENTO SUSTENTÁVEL DE TECNOLOGIAS ALIMENTÍCIAS.

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Dedico este trabalho a Deus e à minha família.

AGRADECIMENTOS

A Deus, por tudo.

À minha família, pelo apoio e pelos ensinamentos.

À minha orientadora, Dra. Maria Cléa Brito de Figueirêdo, pela oportunidade de ser seu orientando e por sua paciência.

À equipe da ACV: Jaqueline, Johnny, Renatinha, Ana Paula, Matheus, Viviane, Jonnathan, Ed e Nayanna.

À equipe do Laboratório de Tecnologia da Biomassa (LTB), especialmente ao Prof. Dr. Men de Sá, pela oportunidade de realizar estágio no laboratório ainda na graduação. Ao Marcelino, Alex, Adriano, Dra. Morsy, Lilian, Vitória, Hallison e a Dra. Ana Irady.

À equipe do Laboratório de Processos Agroindustriais (LPA): Diogo, Dra. Ana Paula Dionísio, Dra. Ingrid, Arthur, Beatriz, Fátima, Gil e Dr. Fernando Abreu.

À Embrapa Agroindústria Tropical, pela valiosa oportunidade de trabalho e aprendizado.

À UECE e ao Programa de Pós-Graduação em Ciências Naturais, pela oportunidade de formação.

À CAPES e ao Good Food Institute pelo apoio financeiro concedido por meio de bolsas.

"Em verdade, em verdade te digo que, quando eras mais jovem, vestia-te a ti mesmo e andavas por onde querias; mas quando fores idoso, estenderás as mãos e outro te vestirá e te levará para onde não queres ir."

(João 21:18)

RESUMO

O desenvolvimento de tecnologias emergentes no setor agroalimentar exige ferramentas de avaliação que transcendam análises isoladas e determinísticas. Embora a literatura reporte abordagens combinadas de viabilidade econômica e impactos ambientais, persiste uma lacuna quanto à integração simultânea e harmonizada de métricas de circularidade material sob condições de incerteza, especialmente em níveis iniciais de maturação tecnológica (TRL 4-5). Este trabalho propõe, de forma inédita, o desenvolvimento e a validação do *Framework* TEEC (Técnico-Econômico, Ambiental e de Circularidade), uma ferramenta de inteligência decisória preditiva que unifica de maneira estocástica e multicritério a Análise Técnico-Econômica (TEA), a Avaliação do Ciclo de Vida (ACV) *ex-ante* e o Índice de Fluxo Linear (LFI). O diferencial metodológico reside na construção de consistência de inventário entre os fluxos de massa e energia e na blindagem contra volatilidades de mercado e de processo, por meio da integração da Simulação de Monte Carlo com o método *Analytic Hierarchy Process* (AHP). A validação do framework ocorreu por meio de dois estudos de caso aplicados ao setor agroalimentar. No primeiro estudo, avaliou-se a produção industrial de Fibra de Caju Desidratada (FCD) a partir do bagaço do caju. Após a modelagem de sensibilidade e escala (capacidade ideal de 6 toneladas/batelada), o método AHP apontou o Cenário 3 (secagem em estufa operada integralmente por matriz solar fotovoltaica) como a rota ótima. Em comparação com a rota de referência, o cenário promissor reduziu o Preço Mínimo de Venda (PMV) em 3,45% (de US$ 12,17 para US$ 11,75 kg^{-1}), mitigou as emissões de Mudanças Climáticas em 45,79% e diminuiu o Uso de Recursos Fósseis em 40,93%. No âmbito da circularidade, o Índice de Fluxo Linear (LFI) do cenário promissor permaneceu em 83,27%, apresentando 0% de melhoria (resultado idêntico ao da rota de referência). Essa estabilidade evidenciou uma importante constatação do modelo: estratégias focadas estritamente na descarbonização da matriz energética alteram as fontes de eletricidade e calor, mas não modificam a massa de materiais que flui linearmente no sistema. No segundo estudo de caso, avaliou-se a extração de Corante Vermelho-Púrpura a partir da pitaya em lotes de 1.000 kg/batelada. O método AHP selecionou o Cenário 2 (valorização e aproveitamento integral da polpa, cascas e mucilagem do fruto) como o de melhor desempenho global. Este cenário apresentou um ganho expressivo de eficiência material em relação à rota de referência, reduzindo o PMV em 47,03% (de US$ 84,86 para US$ 44,95 kg^{-1}). No âmbito ambiental, promoveu reduções consistentes entre 63% e 68% em todas as seis categorias de impacto avaliadas. Adicionalmente, as estratégias de eco-design focadas na massa reduziram o Índice de Fluxo Linear (LFI) de 97,36% para 83,61% no cenário ótimo, o que representa uma melhoria relativa de 14,12% no índice de circularidade em relação à referência. Os resultados globais indicam que os pontos fortes do framework TEEC consistem em: (a) prover previsibilidade financeira e ambiental integrada nas fases iniciais de PD&I; (b) revelar *trade-offs* ocultos por análises isoladas, como o aumento substancial no uso de recursos minerais decorrente da transição para energias renováveis; e (c) orientar o ecodesign de plantas industriais antes do investimento em ativos fixos. Conclui-se que o *Framework* TEEC inova ao fornecer uma metodologia robusta de engenharia de sistemas sustentáveis, mitigando riscos de investimento e orientando o desenho de cadeias alimentícias circulares antes do ganho de escala industrial.

Palavras-chave: Análise Técnico-econômica, ACV ex-ante, Análise Multicritério, Bioeconomia Circular, fibra de caju, corante de pitaya.

ABSTRACT

The development of emerging technologies in the agri-food sector requires assessment tools that transcend isolated and deterministic analyses. Although the literature reports combined approaches to economic viability and environmental impacts, a gap persists regarding the simultaneous and harmonized integration of material circularity metrics under conditions of uncertainty, especially at early levels of technological maturity (TRL 4-5). This work proposes, for the first time, the development and validation of the TEEC Framework (Technical-Economic, Environmental and Circularity), a predictive decision intelligence tool that stochastically and multi-criteria unifies Technical-Economic Analysis (TEA), ex-ante Life Cycle Assessment (LCA), and the Linear Flow Index (LFI). The methodological difference lies in building inventory consistency between mass and energy flows and in shielding against market and process volatilities, through the integration of Monte Carlo Simulation with the Analytic Hierarchy Process (AHP) method. The framework was validated through two case studies applied to the agri-food sector. In the first study, the industrial production of Dehydrated Cashew Fiber (DCF) from cashew bagasse was evaluated. After sensitivity and scale modeling (ideal capacity of 6 tons/batch), the AHP method indicated Scenario 3 (drying in an oven operated entirely by a photovoltaic solar energy mix) as the optimal route. Compared to the reference route, the promising scenario reduced the Minimum Selling Price (MSP) by 3.45% (from US$12.17 to US$11.75 kg^{-1}), mitigated Climate Change emissions by 45.79%, and decreased Fossil Resource Use by 40.93%. In terms of circularity, the Linear Flow Index (LFI) of the promising scenario remained at 83.27%, showing 0% improvement (an identical result to the reference route). This stability highlighted an important finding of the model: strategies focused strictly on decarbonizing the energy mix alter the sources of electricity and heat, but do not modify the mass of materials that flow linearly in the system. In the second case study, the extraction of Red-Purple Colorant from pitaya was evaluated in batches of 1,000 kg/batch. The AHP method selected Scenario 2 (full valorization and utilization of the fruit pulp, peel, and mucilage) as having the best overall performance. This scenario showed a significant gain in material efficiency compared to the reference route, reducing the MSP by 47.03% (from US$ 84.86 to US$ 44.95 kg^{-1}). In terms of environmental impact, it promoted consistent reductions between 63% and 68% in all six impact categories evaluated. Additionally, mass-focused eco-design strategies reduced the Linear Flow Index (LFI) from 97.36% to 83.61% in the optimal scenario, representing a relative improvement of 14.12% in the circularity index compared to the baseline. Overall results indicate that the strengths of the

TEEC framework consist of: (a) providing integrated financial and environmental predictability in the early stages of R&D; (b) revealing trade-offs hidden by isolated analyses, such as the substantial increase in the use of mineral resources resulting from the transition to renewable energies; and (c) guiding the ecodesign of industrial plants before investment in fixed assets. In conclusion, the TEEC Framework innovates by providing a robust methodology for sustainable systems engineering, mitigating investment risks and guiding the design of circular food chains before industrial scaling.

Keywords: Technical-economic analysis, ex-ante LCA, multi-criteria analysis, circular bioeconomy, cashew fiber, dragon fruit dye.

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LISTA DE ABREVIATURAS E SIGLAS

ACV	Avaliação do Ciclo de Vida
AHP	Analytic Hierarchy Process (Método de Análise Hierárquica)
AICV	Avaliação de Impactos do Ciclo de Vida
BC	Bagaço de Caju
BNDES	Banco Nacional de Desenvolvimento Econômico e Social
CTI	Índice de Transição Circular (Circular Transition Indicators)
DCF	Dehydrated Cashew Fiber
DPB	Tempo de Retorno Descontado (Discounted Payback Period)
ELCC	Custo do Ciclo de Vida Ambiental (Environmental Life Cycle Costing)
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária
FCD	Fibra de Caju Desidratada
GEE	Gases de Efeito Estufa
IA	Índice Aleatório
IC	Índice de Consistência
ICV	Análise de Inventário do Ciclo de Vida
ISCC	International Sustainability and Carbon Certification
LCA	Life Cycle Assessment (sigla em inglês correspondente a ACV)
LFI	Índice de Fluxo Linear
MCDA	Análise de Decisão Multicritério (Multi-Criteria Decision Analysis)
MCI	Indicador de Circularidade de Materiais
ONU	Organização das Nações Unidas
PD&I	Pesquisa, Desenvolvimento e Inovação
PMV	Preço Mínimo de Venda
RC	Razão de Consistência
REV	Valor Ambiental Retido (Retained Environmental Value)
R.I.	Índice médio de consistência aleatória
ROI	Retorno Sobre o Investimento
TEA	Análise Técnico-Econômica (Techno-Economic Analysis)
TEEC	Análise Técnico-Econômica, Ambiental e de Circularidade
TIR	Taxa Interna de Retorno
TRL	Níveis de Maturidade Tecnológica (Technology Readiness Levels)
VPL	Valor Presente Líquido
WBCSD	World Business Council for Sustainable Development

SUMÁRIO

1. INTRODUÇÃO

O modelo econômico predominante ainda segue uma lógica linear de “extrair-produzir-usar-descartar”, que intensifica a exploração de matérias-primas e amplia a geração de resíduos, resultando em impactos ambientais significativos (COTTAFAVA; RITZEN, 2021; KO et al., 2024). Diante disso, as empresas têm buscado compreender e reduzir esses impactos ao longo de toda a cadeia produtiva (GESTARO; SCHMIDT, 2021).

Nos últimos anos, a economia circular tem sido apresentada como alternativa ao modelo linear tradicional (AGLIARDI; KASIOUMI, 2023). Esse conceito propõe reduzir o desperdício e otimizar o uso de recursos, mantendo materiais e produtos em circulação pelo maior tempo possível (REN et al., 2023). Com isso, torna-se possível gerar benefícios econômicos e, ao mesmo tempo, diminuir a pressão sobre os recursos naturais (BANJERDPAIBOON; LIMLEAMTHONG, 2023).

No entanto, migrar de uma economia linear para uma circular envolve custos e exige mudanças estruturais. É necessário repensar o modelo atual em todas as etapas, da extração da matéria-prima ao consumo final. Por isso, torna-se essencial desenvolver processos que conciliem sustentabilidade ambiental com viabilidade técnica e econômica (FINDIK; TIRGIL; ÖZBUĞDAY, 2023; IÑARRA et al., 2022).

Nesse contexto, a Avaliação do Ciclo de Vida (ACV) é uma ferramenta importante para apoiar a implementação da economia circular, pois permite identificar rotas produtivas mais sustentáveis (GOH; LAU; YONG, 2023). Mais recentemente, a ACV *ex-ante* tem ganhado destaque por possibilitar a identificação de “pontos críticos” que podem comprometer o desempenho ambiental de tecnologias ainda em fase inicial de desenvolvimento (LU et al., 2019; KARKA; PAPADOKONSTANTAKIS; KOKOSSIS, 2022). Além disso, essa abordagem permite testar intervenções de projeto que favoreçam melhorias e aumentem a atratividade do processo para investimentos (CUCURACHI; VAN DER GIESEN; GUINÉE, 2018).

Ao aplicar os princípios da economia circular, é preciso considerar de forma integrada as dimensões ambiental e econômica (AGLIARDI; KASIOUMI, 2023). Nesse sentido, a Análise Técnico-Econômica (TEA, do inglês *Techno-Economic Analysis*) é fundamental nas fases iniciais de um projeto, pois contribui para avaliar a competitividade do produto em desenvolvimento e ampliar oportunidades de parceria (DAVIDSON et al., 2021).

A transição dos sistemas produtivos também exige, além de marcos regulatórios e modelos de negócio sustentáveis, indicadores capazes de medir as ações de circularidade adotadas e seu desempenho ao longo do tempo (MANI et al., 2025; SHEVCHENKO et al., 2022; DE OLIVEIRA; OLIVEIRA, 2023). Nesse cenário, métricas como o Indicador de Circularidade de Materiais (MCI), desenvolvido pela Fundação Ellen MacArthur e pela ANSYS Granta em 2015, e o Índice de Transição Circular (CTI), do WBCSD (*World Business Council for Sustainable Development*), podem acelerar esse processo (SHEVCHENKO et al., 2022; WALZBERG et al., 2025). A integração dessas ferramentas nas etapas iniciais do projeto gera informações mais consistentes para apoiar decisões econômicas e ambientais (MAHMUD et al., 2021; MANI et al., 2025).

A principal qualidade de um índice ou indicador está em sua utilidade para apoiar a tomada de decisão (BAUMER-CARDOSO; ASHTON; CAMPOS, 2023). No entanto, as abordagens apresentadas (TEA, ACV e indicadores de circularidade), produzem métricas distintas, abrangendo aspectos econômicos, ambientais e circulares.

Para integrar esses diferentes indicadores, podem ser empregados métodos de Decisão Multicritério (MCDA, do inglês *Multi-Criteria Decision Analysis*) (NIERO; KALBAR, 2019), como o método de Análise Hierárquica (AHP, do inglês *Analytic Hierarchy Process*) (BHATTACHARYA; GHOSH; CHOWDHURY, 2017). A aplicação da MCDA permite identificar as alternativas com melhor desempenho global e, ao mesmo tempo, facilita a comunicação dos resultados aos tomadores de decisão e demais partes interessadas (MÜLLER-CARNEIRO et al., 2023).

Na literatura recente, algumas abordagens metodológicas têm integrado TEA e ACV para avaliar produtos de base biológica em baixos níveis de maturidade tecnológica (TRL, do inglês *Technology Readiness Levels*) no contexto da economia circular. Um exemplo é o estudo de De Sá Filho et al. (2026), que demonstrou a viabilidade técnica de uma biorrefinaria integrada de manga e destacou como diferentes cenários de escala afetam o Valor Presente Líquido (VPL) e os impactos ambientais do ciclo de vida.

De forma semelhante, Meramo et al. (2026) analisaram uma biorrefinaria voltada à obtenção de produtos de alto valor agregado a partir do abacate. Com a integração entre TEA e ACV, os autores mostraram que o projeto é financeiramente viável, embora os custos operacionais com solventes sejam relevantes. Do ponto de vista ambiental, o consumo de energia e vapor foi identificado como o principal gargalo para as emissões de carbono e o uso de recursos. Já Ibáñez et al. (2026) aplicaram o Custo do Ciclo de Vida Ambiental (ELCC, do inglês *Environmental Life Cycle Costing*) para incorporar custos ambientais ao Preço Mínimo de Venda (PMV) na comparação entre o ácido lático e alternativas de origem fóssil.

Por sua vez, Arias et al. (2025) avaliaram a sustentabilidade de uma biorrefinaria de macroalgas marinhas voltada à produção de ficoeritrina, um pigmento natural de alto valor. Nesse estudo, TEA e ACV foram aplicadas de forma integrada, sendo a ACV responsável por fornecer os dados quantitativos necessários ao cálculo dos indicadores ambientais e de circularidade. A análise da circularidade baseou-se em indicadores específicos selecionados a partir de documentos oficiais, como o Pacto Ecológico Europeu (*European Green Deal*) e o ISCC (*International Sustainability and Carbon Certification*).

Apesar do crescente volume de publicações científicas dedicadas à transição para a bioeconomia no setor de alimentos, a análise da literatura internacional revela um gargalo metodológico triplo na avaliação de tecnologias inovadoras em estágios iniciais de desenvolvimento (TRL 4-5). O primeiro refere-se à predominância de análises conduzidas de forma isolada, nas quais a Análise Técnico-Econômica (TEA) e a Avaliação do Ciclo de Vida (ACV) são realizadas separadamente ou apenas colocadas lado a lado, sem harmonização matemática dos inventários nem alinhamento das fronteiras do sistema. O segundo é o caráter determinístico da maioria dos modelos de *up-scaling*, que utilizam parâmetros fixos e, assim, desconsideram as volatilidades intrínsecas dos processos estudados. O terceiro, e mais crítico, é a tendência de tratar sustentabilidade ambiental, especialmente a descarbonização, como equivalente à circularidade material. Com isso, processos considerados eficientes pela baixa pegada de carbono podem ocultar fluxos altamente lineares e dependentes de insumos finitos. Dessa forma, ainda falta uma estrutura metodológica padronizada que integre indicadores biofísicos de circularidade material, como o LFI, à viabilidade macroeconômica e aos impactos ecossistêmicos em um contexto estocástico e multicritério de decisão.

Nesse contexto, esta pesquisa propõe um *framework* TEEC (Tecno-economic, Environmental e Circular) para decisão multicritério no desenvolvimento de processos e produtos alimentícios, em nível TRL 4-5. Esse trabalho está alinhado com os Objetivos de Desenvolvimento Sustentável da ONU (Organização das Nações Unidas), em especial, o de n° 2 (Fome Zero e Agricultura Sustentável) e 12 (Consumo e Produção Responsáveis).

O framework TEEC incorpora Análise de Sensibilidade e Simulação de Monte Carlo. A primeira permite identificar as variáveis críticas que influenciam a viabilidade técnica do processo, enquanto a segunda possibilita avaliar estatisticamente o modelo proposto. Essa integração fortalece a tomada de decisão em projetos de Pesquisa, Desenvolvimento e Inovação (PD&I), ao assegurar que o cenário selecionado seja resiliente tanto às oscilações de mercado quanto às incertezas técnicas da modelagem computacional.

Esse framework foi validado por meio de dois estudos de caso distintos e complementares. No primeiro, baseado no trabalho de SALDANHA et al. (2025), foram avaliadas duas rotas de referência para a produção de Fibra de Caju Desidratada (FCD) a partir do bagaço de caju, resíduo gerado na extração do suco. Ambas incluíram as etapas de lavagem e prensagem da fibra, diferenciando-se na fase de desidratação: a Rota 1 (RR1) utilizou secagem em estufa com circulação de ar forçado, enquanto a Rota 2 (RR2) empregou liofilização. O segundo estudo de caso avaliou o processo de obtenção de um corante vermelho-púrpura a partir da pitaya, que foi desenvolvido por ZOCOLO et al. (2021). Neste estudo, foi avaliada uma única rota de referência que envolve as seguintes etapas: maceração enzimática, microfiltração por membranas e concentração a vácuo.

2. OBJETIVOS

2.1. Objetivo geral

Propor, desenvolver e validar um framework metodológico para a tomada de decisão no escalonamento de tecnologias alimentícias emergentes (TRL 4-5), fundamentado na integração sistêmica entre Análise Técnico-Econômica (TEA), Avaliação do Ciclo de Vida (ACV) *ex-ante* e métricas de circularidade, utilizando o método *Analytic Hierarchy Process* (AHP) e modelagem estocástica como ferramentas de mitigação de incertezas operacionais e de mercado.

2.2. Objetivos específicos

- Simular os balanços de massa, energia e custos operacionais de rotas tecnológicas emergentes em escala industrial, gerando os inventários base para as avaliações de sustentabilidade;
- Determinar a viabilidade econômica dos cenários de referência por meio de indicadores financeiros, tais como o Preço Mínimo de Venda (PMV), Retorno Sobre o Investimento (ROI), Taxa Interna de Retorno (TIR), Valor Presente Líquido (VPL) e Tempo de Retorno Descontado;

- Avaliar os impactos ambientais *ex-ante* das rotas propostas, identificando os principais gargalos (*hotspots*) ao longo do ciclo de vida do processo;
- Mensurar o desempenho circular das rotas tecnológicas por meio de indicadores de fluxo de massa, quantificando o potencial de valorização e reinserção de subprodutos no sistema;
- Modelar a variabilidade dos parâmetros operacionais da escala piloto e as volatilidades de mercado via Simulação de Monte Carlo, estabelecendo perfis probabilísticos de risco para o VPL e para os impactos ambientais;
- Propor e avaliar cenários alternativos de bioeconomia circular direcionados à mitigação dos *hotspots* ambientais previamente identificados;
- Integrar e priorizar os indicadores multidimensionais (TEA-ACV-Circularidade) por meio do método AHP, consolidando uma estrutura hierárquica para a seleção da rota tecnológica ótima para o avanço de TRL.

3. REFERENCIAL TEÓRICO

3.1. A transição do modelo de economia

Ao consolidar a produção em larga escala, a Revolução Industrial transformou os padrões de consumo e impulsionou o crescimento econômico global, mas também intensificou os impactos sobre o meio ambiente (ALVES; FREITAS, 2013; NASCIMENTO, 2012). Esse modelo de economia linear baseia-se na lógica extrativista de "explorar-produzir-consumir-descartar" (*take-make-use-dispose*), o que gera pressão insustentável sobre os sistemas ambientais (UPADHYAY et al., 2021).

Atualmente, o aumento do consumo de energia e a escassez de recursos fósseis agravam as preocupações com as mudanças climáticas, estimulando debates entre governos, academia e setor privado sobre a necessidade de superar esse modelo tradicional (REAÑO, 2020; BRÄNDSTRÖM; SAIDANI, 2022). Além disso, o consumidor tem assumido papel cada vez mais relevante ao demandar sustentabilidade nas cadeias produtivas (WAN; JIANG, 2025).

Nesse contexto, a questão ambiental, antes tratada como secundária, passou a integrar o planejamento estratégico e a própria continuidade dos negócios (SILVA; MORAES; MACHADO, 2015; PEREIRA, 2020). Em contraposição ao modelo tradicional, a economia circular propõe manter os materiais em fluxo contínuo, de modo a dissociar o crescimento econômico da degradação ambiental (DE KONING; KASSAHUN; TEKINERDOGAN, 2024; RIESENER et al., 2023). A União Europeia, por exemplo, prevê que a transição para modelos circulares contribuirá para alcançar a neutralidade climática até 2050 (MORENO et al., 2023).

A aplicação prática da economia circular ganhou espaço nas agendas pública e privada, o que exige indicadores capazes de medir essa transição (STEENMANS; ULFBECK, 2023). Entre as principais métricas estão o MCI e o CTI. O MCI considera três pilares: a massa de matéria-prima virgem, a fração de resíduos não recuperáveis e a utilidade do produto em termos de durabilidade e intensidade de uso (Ellen MacArthur Foundation, 2015). Seu cálculo baseia-se no Índice de Fluxo Linear (LFI), que indica a parcela de material que segue um caminho linear, e no fator de utilidade L(X), responsável por mensurar o efeito da utilidade do produto. Já o framework do CTI oferece uma estrutura padronizada para que empresas avaliem sua circularidade e identifiquem riscos e oportunidades relacionados ao uso de recursos (WBCSD, 2026).

A literatura científica também tem avançado na proposição de métricas mais robustas. Haupt e Hellweg (2019) propuseram o REV (*Retained Environmental Value*), que permite comparar processos de reuso e remanufatura e identificar rotas que realmente substituem recursos primários. Os autores alertam, porém, que métricas exclusivamente mássicas, como taxas de reciclagem, podem desconsiderar impactos ecológicos reais ao longo do ciclo de vida.

Na modelagem computacional, Palomero et al. (2024) integraram indicadores de circularidade ao *software* openLCA®, possibilitando o rastreamento simultâneo dos fluxos de materiais e dos impactos ambientais com base na base de dados ecoinvent.

Gallo et al. (2024) utilizaram o MCI em conjunto com a ACV para analisar o setor agroalimentar a partir de Declarações Ambientais de Produto. Os resultados mostraram que maior circularidade nem sempre implica redução automática dos impactos ambientais, pois esse efeito depende da categoria de impacto considerada e das características específicas do produto.

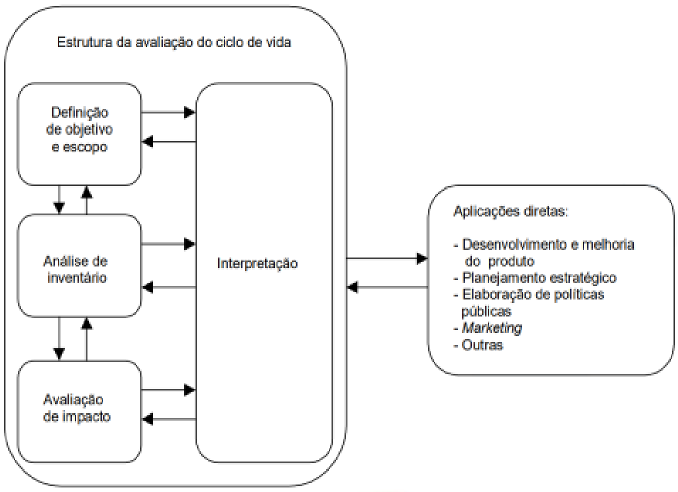
Embora a adoção da economia circular possa gerar benefícios como redução de custos, criação de empregos e vantagem competitiva, ela não elimina a necessidade de uma avaliação ambiental rigorosa (BARROS et al., 2023; DE PASCALE et al., 2021). Por isso, a integração entre métricas de circularidade e ACV é fundamental para assegurar que a transição econômica venha acompanhada da redução efetiva de emissões de gases de efeito estufa (GEE), acidificação e consumo de recursos naturais (BRÄNDSTRÖM; SAIDANI, 2022; MUNOZ; HOSSEINI; CRAWFORD, 2024).

3.2.Análise do Ciclo de Vida (ACV)

O aumento das exigências ambientais e o maior senso crítico do mercado consumidor têm ampliado a demanda por produtos sustentáveis (COELHO FILHO et al., 2016). Nesse contexto, a ACV se consolida como uma ferramenta estratégica para a avaliação abrangente de sistemas, considerando todo o ciclo de vida do produto, da extração das matérias-primas ao descarte final, abordagem conhecida como “do berço ao túmulo” (DE FIGUEIREDO et al., 2007). No setor industrial, essa metodologia permite mensurar o esgotamento de recursos naturais e os impactos ambientais associados (VAN DER WERF; KNUDSEN; CEDERBERG, 2020).

A realização de uma ACV exige o levantamento rigoroso das entradas de energia e materiais, bem como das emissões liberadas nos compartimentos ar, água e solo (QUEIROZ; GARCIA, 2010). De acordo com a norma ABNT NBR ISO 14040 (2009), o estudo deve seguir quatro etapas: i) definição de objetivo e escopo; ii) análise de inventário do ciclo de vida (ICV); iii) avaliação de impactos (AICV); e iv) interpretação dos resultados (Figura 1).

Figura 1: Etapas de uma ACV.



Fonte: ABNT NBR 14040 (2009).

A fase de definição do objetivo e do escopo é fundamental, pois delimita as fronteiras do sistema e a unidade funcional, elementos que orientam toda a modelagem (CLAUDINO; TALAMINI, 2013). Já o ICV corresponde à coleta e à organização dos dados de fluxo e é considerado a etapa mais trabalhosa, devido à necessidade de bases de dados consistentes e da colaboração entre os diferentes elos da cadeia produtiva (CASTRO et al., 2015; CLAUDINO;

TALAMINI, 2013).

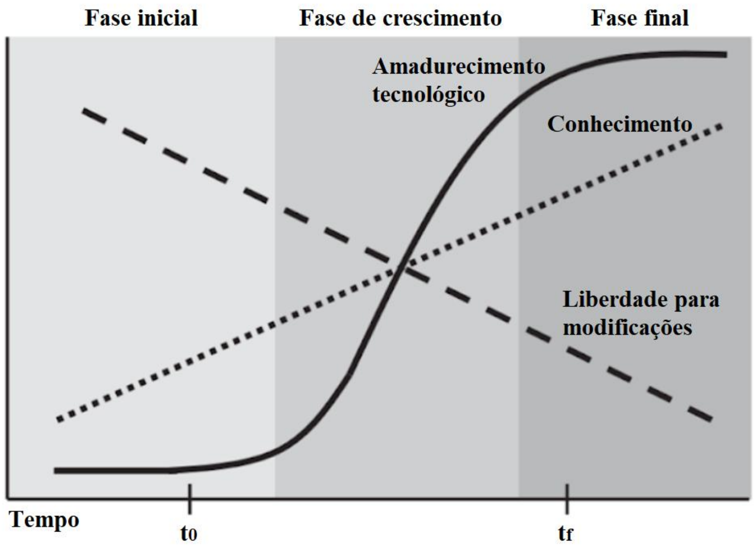
Os dados utilizados podem ser primários, quando coletados diretamente *in loco*, ou secundários, quando provenientes de literatura especializada e bases de dados globais (KULAY, 2004; SAMPAIO et al., 2017). A etapa final da ACV consiste na interpretação dos resultados obtidos no ICV e na AICV. Nessa fase, os achados são analisados e discutidos para subsidiar conclusões, recomendações e decisões coerentes com o objetivo e o escopo previamente estabelecidos (QUEIROZ; GARCIA, 2010).

3.3. Análise do Ciclo de Vida (ACV) *ex-ante*

Avaliar a sustentabilidade nas etapas iniciais do desenvolvimento tecnológico é essencial, pois cerca de 80% dos impactos ambientais de um produto são definidos ainda na fase de projeto (PICCINNO et al., 2016; AKIZU-GARDOKI et al., 2022). No entanto, a ACV tradicional costuma se basear em dados de processos já consolidados, o que pode reduzir sua confiabilidade na análise de tecnologias emergentes, cujos dados laboratoriais ou de escala piloto ainda não representam o desempenho industrial futuro, especialmente em rendimento e eficiência energética (ONAT; KUCUKVAR; TATARI, 2016; TECCHIO et al., 2016).

Nesse contexto, a ACV *ex-ante* surge como uma alternativa para identificar pontos críticos (*hotspots*) nas fases iniciais da pesquisa (LU et al., 2019; KARKA; PAPADOKONSTANTAKIS; KOKOSSIS, 2022). Essa abordagem permite projetar cenários com base em dados modelados em escala industrial, superando as limitações dos estudos em escala de bancada (DELPIERRE et al., 2021; ARVIDSSON et al., 2018). Como mostra a Figura 2, a possibilidade de modificar o projeto diminui à medida que o conhecimento técnico avança; por isso, decisões tomadas nas fases iniciais podem influenciar significativamente o desempenho ambiental e econômico do produto (MONI et al., 2020; BUYLE et al., 2021).

Figura 2: Fases do projeto.



Fonte: ARVIDSSON et al., 2018.

3.4.Análise Técnico-Econômica (TEA)

A viabilidade comercial de inovações tecnológicas depende, necessariamente, de uma análise econômica (MARAVEAS, 2020). Nesse contexto, a TEA é utilizada para avaliar rotas de processo e verificar a viabilidade financeira de projetos por meio de indicadores como Retorno sobre o Investimento (ROI), Tempo de Retorno Descontado (DPB) e Valor Presente Líquido (VPL) (OKE et al., 2022; GOH; LAU; YONG, 2023).

No entanto, a TEA deve ser aplicada em conjunto com a ACV para que os desempenhos econômico e ambiental do projeto sejam avaliados de forma integrada (ORTIZ, 2020). Em baixos níveis de maturidade tecnológica, essa combinação fornece informações mais robustas e consistentes para a tomada de decisão, permitindo que as partes interessadas avaliem com mais segurança a continuidade dos investimentos no projeto (MAHMUD et al., 2021; FABER; MANGIN; SICK, 2021).

Embora tecnologias emergentes possam impulsionar a economia circular, a avaliação de suas incertezas ainda é desafiadora devido ao baixo nível de maturidade tecnológica (TRL) (TSAGKARI et al., 2016). A literatura também destaca a falta de diretrizes padronizadas para integrar TEA e ACV nas etapas de PD&I, apesar do potencial analítico dessa combinação (DE QUEIROZ et al., 2026). Nesse cenário, simuladores de processos, como Aspen Plus® e SuperPro Designer®, têm papel central na previsão do comportamento de plantas industriais, ao fornecer dados que fortalecem as análises de inventário e de custos (BAAQEL et al., 2023; DE QUEIROZ et al., 2026).

Estudos recentes ilustram essa integração. De Queiroz et al. (2026) mostraram que a extração de colágeno a partir da pele de tilápia, embora tecnicamente viável, ainda requer otimizações significativas para competir com alternativas comerciais, devido aos altos custos e aos impactos ecológicos. De Sá Filho et al. (2026) identificaram a recuperação de pectina em biorrefinarias de manga como o principal gargalo produtivo, recomendando modelos mais simplificados para assegurar a rentabilidade. Já David et al. (2025) destacam que, na fermentação de precisão, a abordagem sistêmica proporcionada pela integração entre TEA e ACV é essencial para evitar o deslocamento de impactos ambientais e sustentar a viabilidade comercial. Em síntese, a modelagem em escala industrial gera dados que permitem antecipar impactos ambientais e econômicos, orientar o desenvolvimento do projeto e aumentar a confiança das partes interessadas na aplicação da nova tecnologia (LU et al., 2019; DA CUNHA RODRIGUES et al., 2025).

3.5.Análise Multicritério e tomada de decisão

Segundo Waas et al. (2014), tratar o desenvolvimento sustentável como uma estratégia de decisão torna sua aplicação prática mais efetiva, conferindo-lhe potencial para orientar ações concretas. Nesse contexto, os métodos de Apoio Multicritério à Decisão (MCDA) oferecem uma estrutura sistemática para integrar diferentes fontes de informação e comparar alternativas complexas com base em múltiplos critérios (REBELO; FARABEGOLI, 2025).

Entre os métodos de MCDA, destaca-se o AHP, proposto por Saaty (2001). Esse método organiza o problema em uma hierarquia composta por objetivos, critérios e alternativas, que são comparados par a par com base na escala fundamental de Saaty (Tabela 1). Esses julgamentos, realizados por especialistas, transformam percepções qualitativas em vetores quantitativos de prioridade (VAIDYA; KUMAR, 2006). Além disso, o AHP permite desdobrar critérios em subcritérios, refinando o processo de ponderação conforme os pesos relativos atribuídos (DOUMPOS; ZOPOUNIDIS; GALARIOTIS, 2014; MEHRA et al., 2023).

A consistência matemática da matriz de decisão é verificada por meio do autovalor principal (λmax), do Índice de Consistência (IC) e da Razão de Consistência (RC). O λmax expressa a coerência interna dos julgamentos: em uma matriz perfeitamente consistente, seu valor é igual ao número de critérios (n), enquanto valores superiores indicam inconsistências lógicas nas preferências estabelecidas (SAATY, 2001). Já o IC mede a magnitude dessas inconsistências, conforme a Equação 1.

$$IC = \frac{\lambda_{max} - n}{n - 1}$$ Equação 1.

Por fim, a RC é calculada pela razão entre o IC e um Índice Aleatório (IA) tabelado (Tabela 2). Esse indicador funciona como parâmetro de confiabilidade do modelo: valores de RC $\leq 0{,}10$ indicam que as comparações apresentam consistência estatística e que o vetor de pesos obtido é robusto para apoiar a tomada de decisão (SAATY, 2001; MUNOZ; HOSSEINI; CRAWFORD, 2024). Em síntese, o método AHP permite medir e sintetizar, de forma hierárquica, diferentes fatores envolvidos em um processo decisório complexo, facilitando a integração das partes em um todo coerente (RUSSO; CAMANHO, 2015).

Tabela 1: Escala fundamental de Saaty.

Intensidade de importância	**Definição**
1	"A" é igualmente preferível a "B"
2	"A" é igual a moderadamente preferível sobre "B"
3	"A" é moderadamente preferível sobre "B"
4	"A" é moderada a fortemente preferível sobre "B"
5	"A" é fortemente preferível sobre "B"
6	"A" é fortemente a muito fortemente preferível sobre "B"
7	"A" é muito fortemente preferível sobre "B"
8	"A" é muito forte a extremamente preferível sobre "B"
9	"A" é extremamente preferível sobre "B"

Fonte: Saaty (2001).

Tabela 2: Índice médio de consistência aleatória (R.I.).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
IA	0	0	0,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49

Fonte: Saaty (2001).

3.6.A importância do desenvolvimento de produtos sustentáveis

3.6.1. Corantes naturais

A cor é um atributo sensorial central na aparência dos alimentos, pois influencia a percepção de qualidade do consumidor e, consequentemente, sua aceitação e intenção de compra (WOO, 2011; AZEREDO et al., 2009). Entretanto, muitos aditivos usados para conferir cor aos alimentos são sintéticos e podem representar riscos à saúde humana (PAVOKOVIĆ; KRSNIK-RASOL, 2011).

Com a crescente demanda por alimentos mais saudáveis e o endurecimento das normas que limitam o uso de aditivos artificiais, a indústria alimentícia tem buscado novas fontes de corantes. Nesse cenário, os corantes naturais, especialmente os de origem vegetal, têm ganhado espaço na formulação de produtos (WOO, 2011; PAVOKOVIĆ; KRSNIK-RASOL, 2011).

Entre esses compostos, destacam-se as betalaínas, pigmentos nitrogenados hidrossolúveis (DE MELLO et al., 2014), que vêm se consolidando como substitutos relevantes dos corantes vermelhos artificiais em alimentos como sucos, doces e iogurtes (LEONG et al., 2018; FU et al., 2020). Além da função de coloração, as betalaínas apresentam propriedades bioativas, como atividades antioxidante, anti-inflamatória, antimutagênica e antirreumática, que podem beneficiar a saúde do consumidor (SINGH et al., 2023).

O mercado de corantes naturais tem crescido mais rapidamente que o de corantes sintéticos, impulsionado sobretudo pela indústria de alimentos (BOERIU, 2015). Estima-se que esse setor movimente cerca de 2,3 bilhões de dólares no mercado global, com taxa anual de crescimento de 4,6% (PRAJAPATI; JADEJA, 2022). Esse panorama reforça a importância de buscar fontes alternativas de pigmentos naturais e ampliar sua oferta comercial (STINTZING; CARLE, 2004).

A pitaya de polpa vermelha (*Hylocereus polyrhizus*) destaca-se como fonte promissora de betalaínas, por ser a única fruta comercializada em larga escala que concentra esses compostos tanto na casca quanto na polpa (QINGZHU et al., 2016; XIE et al., 2020). Além da intensa coloração vermelho-púrpura, as betalaínas extraídas da pitaya possuem propriedades antioxidantes, o que tem estimulado estudos voltados ao desenvolvimento de alimentos funcionais (GENGATHARAN; DYKES; CHOO, 2016; DE LIMA et al., 2020; DE SOUSA SILVA et al., 2024).

Apesar do potencial dessas moléculas, as betalaínas apresentam baixa estabilidade térmica e sofrem degradação significativa em temperaturas acima de 50 °C, o que dificulta seu processamento industrial (REYNOSO et al., 1997; FU et al., 2020). Nesse contexto, a filtração por membranas surge como alternativa promissora para sua extração, pois opera entre 4 e 50 °C e reduz as perdas causadas pela degradação térmica (GIRARD; FUKUMOTO, 2000; FU et al., 2020).

Diversos estudos têm investigado a combinação de tratamentos enzimáticos prévios com a filtração por membranas para aumentar a eficiência de extração. Ushikubo, Watanabe e Viotto (2007), por exemplo, aplicaram maceração enzimática antes da microfiltração do suco de umbu (Spondias tuberosa Arr. Cam.). Mais recentemente, De Lima et al. (2020) obtiveram, em escala piloto, um concentrado líquido de pitaya rico em betalaínas por meio da microfiltração precedida de maceração enzimática da polpa.

Diante desse cenário, pesquisas voltadas à extração de betalaínas em escala industrial tornam-se cada vez mais relevantes, pois contribuem para aperfeiçoar processos convencionais e ampliar a comercialização desses compostos (VISOCKIS et al., 2021).

3.6.2. Uso de resíduos agrícolas para produção de proteínas alternativas

O cajueiro (*Anacardium occidentale* L.) produz o caju, fruto sazonal formado pela castanha, que corresponde ao fruto verdadeiro, e pelo pedúnculo, também chamado de pseudofruto (DAS; ARORA, 2017). Adaptada a climas tropicais e solos arenosos, essa cultura perene tem grande relevância socioeconômica em países emergentes e subdesenvolvidos (DE OLIVEIRA et al., 2020). O Brasil está entre os principais produtores mundiais, atrás de Costa do Marfim, Vietnã, Nigéria e Índia (SAHIE et al., 2023), com produção fortemente concentrada no Nordeste, responsável por 99,7% da área cultivada (ASSIS, 2007; BRAINER, 2022).

Embora a amêndoa da castanha seja o principal produto de exportação (SAHIE et al., 2023; DE FRANÇA SERPA et al., 2020), o pedúnculo ainda é pouco aproveitado, apesar de seu alto teor de ácido ascórbico e de seu potencial para a indústria de bebidas (AKYEREKO et al., 2023). Sua elevada perecibilidade, com estabilidade de apenas 24 a 48 horas após a colheita, limita a comercialização e faz com que somente cerca de 10% da produção seja processada industrialmente (SINGH et al., 2019; TALASILA; SHAIK, 2015). Após a retirada da castanha, o restante costuma ser descartado no campo, revelando uma falha na agregação de valor que compromete a sustentabilidade da cadeia produtiva da cajucultura (HONORATO et al., 2007; DEDEHOU et al., 2016).

Outro desafio importante é a destinação do Bagaço de Caju (BC), subproduto gerado após a extração do suco e que representa cerca de 20% do peso total do fruto (PROMMAJAK; LEKSAWASDI; RATTANAPANONE, 2014). Composto por celulose (18,31%), hemicelulose (27,18%) e lignina (23,91%), o BC apresenta amplo potencial de valorização (DOS SANTOS LIMA, 2012; SILVA et al., 2018). Estudos recentes apontam aplicações variadas, como produção de barreiras acústicas e briquetes (LAWAN et al., 2023), obtenção de etanol (ROCHA et al., 2011), lignina e ácido lático (DE FRANÇA SERPA, 2020; JÚNIOR et al., 2024).

Também se destaca a conversão do BC em Fibra de Caju Desidratada (FCD), um ingrediente promissor para o mercado de alimentos *plant-based* (LIMA et al., 2014). Estudos de Saldanha et al. (2025) e Portela et al. (2023) validaram o uso da FCD em formulações de croquetes e vatapá, respectivamente, com resultados satisfatórios de aceitação sensorial. O aproveitamento sistemático desse resíduo pode impulsionar o desenvolvimento regional e a geração de empregos (AIDOO; KWOFIE; NGADI, 2022), além de contribuir para as metas globais de redução do desperdício de alimentos previstas na Agenda 2030 da ONU (DA SILVA GOIANA et al., 2025).

No entanto, a passagem dessas inovações da escala laboratorial para a industrial requer a comprovação de sua viabilidade técnica, econômica e ambiental (AMEZCUA-ALLIERI et al., 2019). Nesse cenário, a integração entre ferramentas analíticas como TEA e ACV é essencial para reduzir riscos e garantir que o desenvolvimento de novos bioprocessos esteja alinhado aos princípios da sustentabilidade industrial (BHARATHIRAJA et al., 2022; HELLVIG; FLORES-SAHAGUN; CURADO, 2024).

4. ARTIGOS

Esta seção apresenta os resultados centrais desta pesquisa, estruturados na forma de dois artigos científicos originais, desenvolvidos de maneira complementar para validação do framework TEEC (Análise Técnico-Econômica, Ambiental e de Circularidade).

4.1. Artigo 1

Integrated Techno-Economic and ex-ante Life Cycle Assessment of Cashew Apple Fiber, an ingredient for plant-based products

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Keywords: Circular Bioeconomy, Techno-Economic Analysis (TEA), Life Cycle Assessment (LCA), Agro-industrial Waste Valorization, Process Simulation.

Abstract

In the cashew processing chain, approximately 10% of production is directed to juice extraction, and about 10% of this fraction becomes cashew bagasse. Scaling up technological routes that convert this residue into plant-based food ingredients is limited by insufficient knowledge regarding their techno-economic and environmental feasibility. This study conducted an ex-ante evaluation of producing Dehydrated Cashew Fiber (DCF) via conventional oven-drying (Route 1) or freeze-drying (Route 2). The integrated methodological framework comprised six stages: (i) scope definition; (ii) pilot-scale data collection; (iii) industrial scaling-up; (iv) Techno-Economic Analysis (TEA); (v) Life Cycle Assessment (LCA); and (vi) multi-criteria decision analysis using the Analytic Hierarchy Process (AHP). Industrial-scale simulations were generated from pilot-scale data using SuperPro Designer v.11, while environmental performance was evaluated in SimaPro v.10.2.0. The TEA employed Return on Investment (ROI), Discounted Payback Time (DPBT), and Minimum Selling Price (MSP), supported by sensitivity analyses of processed capacity (3, 6, 9, and 12 t batch^{-1}) and economic risk assessment via Monte Carlo simulations. For each route, the plant configurations showing the highest economic viability were then assessed using the Product Environmental Footprint (PEF) method to identify hotspots and explore alternative utility scenarios. Route 1 optimized at 6 t batch^{-1} showed the lowest baseline MSP (USD 12.17 kg^{-1}),

while Route 2 was most favorable at 9 t batch^{-1} (USD 40.47 kg^{-1}). Under commercial pricing conditions, the ROI (~16.18%) and DPBT (~16.09 years), although acceptable within the Brazilian macroeconomic context, indicate the need for financial optimization to enhance investor appeal. The ex-ante LCA showed that global Climate Change and Fossil Resource Use categories were highly sensitive to process scaling and utility energy mix configurations. Multi-criteria analysis via AHP identified Route 1 at 6 t batch^{-1}, fully powered by an electrified solar photovoltaic mix for both electricity and heat (SC3-RR1-6T), as the most sustainable alternative (global priority score of 0.1761). The integrated TEA-LCA-Circularity framework demonstrated here offers a robust, high-throughput, and replicable approach for guiding decision-making in emerging circular bioeconomy technologies.

1. Introduction

The increase in the world's population brings several challenges, including the growing demand for food and the management of food waste, the latter causing negative impacts on the environment and the economy (Agraso-Otero; Rebolledo-Leiva; González-García, 2025; Tamasiga et al., 2022). The agro-industrial sector of fruit and vegetable processing is one of the main contributors to the generation of organic waste. This puts significant pressure on the sector to optimize resource use (Cano-Gómez et al., 2025).

The circular economy (CE) is a production and consumption model that aims to minimize waste (Agraso-Otero et al., 2025). Another related model is the circular bioeconomy (CBE), which incorporates the principles of the CE but focuses on renewable biological resources (Khanna et al., 2024). One way to achieve the goal of these models is to develop processes that convert residual biomass into value-added products (Moonsamy et al., 2024).

Numerous studies seek to develop processes in the context of BCE or CE. For example, Vieira et al. (2026) worked on the valorization of avocado waste (peels and seeds), transforming them into sustainable sources of phenolic compounds. Cordeiro et al. (2024) obtained activated carbon from banana waste. Ekloh and Yafetto (2024) investigated the valorization of watermelon rind waste to produce nutritious animal feed.

The cashew tree (Anacardium occidentale L.) is an important tropical fruit tree, its main products being the cashew nut, cashew nutshell liquid (CNSL), and the cashew fruit (Santos et al., 2007). The cashew bagasse (CB) is the agro-industrial subproduct of cashew processing (Fonteles et al., 2016; Aslam et al., 2024). The physicochemical characterization of CB was carried out by Barroso et al (2025), which revealed that this biomass is rich in dietary fiber (45%), proteins, and bioactive compounds, such as anacardic acids and flavonoids, which have antioxidants and anti-inflammatory properties. Furthermore, due to its thermal stability up to 360 °C and fibrous structure, the residue proves ideal for applications in functional foods, biopolymers, and bioenergy.

In literature, there are studies that utilize CB to obtain lactic acid (Junior et al., 2024), and to produce functional food ingredients rich in phenolic compounds (de Sena Andrade et al., 2023). Another possibility is obtaining Dehydrated Cashew Fiber (DCF) for use as an ingredient in plant-based foods, such as vatapá (Portela et al., 2023) and croquettes (Saldanha et al., 2025), products that have shown good acceptance in sensory analyses. DCF's production is directly aligned with Sustainable Development Goals (SDGs) No. 2 and 12, developed by the United Nations (UN), and with the concepts of CE and CBE.

However, a key barrier to scaling emerging routes that convert agro-industrial residues into value-added products is the limited understanding of their technical-economic and environmental feasibility (Amezcua-Allieri et al., 2019; Agraso-Otero, Rebolledo-Leiva, and Gonzalez-García, 2025). The integration of Techno-Economic Analysis (TEA) with Life Cycle Assessment (LCA) is of great relevance to support the decision of which process to choose for scaling up production, reducing investment risks and potential environmental impacts (Almeida et al., 2024).

TEA is a tool that aims to assist in the development of a product or process, helping it reaches commercial scale (Bharathiraja et al., 2022). Ex-ante LCA applied to processes and products under development makes it possible to identify critical points and investigate improvements from lab experiments (Karka et al., 2022), and complements TEA in the evaluation of emerging technologies (De Sá Filho et al., 2026; De Queiroz et al., 2026). These two tools enable improvements in the initial development phases and increase the chances of investment in these new technologies (Cucurachi; van der Giesen; Guinée, 2018; Davidson et al., 2021).

Several studies present methodological approaches for integrating TEA and traditional or Ex-ante LCA in the evaluation of technologies in the early stages of development in the context of BCE. Agraso-Otero, Rebolledo-Leiva, and Gonzalez-García (2025) analyzed the environmental and economic viability of a biorefinery designed to process tomato industry waste for the extraction of seed oil and pectin. Alherbawi et al. (2024) analyzed the pyrolysis of vegetable waste (cucumber, tomato, and carrot) to produce bioproducts such as bio-oil, biochar, and synthesis gas. De Sá Filho et al (2026) evaluated a mango biorefinery to produce pulp, starch, pectin, lignin and cellulose. Qing Jin et al. (2025) developed an innovative biorefinery model focused on the production of sugars from various food wastes.

Finally, Arias et al (2025), in addition to applying TEA and LCA to the process of obtaining R-phycoerythrin, also applied process circularity analysis. All the works mentioned above fall within the perspective of a BCE or CE; however, only one applied a metric aimed at measuring the level of circularity of the developed process. Thus, a gap is noted in studies that integrate TEA-LCA and circularity metrics.

According to Munonye (2025), circular thinking is not just a political trend or a buzzword, but a crucial reshaping of how modern economies can function. Circular business models and how they can be profitable have been a relevant topic in industry, government agencies, and academia (Chen; Hung; Ma, 2020).

For an industry to be aligned with a circular and sustainable economic model, it is essential to assess its circularity potential (Edirisinghe et al., 2024). Integrating circularity analysis with TEA and LCA assessments in the initial phase of the project is crucial, as it increases the probability that the plant will be implemented based on a circular model from the outset. This avoids additional costs associated with changing from linear to circular processes (Tleuken et al., 2026). Furthermore, the industry is already complying with new legislation that tends to be increasingly demanding in environmental matters.

In this context, the present work aims to evaluate the technical-economic, environmental and circularity viability of alternative routes for obtaining DCF, currently tested on a pilot scale (Saldanha et al., 2025), through a multi-criteria approach that considers the principles of circular bioeconomy.

This approach initially determines the most economically favorable production condition for each route, then evaluates its critical environmental points and investigates improvement scenarios. The baseline routes and scenarios are compared using multi-criteria analysis, which allows identifying the best-performing route, supporting decision-making in the Research, Development and Innovation (R&DI) process.

2. Materials and Methods

2.1. Methodological Approach

The integrated Tecno-economic, Environment and Circularity analysis (TEEC) with study case of DCF production, was performed following the steps described in Figure 1: i) Scope definition; ii) Data collection; iii) Scaling-up of technological routes; iv) TEA; v) ex-ante LCA; vi) Circularity Analysis; and vii) Multi-criteria Analysis.

In step 1, the reference routes (RRs) for the DCF production process at the pilot scale were based on research developed by Saldanha et al. (2025). Furthermore, the overarching system boundary and the functional unit were established to guide the subsequent technical-economic, and environmental assessments.

In step 2, data on inputs and outputs of the unit processes of each route, as well as other processes related to the DCF system, were collected through mass balances at the pilot scale. Furthermore, the production conditions with the best yield, types and costs of industrial equipment with functions equivalent to those at the pilot scale, and the costs of inputs and labor were identified.

In step 3, the data collected at the pilot scale were used to model each reference route at the industrial scale using simulation software. This modeling generated new mass and energy balances, which formed the basis for conducting the TEA and ex-ante LCA. Furthermore, a sensitivity analysis was performed to examine different plant capacities, while a Monte Carlo Simulation (MCS) was employed to model the uncertainty of drying performance, thereby generating discrete operational alternatives for each plant size.

Within step 4, the TEA was performed for all simulation models (RRs, operational alternatives, and improvement scenarios generated in step 5) to evaluate key economic indicators: return on investment (ROI), discounted payback time (DPBT), net present value (NPV), and minimum selling price (MSP). The MSP was determined when the NPV was equal to zero (Melitos et al., 2025), while the other economic feasibility indexes were calculated according to methodologies proposed in the literature (Cucchiella, D'Adamo and Gastaldi, 2019; Towler and Sinnott, 2021). Upon establishing the processing capacity with the best economic performance for each route, a 10% markup was applied over the MSP to determine the Product Selling Price (PSP). Furthermore, an economic risk analysis was performed via MCS to evaluate the impact of discount rate fluctuations on the NPV for these optimal plant sizes, considering both the MSP and the PSP scenarios.

In step 5, the ex-ante LCA was executed exclusively for the processing capacities of each route that demonstrated the best financial performance. This assessment was carried out following methodology developed by Müller-Carneiro et al. (2023), and ISO's 14040 and 14044 (ISO, 2006a; ISO 2006b). The Product Environmental Footprint (PEF) method was employed to assess the impact categories. To investigate critical points, the categories representing at least 80% of the normalized and weighted results were initially identified (Zampori and Pant, 2019). Subsequently, potential process improvements addressing these critical points were proposed based on circular bioeconomy principles (Stegmann, Londo, and Junginger, 2020).

Promising modifications were then organized into new improvement scenarios. These new improvement scenarios were directly modeled in simulation software (step 3) and immediately subjected to economic, environmental, and circularity assessments (steps 4 to 6). The PSP (step 5) was also determined for the improvement scenarios; however, it is important to emphasize that, unlike the baseline models, no MCS was applied to these improvement scenarios at any stage of their evaluation. This exclusion occurs because the new improvement scenarios consist of theoretical prospective models, thus lacking the experimental variance data required for the stochastic modeling of drying performance (step 3). Furthermore, the economic risk assessment via MCS (step 4) was methodologically restricted to validating the optimized baseline routes, rather than being applied to exploratory alternatives.

In step 6, circularity is assessed for the reference routes and the proposed improvement scenarios. This assessment uses the Linear Flow Index (LFI) as an indirect measure of circularity, taking production losses into account (Ellen MacArthur Foundation [EMF] & Granta Design, 2015). According to Vásquez-Cabrera et al. (2025), the LFI varies according to the circularity strategy adopted. In this framework, it measures the share of material that remains in a linear flow relative to the total material input of a technological route, which explicitly encompasses the mass flows of the cashew fiber biomass as well as the water utilized throughout the process (including water for washing the fiber and the equipment).

Finally, a multicriteria analysis (step 7) was conducted using the AHP (Analytic Hierarchy Process) method (Saaty, 1990) to evaluate the indicators of the reference routes and the proposed improvement scenarios. In accordance with the AHP methodology, the relative weights of the economic, environmental, and circularity criteria were assigned by an expert from each respective field. This expert-driven evaluation allowed for the hierarchization of alternatives, ultimately indicating the configuration with the best overall performance.

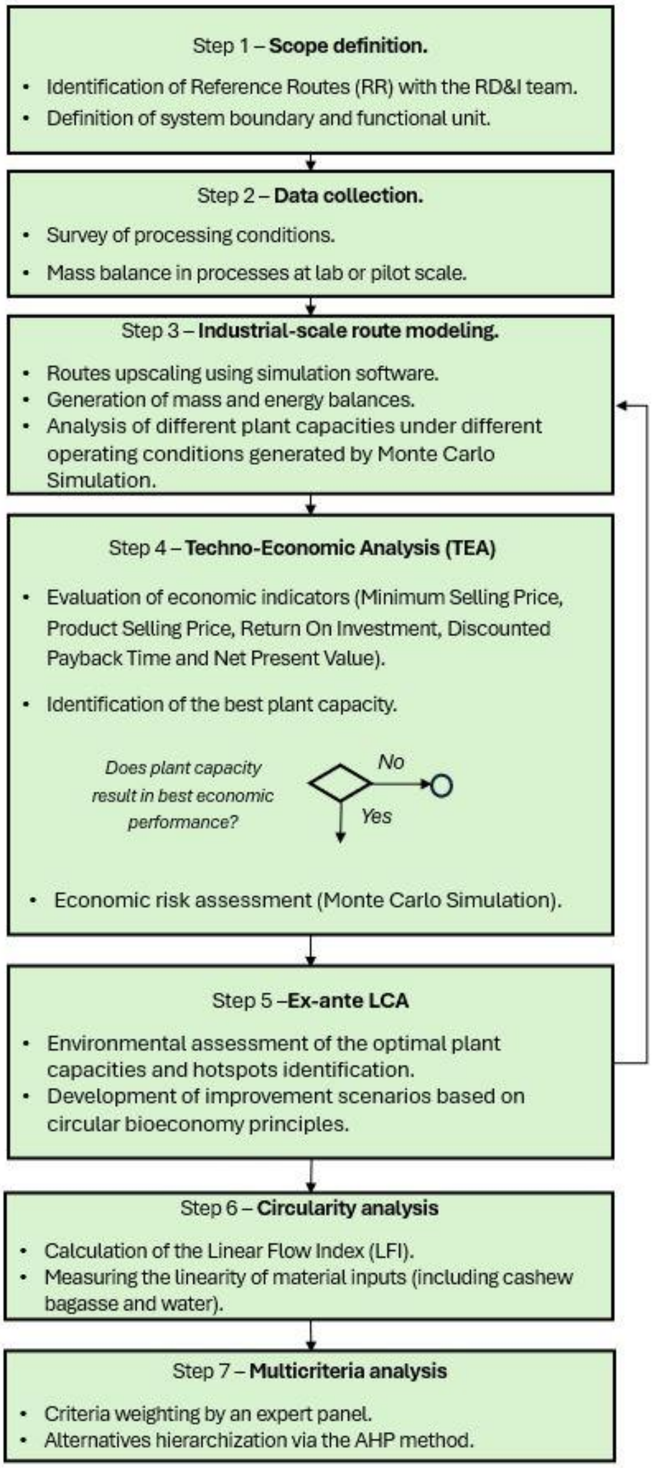

Figure 1. Flowchart illustrates the methodological approach used in this research.

2.2. Integrated DCF Analysis

Applying the scope defined in step 1, the integrated assessment of DCF evaluated two baseline fiber dehydration routes: drying in a forced-air circulation oven (RR1) and freeze-drying (RR2). The established system boundary encompassed the agricultural production, pulp extraction, and DCF production processes, adopting 1 kg of dehydrated fiber as the functional unit (Figure 2).

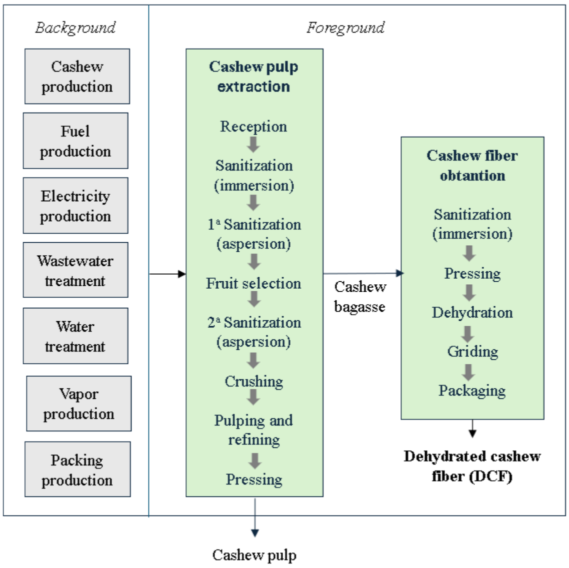

Figure 2. System boundary schematics.

During data collection (step 2), information regarding the agricultural production process was in accordance with Sales et al. (2025). Data and processing conditions for pulp extraction were gathered through interviews with the management of a cashew processing company located in the state of Ceará, Brazil. A description of the juice extraction process is available in Supplementary information (SI) in section 1. Data on DCF production were collected at a pilot plant located at the Brazilian Agricultural Research Corporation (Embrapa), through mass balances in the unit processes. The process description, as well as the collected data, are in section 2 and Table S1, respectively.

For step 3 (Scaling-up), the baseline plant models for each route were built in SuperPro Designer® (SPD) v.11 software (Intelligen, Inc., Scotch Plains, NJ, USA). The plants were designed to be coupled to a cashew apple processing line that typically handles 90 t day^{-1} of raw fruit and generates 9 t day^{-1} of bagasse for 90 days a year. Thus, the baseline RR plants were modeled with a processing capacity of 9 tons of bagasse per batch. Additionally, a scale-related sensitivity analysis was performed by implementing processing variations of 3, 6, and 12 tons of bagasse per batch for each RR. The selection of these operating capacities was based on specific process constraints: (i) the base capacity of 9 tons prevents the need for cold storage of the highly perishable raw bagasse; (ii) for capacities of 3 and 6-ton, the remaining biomass is treated as a waste stream from cashew processing; and (iii) the 12-ton scale simulates an optimistic high-crop season.

Hereafter, these variations are referred to as RR1-X or RR2-X, where RR denotes the processing route and X indicates the batch size (3, 6, 9, or 12 t · batch^{-1}). Moreover, to account for the experimental variability of the final product moisture, this parameter was treated as a stochastic variable. Based on experimental data (mean and standard deviation), a MCS with 10,000 iterations was performed to model the uncertainty of the drying performance. From the MCS output, three discrete operational alternatives were defined using percentiles: a 5th percentile (P5) representing the lower moisture bound (optimistic alternative regarding product stability and quality), a 50th percentile (P50) for the typical moisture (realistic alternative), and a 95th percentile (P95) representing the upper moisture bound (pessimistic alternative regarding final product moisture content). Consequently, these moisture percentiles were combined with the four plant capacities, resulting in 12 distinct simulation models evaluated in SPD for each RR. The plant diagrams at the industrial scale and their description are found in section 4 of SI, while the inventories of the pulp extraction and DCF processes (RR1-9T and RR2-9T) are in Tables 1 and 2, respectively.

Table 1. Inventory of annual cashew pulp extraction.

Inputs and Outputs	Inventories of ecoinvent v. 3.9.1 and literature	Unity	Annual quantity
Product output			
Cashew pulp		ton.	7,290.00
Cashew bagasse		ton.	684.00
Inputs			
Cashew	Sales et al (2025)	ton.	8,100.00
Water		m^3	600,000.00
Chlorine	Chlorine, liquid {RoW}| market for chlorine, liquid | Cut-off, U	ton.	1.29
Sodium Carbonate	Soda ash, light {RoW}| market for soda ash, light | Cut-off, U	ton.	2.25
Electricity	Electricity, high voltage {BR-North-eastern grid}| market for electricity, high voltage | Cut-off, U	kW h^{-1}	410343
Polyethylene	Polyethylene terephthalate, granulate, bottle grade {RoW}|polyethylene terephthalate, granulate, bottle grade, recycled to generic	ton.	0.129

	market for bottle grade PET granulate | Cut-off,U		
Waste and emissions for treatment			
Solid waste	Biowaste {RoW} Modified | treatment of biowaste, industrial composting | Cut-off, U	ton.	126.00
Wastewater	Wastewater, average {RoW} Modified| treatment of wastewater, average, wastewater treatment | Cut-off, U	m^3	10,000.00

Table 2. Inventory of annual DCF extraction on an industrial scale.

Inputs and outputs	**Inventories of ecoinvent v. 3.9.1**	**Unity**	**Annual quantity**	
			RR1-9T	**RR2-9T**
Product output				
DCF		ton.	333.94	325.16
Inputs				
Cashew bagasse	Cashew pulp production	ton.	1404.00	1386.00
Cardboard boxes	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	ton.	3.34	3.25
Plastic packaging	Polyethylene terephthalate, granulate, bottle grade {RoW}| polyethylene terephthalate, granulate, bottle grade, recycled to generic market for bottle grade PET granulate | Cut-off, U	ton.	0.67	0.65
Chlorine	Chlorine, liquid {RoW}| market for chlorine, liquid | Cut-off, U	ton.	2.99	2.95
Water		m^3	3,405.65	3,361.99
Electricity	Electricity, high voltage {BR-North-eastern grid} | market for electricity, high voltage | Cut-off, U	MW h^{-1}	1,67	3,37
Steam	Steam, in chemical industry {RoW}| market for steam, in chemical industry | Cut-off, U	ton.	472.00	466.00
Waste and emissions for treatment				

Solid waste	Biowaste {RoW} Modified | treatment of biowaste, industrial composting | Cut-off, U	ton.	60.04	59.27
Wastewater	Wastewater, average {RoW} Modified| treatment of wastewater, average, wastewater treatment | Cut-off, U	m^3	2,806.87	2,771,06

For the TEA (step 4) of the routes modeled at the industrial scale, considering the 12 distinct simulation models per route previously defined, a discount rate of 10.96% per year was applied to calculate the previously described economic indicators. This value reflects the average basic interest rate (Selic Rate) for the year 2024 (Central Bank of Brazil, 2025) and does not represent a mandatory standard for other applications. The choice aligns with the principle that the minimum acceptable rate of return should reflect the highest earning rate on safe investments available to investors, such as government bonds (Timmerhaus and West, 2004). In Brazil, the Selic rate represents this risk-free baseline.

Purchase equipment costs were estimated using the software's database, which is updated according to CEPCI (Petrides et al., 2000). When it was not possible to obtain the equipment values from the database, the acquisition costs were estimated according to the equation proposed by Russo et al. (2022) using estimated prices in the local market. The costs of materials and other relevant information for the economic analysis are detailed in Table 3.

Table 3. Parameters used in the plant configuration in SuperPro Designer.

Parameters	Values	Reference
Location	Brazil	
Reference year	2024	
Project lifetime	25 years	
Construction period	2.5 years	
Startup period	4 months	
Income taxes	25%	Brazil (2023)
US Dollar to Brazilian Real exchange rate	R$ 5.39	Central Bank of Brazil (2025)
Depreciation period (straight-line method)	10 years	
Cost of cashew bagasse	R$ 0.00 kg^{-1}	
Water cost (m^3)	US$ 9.83	CAGECE

Electricity costs (kw·h^{-1})	US$ 0.15	ENEL
Chlorine (kg^{-1}) [a]	US$ 9.70	
Cost of the operator's working hour	US$ 4.55	Ministério do Trabalho
Cost of the supervisor's working hour	US$ 5.82	Ministério do Trabalho

[a] Price determined by consultation with local businesses.

Based on the analysis of previously described economic indicators, the processing capacity of each route with the best economic performance was determined. For these optimal configurations, a 10% markup was applied over the base cost directly within the SPD economic evaluation module to determine the Product Selling Price (PSP). Subsequently, an economic risk analysis was carried out exclusively for these selected plant sizes using a second MCS. Based on the procedure proposed by Bruni, Famá, and Siqueira (1998), the average (8.75%) and standard deviation (4.47%) of the Selic rate between the years 2020 and 2024 were used in the MCS to generate ten thousand random values for the discount rate. Consequently, ten thousand NPV values were calculated based on the cash flows of the optimal routes identified, evaluating the alternatives under both the baseline MSP and the newly defined PSP.

After the economic assessment, the ex-ante LCA (step 5) was carried out only for the processing capacities of each route that showed the best financial performance. This analysis identified the main critical points and supported the development of improvement scenarios, which were also evaluated from an environmental perspective. This environmental impact evaluation was carried out using SimaPro v.10.2.0 software (PRé Sustainability, Netherlands) combined with the ecoinvent database (v.3.9.1).

The improvement scenarios were defined after identifying the main environmental hot spots in the two most economically viable routes and applying principles of the circular bioeconomy to address them (Table 4). Although waste treatment was not the main hotspot, improvement scenario 1 (SC1-RR1-6T and SC1-RR2-9T) explored the use of liquid effluent for carotenoids extraction (Concentrate liquid).

No studies were identified on specific uses for the solid waste generated during pressing; therefore, no reuse scenarios were proposed, although its characterization is recommended to support future valorization. Evaporated water was excluded from environmental and circularity analyses.

Improvement scenario 2 (SC2-RR1-6T and SC2-RR2-9T) replaced the hydroelectric energy mix with a photovoltaic energy mix to meet the equipment demand. Scenario 3 (SC3-

RR1-6T and SC3-RR2-9T) extended this replacement to both the operation of the equipment and the generation of heat for washing the bagasse. Inventories and flow diagrams for all scenarios are provided in Tables S2 and Figures S3–S6, respectively.

Table 4. Improvement Scenarios definition.

Environmental hotspots	**Circular of principles of the bioeconomy**	**Improvement based on the BCE**	**Improvement Scenarios**	**Premise**
Wastewater treatment	Use of waste and residues as a resource	Converting wastewater into value-added products	SC1-RR1-6T and SC1-RR2-9T	Theoretical (speculative) scenario, based on literature (De Abreu, 2012) suggests that effluent contains carotenoids. No laboratory experiment was performed. The Vacuum concentration at 50°C was simulated only in SPD.
Electricity production	Resource Efficiency	Use of photovoltaic energy mix for equipment operation	SC2-RR1-6T and SC2-RR2-9T	The energy transition occurs through a Distributed Generation business model (e.g., energy subscription), eliminating the need for more space and capital expenditure (CAPEX) for solar panels at the power plant. This premise is reflected in the change in the utility tariff (cost of kWh in SPD) and in the emissions energy mix associated with electricity consumption.
Steam Production	Resource Efficiency	Use of photovoltaic electrical energy for use in equipment and as a heating source in the process steps	SC3-RR1-6T and SC3-RR2-9T	

The circularity analysis (step 6) was conducted to evaluate the circular performance of the reference routes and the most promising improvement scenarios identified in the previous steps. Using the mass balance data derived from the industrial scale models built in SPD (step 3)—specifically accounting for the mass flows of the cashew fiber biomass and the process water (used for washing both the fiber and the equipment)—the Linear Flow Index (LFI) was calculated for each configuration. This assessment quantified the share of materials remaining in a linear flow by accounting for production losses relative to the total material inputs of the DCF production routes, providing an indirect measure of their circularity before proceeding to the final decision-making stage.

Finally, the multicriteria analysis (step 7) was performed using the AHP method with the Three Decision Methods (3DM) Software Web platform (v.1) (BOZZA et al., 2020). This method hierarchically classifies alternatives to support the investment decision for the industrial plant. The decision matrix was constructed through pairwise comparisons encompassing three main pillars: economic criteria (represented by MSP, ROI, and DPBT), environmental criteria (based on the selected impact categories from the ex-ante LCA), and circularity criteria (derived from the LFI). During the weighting process, an expert from each area (economic and environmental) evaluated the criteria. Based on their expert judgment, the environmental criterion was considered slightly more important than the economic one, which corresponds to level 2 on the Saaty scale (SAATY, 1990).

3. Results and Discussion

3.1. Technoeconomic Analysis

The TEA of the routes showed that in the reference situation, DCF originating from route 1 (RR1-9T) obtained a lower MSP of US$14.50 kg^{-1} of DCF compared to route 2 (RR2-9T), which was US$40.47 kg^{-1}. To arrive at an NPV equal to zero in the MSP calculation, sales revenue of US$4,841,000.00 was considered for RR1-9T and US$13,161,000.00 for RR2-9T.

For the investment to be economically favorable, the MSP of the product under development must be less than or equal to that of a similar product on the market (MANHONGO et al., 2021). Thus, a comparison was made between the MSP of DCF and the selling price of wet jackfruit meat sold in Brazil (US$ 12.05 kg^{-1}). It was observed that the price per kilogram of DCF obtained via both routes was higher than the market price for a similar product.

However, DCF requires hydration (PORTELA et al., 2023; SALDANHA et al., 2025), which reduces the price per kilogram of DCF. This particularity makes DCF more economically viable for the consumer, especially when considering the cost-benefit ratio of acquiring the product. The moisture content of the commercial product also directly influences storage and marketing logistics, requiring adequate infrastructure to guarantee the maintenance of quality during the shelf life.

Another important result is the ROI values, which were similar for both routes: 14.15% for RR1-9T and 14.16% for RR2-9T. According to De Paula Pessoa (2017), the expected ROI percentage should be at least twice that of a low-risk investment. In the Brazilian scenario, a baseline low-risk investment to consider for comparison is the savings account, which yielded an accumulated return of 7.03% in 2024. Thus, the ROI values obtained for the evaluated projects are considered acceptable by Brazilian market standards.

Regarding the DPBT, in RR1-9T it was 24.01 years and in RR2-9T, 24.00 years. According to Da Silva (2015), BNDES (National Bank for Economic and Social Development), an important financing institution in Brazil, considers a loan amortization period of up to 5 years. Reducing the investment payback period can make the project more attractive to potential investors and facilitate obtaining credit lines from financial institutions.

In this study, MSP was the financial break-even point of the project. Thus, it represents the baseline from which the entrepreneur adds a desired profit margin, which may in turn reduce the DPBT. It is important to emphasize that this cannot be the sole strategy, as an excessive profit margin may render the product uncompetitive and prevent the projected revenue from being achieved. Therefore, a market analysis is also necessary.

The better results of MSP in RR1-9T are explained by the lower CAPEX (Capital Expenditure) and OPEX (Operational Expenditure) costs obtained, compared to RR2-9T. The costs of acquiring equipment are one of the main causes of the large differences between the CAPEX of the two factories (Figure 3). In RR2-9T, it was necessary to acquire 12 freezing dryers at a cost of US$5,484,000.00, corresponding to 66.87% of the total equipment acquisition cost for that route. Tables S3 (RR1-9T) and S4 (RR2-9T) present all equipment prices, as well as their technical characteristics.

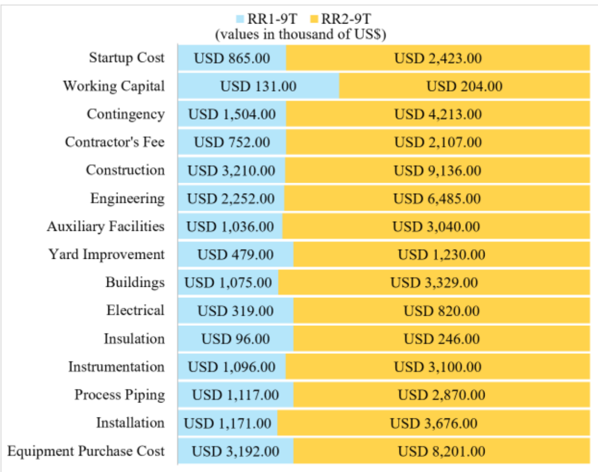

Figure 3. Composition of initial investment costs (CAPEX) for the production processes of oven-dried (RR1-9T) and freeze-dried (RR2-9T) DCF.

The cost of producing one kilogram of DCF in the RR1-9T was US$10.72, while in the RR2-9T it was US$29.68. The OPEX composition is presented in Figure 4. According to literature (Granata and Petrides, 2022; Sano Coelho et al., 2021), the 'Other Facility-Dependent', presented in Figure 4, represents the costs associated with plant infrastructure, including industrial buildings, civil works, service facilities, and equipment maintenance. These costs represent 42.98% and 45.92% of the total annual operating costs for RR1-9T and RR2-9T, respectively. For RR2-9T, the facility-dependent expenditure is approximately 2.88 times higher than that of RR1-9T. This substantial increase is mainly attributed to the high purchase cost, technical complexity, and intensive maintenance requirements inherent to industrial freeze-dryers.

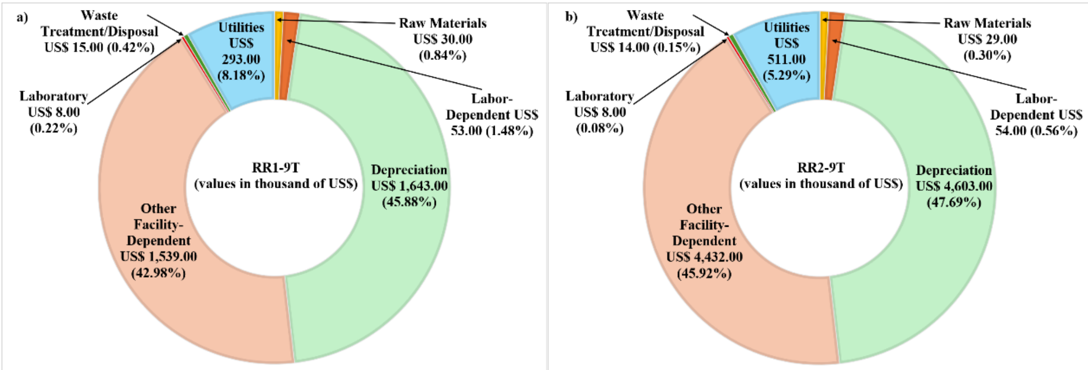

Figure 4. Composition of operational costs (OPEX) for the production processes of RR1-9T (a) and RR2-9T (b). Costs considering an annual operating time of approximately 90 days.

3.1.2 Sensitivity and Risk Analysis

Analysis of other processing capacities for the routes revealed significant differences in MSP as a function of scale change (Figures 5a and 5b). For the RR1, the baseline scenario (RR1-9T) was preceded by a conventional economy of scale effect (OLUGHU et al., 2023), where the MSP dropped from USD \$14.29 kg^{-1} (RR1-3T-P50) to its lowest economic threshold of USD \$12.17 kg^{-1} (RR1-6T-P50). Furthermore, expanding the batch capacity further to RR1-12T introduced severe process penalties, driving the MSP up to USD \$17.76 kg^{-1}. A similar behavior was observed in the freeze-drying route (RR2).

However, in RR2, the advantages of economies of scale were maintained up to the reference capacity (RR2-9T), systematically reducing the MSP from US\$ 44.04 kg^{-1} (RR2-3T) to an MSP of US\$ 40.47 kg^{-1} (RR2-9T). The increased fiber load to be processed caused a substantial increase in the transport time of the washed fiber (washing and pressing stage) to the drying stage, thus reducing the total number of batches that can be produced per year (Figures 6a and 6b). It should also be noted that the P5 alternatives presented higher MSP than the P95 alternatives. This occurred due to the higher energy expenditure required to obtain the lower moisture content. These results indicate that economies of scale can only be achieved when processing capacity is accompanied by an optimization of batch time.

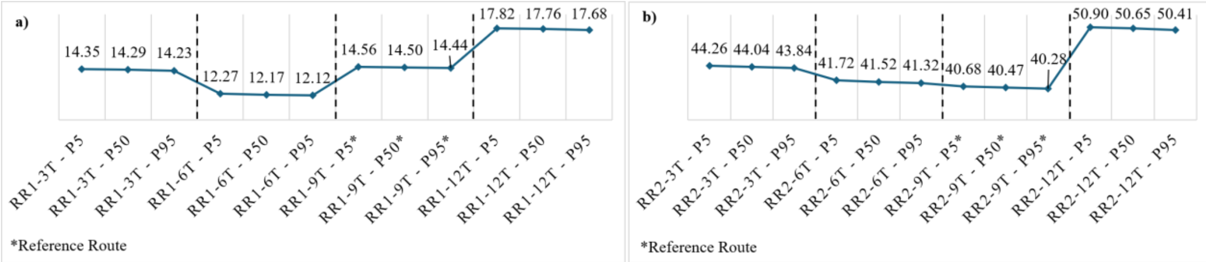

Figure 5. (a, b) Minimum Selling Price (MSP) of the dehydrated cashew fiber (DCF) as a function of processing batch capacity (3, 6, 9, and 12 tons) for Route 1 (oven-drying) and Route 2 (freeze-drying).

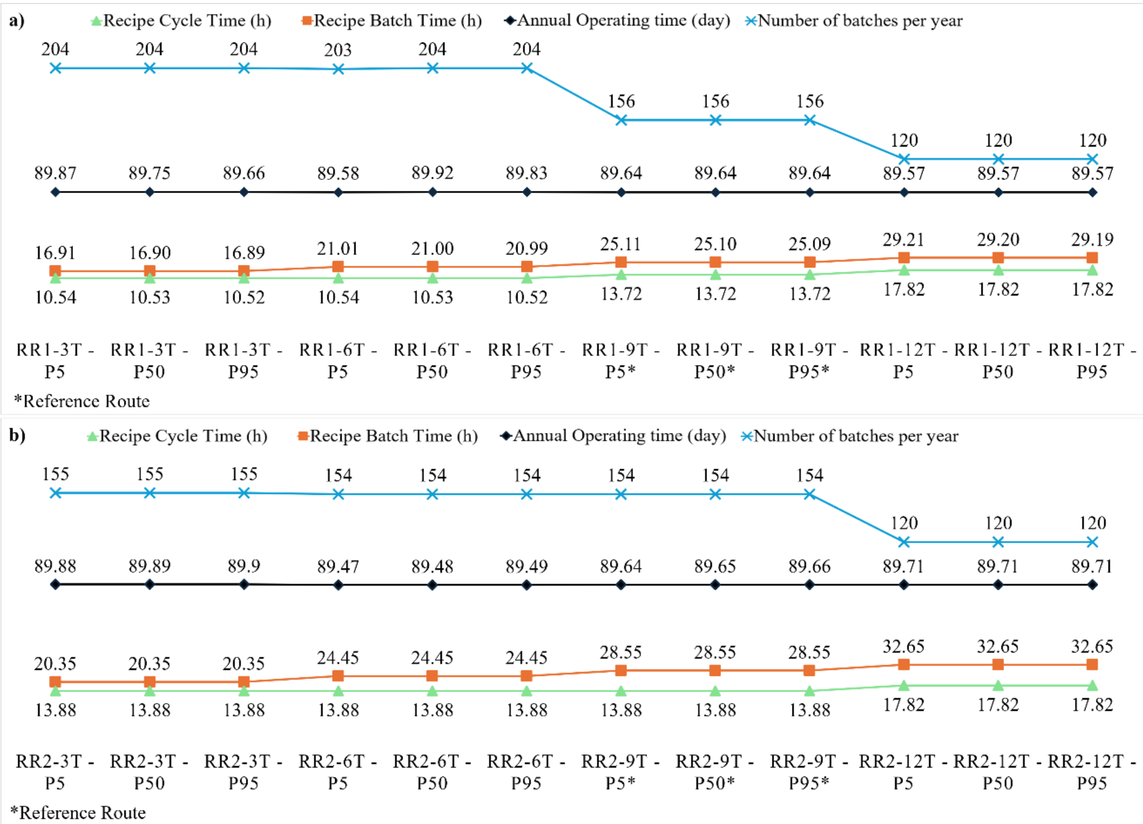

Figure 6. (a, b) Effect of processing scale expansion on plant scheduling parameters for Route 1 and Route 2: Annual Operating Time (days), Recipe Batch Time (h), Recipe Cycle Time (h), and total Number of Batches per Year.

Regarding ROI and DPBT, the variation was minimal between processing loads (Figure 7a and 7b). This behavior indicates a linear proportionality between the total capital investment (CAPEX), operating costs (OPEX), and annual revenues within the simulated range. Consequently, the economic attractiveness parameters remained stable, demonstrating that all evaluated scenarios are robust and economically viable, NPV > 0.

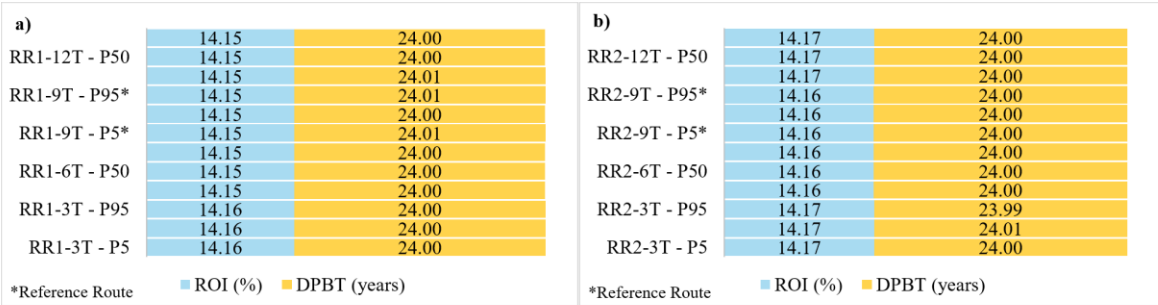

Figure 7. (a, b) Return on Investment (ROI) and Discounted Payback Time across different processing loads for the simulated cashew bagasse valorization plants.

For project design and baseline economic forecasting, the P50 alternatives were selected as the standard reference, as it represents the most statistically probable operational condition based on experimental data. However, the integration of P5 (optimistic alternative with lower fiber moisture) and P95 (pessimistic alternative with higher fiber moisture) thresholds provides robust risk assessment boundaries, demonstrating that the minimum selling price of the dehydrated cashew fiber remains within a competitive and commercially viable range.

Therefore, because MSP was the main factor differentiating the economic performance of the two routes, the best technical-economic configuration was 6 t per batch for RR1 (RR1-6T-P50) and 9 t per batch for RR2 (RR2-9T-P50). From now on, these routes will be described only as RR1-6T and RR2-9T.

The application of the PSP (USD 13.38 kg^{-1} for RR1-6T and USD 44.52 kg^{-1} for RR2-9T) improved all evaluated economic indicators. The ROI of both routes was 16.18% (RR1-6T) and 16.10% (RR2-9T). The DPBT dropped from 24.00 years to 16.09 years (RR1-6T) and 16.30 years (RR2-9T). Furthermore, the NPV of the project reached USD 1,818,000 (RR1-6T) and USD 6,751,000 (RR2-9T), confirming the economic viability of both projects.

Considering the variation in the Selic rate (discount rate) and the use of the MSP, the risk analysis revealed that RR1-6T presented an average NPV of US$4,261,584.00, with a standard deviation of US$367,616.06, meaning the NPV for RR1-6T could range from US$3,893,967.94 to US$4,629,200.06. RR2-9T, on the other hand, presented an average NPV of US$16,561,410.00 and a standard deviation of US$1,002,478.62 (US$15,558,931.38 to US$17,563,888.62). It is important to note that the average SELIC rate that generated these results was 8.75% (± 0,04) in both routes. This risk analysis showed that the probability of loss (NPV < 0) was 29.77% in RR1-6T and 29.70% in RR2-9T.

When the PSP is applied, the project risk decreases to 23.92% in RR1-6T and 24.37%

in RR2-9T. These results were obtained with average NPV values of US$ 6,614,161.00 for RR1 and US$ 25,573,588.00 for RR2, with deviations of US$ 245,994.76 in RR1-6T and US$ 1,502,676.18 in RR2-9T. Furthermore, the average discount rate for each route remained close to that observed for the MSP, with values of 8.76% (± 0,03) for RR1 and 8.73% (± 0,05) for RR2.

This slight advantage observed in RR2-9T suggests greater financial robustness, possibly associated with the larger processing scale, which tends to dilute fixed costs and improve the economic efficiency of the system. However, the difference between the risk probabilities is only 0.07% (MSP) and 0,45% (PSP), which may be the result of a random fluctuation in the simulation. Thus, the projects present similar risks, which makes it important to evaluate the environmental criteria for choosing the best route.

3.2 Ex-ante LCA

Ex-ante LCA was performed for the processing capacities of the routes with the best economic performance: RR1-6T and RR2-9T. Analyzing the contribution of the impact categories in these plants (Figure 8), it is observed that five categories contribute at least 80% to the composition of the final PEF index: Acidification (AC), Climate change (CC), Eutrophication terrestrial (EUT), Particulate matter (PM), Resource use, fossils (RUF) and Resource use, mineral and metals (RUM).

This analysis of the contribution of categories shows that the increase in scale and production of DCF, when moving from the RR1-6T route to the RR2-9T route, promoted a change in the percentage distribution of environmental critical points, despite both routes presenting profiles with the same impact categories.

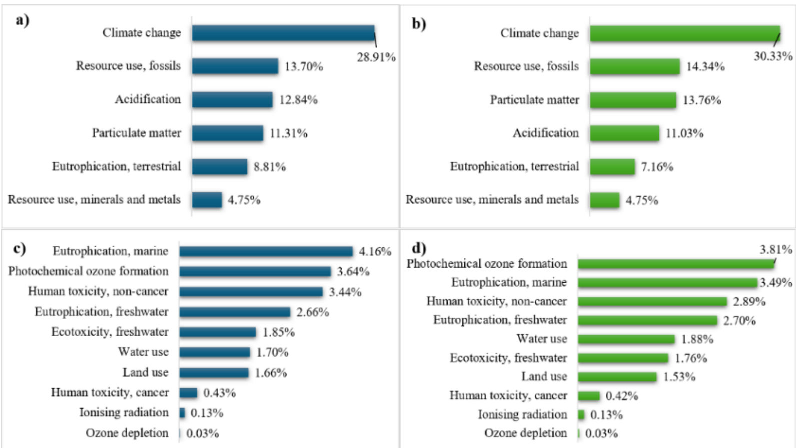

Figure 8. (a, b) PEF method categories that contributed most to the total impact of each route (at least 80%). The bars show the contribution of each category after normalization and weight. The remaining categories were grouped in (c, d).

The critical point analysis of the most relevant categories, considering the three main processes (cashew farm, juice and DCF production), showed that agricultural production is most relevant to the categories of EUT, AC, and RUM (Figure 9) in both routes. Analyzing the impact network (Figures S7 to S18), the origin of the impacts in these categories comes from the production of agricultural inputs (urea, single superphosphate, and dolomite). DCF extraction is most relevant for the CC, RUF, and PM categories (both routes). The impacts of juice production are small when compared to the other two processes.

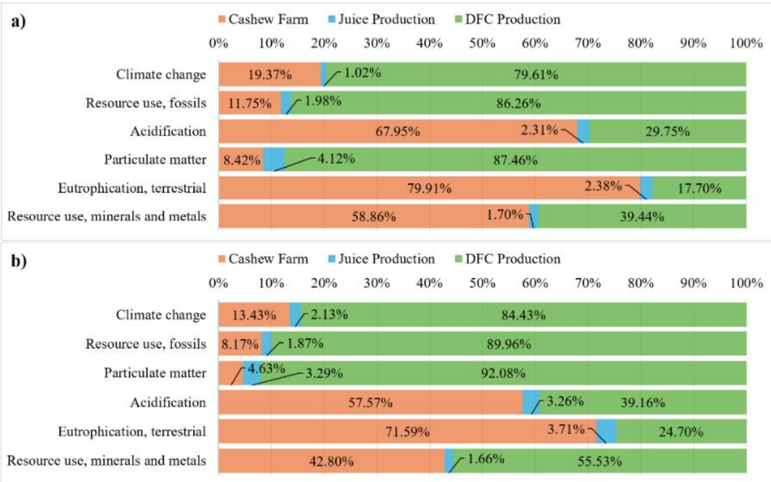

Figure 9. Environmental impacts of RR1-6T (a) and RR2-9T (b) of the three main processes of DCF production analyzed using the PEF method.

Regarding DCF extraction (Figure 10), the main contributors across both routes were electricity generation, steam production, bagasse production, and biowaste treatment.

a)

	Climate change	Resource use, fossils	Acidification	Particulate matter	Eutrophication, terrestrial	Resource use, minerals and metals
Treatment of wastewater	0.02%	0.00%	0.01%	0.01%	0.01%	0.00%
Treatment of biowaste	1.12%	0.65%	9.29%	2.62%	17.82%	1.01%
Steam Production	49.49%	55.83%	38.59%	25.61%	26.93%	6.58%
Electricity Production	45.12%	39.66%	43.25%	65.54%	41.31%	85.57%
Production of PET bottles	0.19%	0.17%	0.21%	0.29%	0.18%	0.49%
Corrugated board box Production	1.33%	1.43%	1.45%	1.41%	1.88%	2.21%
Chlorine Production	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
Bagasse Production	2.74%	2.25%	7.20%	4.50%	11.87%	4.13%

b)

	Climate change	Resource use, fossils	Particulate matter	Acidification	Eutrophication, terrestrial	Resource use, minerals and metals
Treatment of wastewater	0.16%	0.10%	0.10%	0.18%	0.30%	0.36%
Treatment of biowaste	0.82%	0.49%	1.71%	6.73%	12.79%	0.60%
Steam Production	36.44%	42.52%	16.83%	28.15%	19.44%	3.92%
Electricity Production	59.02%	53.66%	76.50%	56.06%	52.98%	90.64%
Production of PET bottles	0.14%	0.13%	0.19%	0.15%	0.13%	0.29%
Corrugated board box Production	0.96%	1.07%	0.91%	1.04%	1.33%	1.29%
Chlorine Production	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Bagasse Production	2.47%	2.04%	3.76%	7.69%	13.05%	2.90%

Figure 10. Environmental impacts of RR-6T (a) and RR2-9t (b) of the three main stages of DCF production analyzed using the PEF method.

Analyzing the process impact network (Figure S19 to S30), it is observed that the impacts of the electricity production process originate from the use of biomass (sugarcane bagasse and eucalyptus logs), the construction of wind turbines, the burning of diesel, and the use of coal and natural gas. The impacts of production of steam originate from the use of natural gas, hard coal and light fuel oil. The impacts of bagasse production originate from the composting process.

The DCF production process generates two main residues during the pressing step (Figures S1 and S2): a solid residue from the CB itself and the water used to wash the CB. Annually, RR1-6T generates 52.34 t of solid residue, whereas RR2-9T generates 59.27 t. Over the same period, liquid residue generation reaches 2,446.87 m^3 in RR1 and 2,771.06 m^3 in RR2. The impacts of solid waste treatment are mainly due to the composting process and the use of diesel in transportation.

These results reinforce that the energy demand (electricity and steam) used in both routes is the main critical point that causes environmental pressure in the DCF production process, requiring mitigation strategies focused on energy efficiency. The results also show the importance of characterizing liquid and solid waste, even at the pilot scale, so that new valorization opportunities can be identified.

3.3 Improvement Scenario Analysis

From an economic standpoint, SC1 did not compromise the commercial viability of the main product (DCF). For both routes, the MSP remained identical to their respective reference values (USD 12.17 kg^{-1} for RR1-6T and USD 40.47 kg^{-1} for RR2-9T) (Figure 11). This stability occurs because the additional capital and operational investments (CAPEX/OPEX) required for the effluent recovery units were fully offset by the revenues generated by the carotenoid-rich concentrate.

On the other hand, in Scenarios 2 (SC2) and 3 (SC3), the DCF MSP decreased (Figure 11) due to the lower cost per kWh of photovoltaic mix energy compared to hydroelectric energy. The change in the financial model to the PSP significantly improved all economic indicators; the DPBT fell to approximately 16 years, and the ROI stabilized at around 16% for both scenarios. The uniformity of the ROI and DPBT profiles is related to the method used to obtain the MSP, which was the exact break-even point where the Net Present Value is zero (NPV = 0). In the scenario with the PSP, the constant values between the routes persist because the 10% margin applied to the MSP was the same for all scenarios. All economic results are presented in Table S5 of support information.

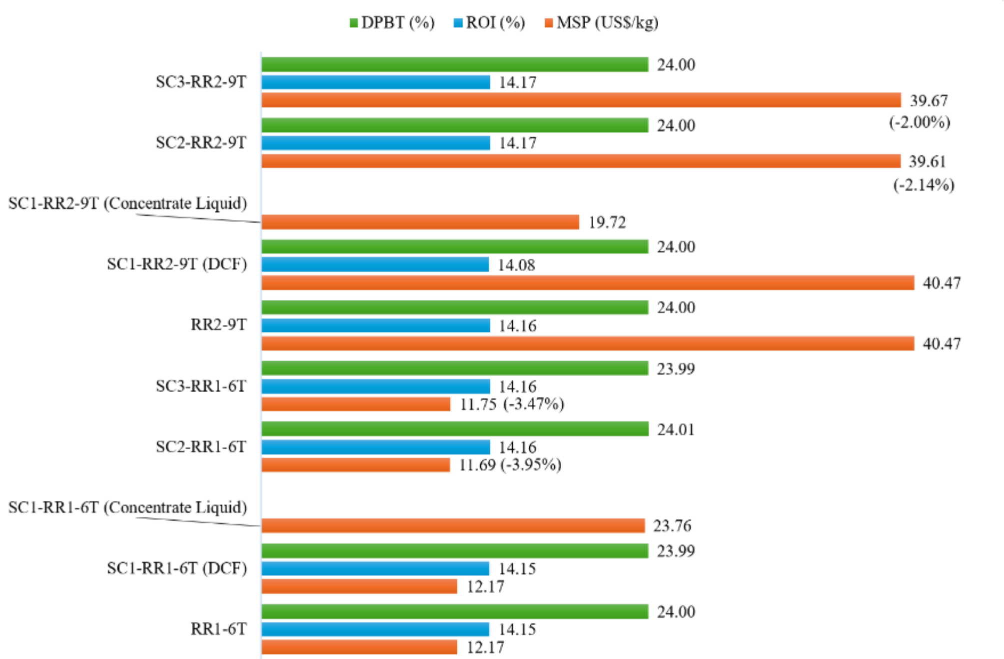

Figure 11. Economic results of the scenarios (SC1 to SC3) compared to the reference routes (RR1 -6T and RR2-9T).

The life cycle environmental impacts are compiled in Table S6. Within the SC1 framework, environmental impacts were distributed between DCF (67.90% for Route 1 and 67.59% for Route 2) and liquid concentrate co-product (32.10% for Route 1 and 32.41% for Route 2) under a mass allocation framework. Due to this distribution, the environmental footprint attributed to DCF increased compared to reference routes.

In SC1, an increase in carbon footprint is observed in almost all impact categories for both routes. For Route 1, in the Climate Change category, the value jumped from 0.98 kg CO_2 eq. in RR1-6T to 2.15 kg CO_2 eq. under mass allocation (an increase of 118.5%), while Fossil Resource Use expanded by 137.9%, reaching 26.39 MJ.

This environmental burden is driven by the increase in operational times caused by effluent recovery operations, which reduced the annual batch quantity from 204 to 118. As the functional unit is expressed in kilograms of DCF, this contraction in the scale of production has hampered the dilution of environmental impacts.

For Route 2 under mass allocation, the impact on climate change increased similarly to 2.32 kg CO_2 eq. It is observed that with the decrease in the number of batches (from 154 to 80 annual batches), categories such as Particulate Matter and Use of Mineral and Metallic Resources showed reductions of 18.0% and 77.0%, respectively. This mitigation indicates that operating with fewer annual cycles reduced the consumption of inputs. However, the overall reduction in batches generated more environmental liabilities than benefits in both technological alternatives.

By shifting the methodological perspective to the economic allocation structure, which distributes charges based on the annual revenue generated by the MSP of each route, the environmental profiles were reorganized. The resulting economic split allocated 52.59% (SC1-RR1-6T) and 81.43% (SC1-RR2-9T) of the charges to DCF, while the remaining 47.41% and 18.57% were directed to liquid concentrate, respectively.

For Route 1, since the concentrated liquid has a higher MSP (USD 23.76 kg^{-1}) compared to the DCF (USD 12.17 kg^{-1}), this co-product absorbed a significant portion of the process emissions. Consequently, the economically allocated carbon footprint of the DCF was limited to 1.66 kg CO_2 eq., while the liquid by-product had a higher load of 3.17 kg CO_2 eq.

For Route 2, this behavior is reversed. Due to the MSP of DCF being quite high (USD 40.47 kg^{-1}) compared to the byproduct (USD 19.72 kg^{-1}), DCF retained most of the environmental impacts, registering a Climate Change Index of 2.79 kg CO_2 eq., while the liquid concentrate presented a milder profile of 1.33 kg CO_2 eq. This divergence demonstrates that economic allocation prevents a homogeneous comparison between the coproducts, directly linking the environmental footprint to variations in the MSP of each route.

Ultimately, the findings of SC1 validate that the choice of allocation method redefines the environmental interpretation of the process. Mass allocation penalizes DCF identically on both routes due to productivity loss, while economic allocation introduces a reversal of burdens, transferring environmental liabilities to the co-product with the higher MSP, while simultaneously burdening DCF on route 2.

In SC2, there was an increase in most categories in both routes. In Acidification, the increase was 30.03% in route 1 (reaching 0.00563 mol H^+ eq.) and 36.78% in route 2 (reaching 0.00829 mol H^+ eq.). The most critical impact was recorded in Resource Use Mineral and Metals, which increased from 1.93x10^{-6} to 2.90x10^{-5} kg Sb eq. in route 1 and from 3.31x10^{-6} to 5.22x10^{-5} kg Sb eq. in route 2. This increase arises directly from the supply chain of solar panel manufacturing, which relies on metals such as silver, gold, and copper.

On the other hand, the global impact of climate change decreased by 3.49% for Route 1 (0.948 kg CO_2 eq.) and 6.92% for Route 2 (1.27 kg CO_2 eq.), indicating that simply replacing the energy mix offers limited capacity to mitigate the environmental impacts of the drying routes.

On the other hand, the impacts of climate change decreased by 3.49% for Route 1 (0.948 kg CO_2 eq.) and 6.92% for Route 2 (1.27 kg CO_2 eq.), indicating that the replacement of the energy mix offers limited capacity to mitigate the environmental impacts of the drying routes. Thus, the partial transition to solar energy proposed in this scenario indicates that the decrease in MSP to US$ 11.69 kg/DCF (-3.95% lower compared to Route 1) may not compensate for the increase in environmental impacts, especially in the RUM category, which showed increases above 1,000%.

In SC3, the expansion of the photovoltaic solar array to achieve full electrification enabled substantial mitigations in most of the evaluated categories. For Route 1, climate change fell to its minimum of 0.532 kg CO_2 eq. (a 45.79% reduction compared to the baseline), while the use of fossil resources decreased by 40.93%, to 6.55 MJ. Particulate matter emissions were also halved, reaching 4.02x10^{-8} disease incidences.

For Route 2, although the complete energy mix switches reduced CO_2 equivalent emissions to 0.866 kg (a 36.3% reduction compared to the baseline) and fossil fuel consumption to 10.74 MJ, its absolute carbon footprint remained critically high compared to Route 1. Under SC3 conditions, the carbon footprint of Route 2 remained 62.7% higher than that of Route 1. Furthermore, the Use of Mineral and Metallic Resources reached an absolute maximum peak of 3.41 x 10^{-5} kg Sb eq. for Route 1 and 5.73 x 10^{-5} kg Sb eq.

Finally, SC3 consolidates itself as the best route for mitigating environmental impacts, reducing carbon emissions and fossil fuel use by more than 40% in oven drying. However, the model exposes the limitations of freeze-drying, which, even operating in a 100% renewable energy mix, remains a more impactful technology than oven drying.

3.4 Circularity analysis

The circularity of the reference routes and scenarios was evaluated using the Linear Flow Index (LFI). Both reference routes (RR1-6T and RR2-9T) achieved the same LFI score (83.27%), reflecting the proportionality of the mass yields obtained in the SPD simulations, although different moisture contents were considered for each drying equipment.

Scenarios SC2 and SC3 also presented identical LFI values (83.27%) for both routes, as the indicator accounts solely for material mass flows. Consequently, changes in the energy mix did not influence the LFI, demonstrating that the metric does not fully capture the benefits of circular bioeconomy strategies focused on decarbonization.

In contrast, Scenario SC1 significantly reduced the LFI to 52.08% (Route 1) and 52.03% (Route 2), driven by the valorization of washing wastewater for carotenoid concentrate production. This strategy effectively altered the material boundaries of the system, reducing linearity and increasing circularity.

Overall, the results indicate that material circularity represents only one dimension of the circular bioeconomy. While the LFI successfully captured the waste-valorization strategy implemented in SC1, it did not reflect the substantial environmental benefits associated with the decarbonization strategies in SC2 and SC3, as discussed in Section 3. Therefore, circularity and decarbonization strategies should be viewed as complementary, reinforcing the need for integrated assessment approaches capable of simultaneously evaluating circularity, environmental performance, and economic feasibility in systems aligned with circular bioeconomy principles.

3.5 Multicriteria analysis for selecting the best route

The integration of economic (NPV, DPBT), environmental (LCA), and circularity (LFI) dimensions was performed using the AHP method to determine the most sustainable processing route. The final classification results are presented in Table 5. The quantitative values used in the AHP method and the weights assigned to each criterion are in Tables S6 and S7, respectively.

The AHP method revealed a hierarchy of alternatives, establishing SC3-RR1-6T as the ideal solution, with the highest priority score (0.1761), followed by the reference route RR1-6T (0.1397).

The choice of SC3-RR1-6T is justified by the alignment between a balanced economic result and greater mitigation of environmental critical points in the categories analyzed. As discussed in the previous sections, the SC3-RR1-6T reduced Climate Change emissions by 45.79% (0.532 kg CO_2 eq.) and the Use of Fossil Resources by 40.93%, maintaining the maximum number of 204 annual batches by not introducing the operational bottleneck of effluent treatment. Economically, the AHP model valued the stability of economic indices (DPBT = 16.24 years, and competitive MSP of USD \$11.75 kg^{-1} and PSP of USD \$12.92 kg^{-1}) and an NPV of US\$1.75 million.

Table 5. Final ranking by score.

Route/Scenario	Score Obtained
SC3-RR1-6T	0.1761
RR1-6T	0.1397
SC3-RR2-9T	0.1256
SC1-RR2-9T (with mass allocation)	0.1218
RR2-9T	0.1203
SC2-RR1-6T	0.1145
SC1-RR1-6T (with mass allocation)	0.1011
SC2-RR2-9T	0.1009

3.6 Limitations of the study

The recommended SC3-RR1-6T scenario presents specific techno-economic and environmental bottlenecks that must be addressed to successfully advance this pathway along the technology readiness level (TRL) scale. Within the techno-economic analysis (TEA), even after implementing the Product Selling Price (PSP) framework with a commercial profit margin, the project yielded a prolonged Discounted Payback Time (DPBT) of approximately 16.24 years. This recovery period significantly exceeds the conventional 5-year amortization threshold typically mandated by the Brazilian National Bank for Economic and Social

Development (BNDES) for industrial loans, which represents a critical barrier to securing domestic financing. Furthermore, a comprehensive market dynamic analysis was not integrated into this study, which limits a precise definition of higher commercial markups and real consumer willingness to pay that could potentially accelerate capital recovery.

Regarding the environmental lifecycle profile, although the absolute electrification pathway (SC3-RR1-6T) proved to be the most effective strategy for mitigating global climate impacts, it induced a massive burden-shifting effect. Specifically, it triggered a 1,662.18% escalation in the Resource Use, Minerals and Metals category, indicating a severe trade-off that requires further technological investigation and mitigation.

Consequently, the following actions are highly recommended for future research directions:

1. Conducting a target market and consumer behavior study to assess the commercial demand and pricing elasticity for novel bio-based vegetable protein ingredients, aiming to identify premium pricing strategies;

2. Performing a dedicated lifecycle and technological review focused on end-of-life recycling methods, circular manufacturing matrices, and public policies aimed at cross-mitigating the material extraction footprints of photovoltaic infrastructures.

4 CONCLUSIONS

This study successfully fulfilled its objective by delivering a comprehensive evaluation of the economic, environmental, and material circularity performance of alternative processing routes for Dehydrated Cashew Fiber (DCF) extraction through a synchronized, ex-ante framework. The integrated findings indicate that the drying pathway utilizing a conventional forced-air circulation oven (RR1), scaled at an industrial configuration of 6 t batch^{-1} of cashew bagasse and fully powered by an electrified solar photovoltaic energy mix for both electrical and thermal loads (SC3-RR1-6T), emerges as the most sustainable and balanced configuration.

Although the resulting Return on Investment (ROI) reached 16.12%—a threshold highly acceptable within the Brazilian macroeconomic context—the long-term DPBT of 16.24 years under PSP conditions highlights the economic challenges of high-CAPEX renewable transitions, reinforcing the need for subsequent market validation and optimized financial structures. Environmentally, the ex-ante LCA unmasked a critical macro-system trade-off: the integration of a photovoltaic energy mix expanded the facility's mineral and metal resource depletion risk, despite successfully unlocking mitigation efficiencies exceeding 40% across all other global climate and fossil-dependent impact categories.

Finally, the proposed methodological pipeline developed for the integrated assessment of DCF significantly minimized the requirements for time and human resources during the engineering design phase. The introduction of an initial technical and economic performance filter successfully screened out suboptimal plant scales prior to the comprehensive life cycle assessment, thereby streamlining the multi-criteria evaluation framework. This systematic, high-throughput approach proves to be highly replicable and can be confidently extended to guide sustainability assessments for a wide range of emerging bioeconomy technologies.

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Author Contributions
The manuscript was written through contributions of all authors. / All authors have given approval to the final version of the manuscript. / ‡These authors contributed equally. (match statement to author names with a symbol)

Funding Sources
This research was funded by The Good Food Institute – GFI (SEG 20.20.00.158.00.00) and INCT Circularity in Polymer Materials No 406925/2022-4.

Conflict of interests
The authors declare no competing financial interest.

Abbreviations
AHP, Analytic Hierarchy Process; BCE, Circular Bioeconomy; BNDES, National Bank for Economic and Social Development; CAPEX, Capital Expenditure; CO_2 eq kg^{-1}, kilograms of carbon dioxide equivalent; CTUh, Comparative Toxic Unit for Human Toxicity; DCF, Dehydrated Cashew Fiber; DPBT, Payback time; 3dm, Three Decision Methods (Software Web); LCA, Life Cycle Assessment; Mj, Megajoule; mol N eq, moles of equivalent nitrogen; MSP, Minimum Selling Price; NPV, Net Present Value; OPEX, Operational Expenditure; PEF, Product Environment Footprint; RD&I, Research, Development and Innovation; ROI, Return on Investment; RR, Reference Routes; RR1, Route 1 (Dehydration by drying in a forced-air circulation oven); RR2, Route 2 (Freeze-drying); RR1-3T, Route 1 with processing 3 tons of bagasse $batch^{-1}$; RR1-6T, Route 1 with processing 6 tons of bagasse $batch^{-1}$; RR1-9T, Route 1 with processing 9 tons of bagasse $batch^{-1}$; RR1-12T, Route 1 with processing 12 tons of bagasse $batch^{-1}$; RR2-3T, Route 2 with processing 3 tons of bagasse $batch^{-1}$; RR2-6T, Route 2 with processing 6 tons of bagasse $batch^{-1}$; RR2-9T, Route 1 with processing 9 tons of bagasse $batch^{-1}$; RR2-12T, Route 1 with processing 12 tons of bagasse $batch^{-1}$; SC1-RR1, Scenario 1 route 1; SC2-RR1, Scenario 2 route 1; SC3-RR1, Scenario 3 route 1; SC1-RR2, Scenario 1 route 2; SC2-RR2, Scenario 2 route 2; SC3-RR2, Scenario 3 route 2; SDGs, Sustainable Development Goals; SI, Supporting Information; TEA, Techno-Economic Analysis; UN, United Nations.

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4.2.Artigo 2

Integrating Techno-Economic, Environmental, and Circularity Analysis (TEEC)

for Early-Stage Food Technologies: A Case Study on Sustainable Colorant Production from dragon fruit.

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Abstract

The food industry faces increasing pressure to adopt sustainable practices aligned with the United Nations 2030 Agenda. However, a gap remains in integrating Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) with circularity metrics for early-stage technologies. This study proposes the Techno-Economic, Environmental and Circularity (TEEC) framework, a seven-step methodology integrating industrial modeling, TEA, ex-ante LCA, and Circularity analysis through Multi-Criteria Decision Analysis (MCDA) to evaluate food colorants at early Technology Readiness Level (TRL). This framework is applied to the production of a red-purple colorant (RPC) from dragon fruit at laboratory to pilot stage. Process simulation showed that the highest plant capacity (1000 kg batch^{-1}) achieved the best economic performance, with a Minimum Selling Price (MSP) of US$ 84.86 kg^{-1}. The risk analysis of MSP showed a 16.40% probability of negative Net Present Value, which decreased to 4.24% with a 10% profit margin, resulting in a discounted payback time of 12.40 years. Environmental assessment using the Product Environmental Footprint (PEF) indicated that agricultural cultivation was the main impact driver in most impact categories, contributing over 90% to marine eutrophication and human toxicity due to fertilizer use. Industrial impacts were mainly associated with electricity and waste treatment. From hotspot analysis, five circular alternative scenarios were built: water reuse, waste valorization, by-product recovery, photovoltaic integration, and a fully integrated system. Circularity analysis showed low efficiency, with the lowest Linear Flow Index for waste valorization (83.61%) and the integrated (87.12%) scenarios. MCDA identified waste valorization (1000 kg batch^{-1}) as the most promising option, with Net Present Value of US$ 2.76 million and an Internal Rate of Return of 17.70%. The TEEC framework demonstrates strong potential as a decision-support tool for sustainable food colorants and is well-suited for assessing other food processing technologies.

Keywords: Natural Food Coloring, *Hylocereus polyrhizus*, Techno-economic Analysis, ex-ante Life cycle assessment, Circular Economy.

List of acronyms:

AC: Acidification
AHP: Analytic Hierarchy Process
BCB: Central Bank of Brazil
BRLUC: Brazilian Land Use Change
CAPEX: Capital Expenditures
CBE: Circular bioeconomy
CC: Climate Change
CCRD: Central Composite Rotatable Design
CE: Circular Economy
CR: Consistency Ratio
DPB: Discounted Payback Time
DR: Discount Rate
EMF: Ellen MacArthur Foundation
EuM: Eutrophication, marine
EuT: Eutrophication, terrestrial
HTnc: Human toxicity, non-cancer
IBGE: Brazilian Institute of Geography and Statistics
IRR: Internal Rate of Return
ISO: International Organization for Standardization
PF: Permeate Flow
LCA: Life Cycle Assessment
LFI: Linear Flow Index
MCDA: Multi-Criteria Decision Analysis
MCS: Monte Carlo Simulation
MSP: Minimum Selling Price
MTE: Ministry of Labor and Employment of Brazil
NPV: Net Present Value
OPEX: Operational Expenditures
PEF: Product Environmental Footprint
PSP: Product Selling Price
RD&I: Research, Development and Innovation
RR: Reference Route
RPC: Red-Purple Colorant
RUm: Resource use, minerals and metals
SELIC: Special System for Settlement and Custody
SPD: SuperPro Designer

TEA: Techno-Economic Analysis
TEEC: Techno-Economic Environmental and Circularity Assessment
TRL: Technology Readiness Level
VRR: Volumetric Reduction Ratio

1. Introduction

Throughout history, the food production sector has undergone continuous innovation driven by scientific and technological advances and changes in consumer eating habits (Yannou-Le Bris, 2020). Recently, consumer concern regarding the environmental sustainability of products and production processes has increased significantly (Galdeano-Gómez and García-Fernández, 2024). Consequently, environmental issues have increasingly been incorporated into industrial practices. Environmental sustainability is now an important component of Research, Development and Innovation (RD&I), contributing to the long-term viability and competitiveness of businesses (Gestaro and Schmidt, 2021; Del Borghi et al., 2022; Silva et al., 2015).

In this context, the circular economy (CE) has emerged as an important strategy to minimize waste and maximize resource efficiency by keeping materials and products in use for as long as possible (Ren et al., 2023). By promoting reuse, recycling, and resource valorization, CE can generate economic benefits while reducing the exploitation of natural resources (Riesener et al., 2023; Banjerdpaiboon and Limleamthong, 2023). A related concept is the circular bioeconomy (CBE), which builds on circular economy principles while emphasizing the use of renewable biological resources (Khanna et al., 2024). These concepts are of value to the food industry, since approximately 30% of all food produced is not consumed due to losses and waste generated from agricultural production to the consumer (Forbes et al., 2024).

The growing relevance of CE or CBE has attracted attention from governments and international organizations (Steenmans and Ulfbeck, 2023; Ballardini et al., 2021). Over the past two decades, several countries and institutions, including China, the European Union, the United Nations, Mexico, and Brazil, have implemented policies to promote circular production systems (Government of China, 2008; European Commission, 2020; United Nations, 2023; Steenmans and Ulfbeck, 2023; Brasil, 2025).

These policies encourage the transition from linear production models to circular systems that consider the entire product life cycle, from raw material acquisition to final use. This transition requires circular technological solutions with techno-economic viability and low environmental impacts (Iñarra et al., 2022). Therefore, integrating techno-economic, environmental, and circularity assessments at early Technology Readiness Levels (TRLs) is essential to support decision-making in RD&I processes (Pérez-Almada et al., 2023; Ortiz, 2020).

Recent studies proposed frameworks to integrate Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) in the assessment of bio-based products at low TRLs. For instance, recent investigations have assessed the techno-economic and environmental performance of fruit-based biorefineries, including mango (De Sá Filho et al., 2026) and avocado systems (Meramo et al., 2026).

Regarding food colorants, few studies have applied LCA and/or TEA to analyze the performance of processes at low TRL. Patiño et al. (2023) and Zabot and Silva (2026) assessed the environmental performance of bixin and norbixin, extracted from annatto. Patiño et al. (2023) applied a cradle-to-gate LCA to evaluate annatto cultivation, carbon sequestration, and processing scenarios, with residual solids and purification effluents were assumed to be conventionally disposed of. Zabot and Silva (2026) applied a Path2Green framework and found that approximately 30% of fiber residues generated during the aqueous starch step remained unvalorized. Thomsen et al. (2023) integrated TEA and LCA to compare technological routes (microbial versus traditional extraction) for obtaining betanin. Arias et al (2025) applyed TEA, LCA and circularity indicators to assess the performance of three scenarios for obtaing R-phycoerythrin, a high-value natural pigment extracted from a marine macroalgae. However, no previous study presented a stepwise framework for integrating TEA, ex-ante LCA and circularity indicators for process improvement and selection at low TRL.

To address this gap, this study proposes a seven-step framework that integrates TEA, ex-ante LCA and circularity assessment for processes improvement and selection during food colorant development, in the transition from laboratory research to pilot-scale production. Sensitivity analysis is applied to define the best plant capacity and operating conditions while uncertainty analyses are used for assessing the effect of variations in economic and operational parameters in plant economic performance. Scenarios are built from hotspot analysis, and decisions are made through multicriteria analysis.

This framework was applied to support the sustainable development of a red-purple colorant (RPC) extracted from dragon fruit (*Hylocereus polyrhizus*) (Zocolo et al., 2021). RPC represents an alternative to artificial colorants associated with potential health risks (Munawar et al., 2014) and to natural colorants such as carmine, which may cause allergic reactions (Alizadeh et al., 2022), and beetroot-based colorant, often rejected due to their earthy flavor caused by geosmin (Buttery and Garibaldi, 1976). Sensory tests indicate that RPC does not alter yogurt aroma or taste (De Lima et al., 2020). Recent studies also suggested that RPC may contribute to diabetes control (De Sousa Silva et al., 2024), reinforcing its potential industrial relevance and adding value to dragon fruit value chain.

2. Material and methods

2.1. The Techno-economic, Environmental, and Circularity (TEEC) framework

The TEEC framework, for use at the laboratorial stage of food colorant development, is structured in seven steps (Figure 1): i) Scope definition; ii) Data collection; iii) Scaling of technological routes; iv) TEA; v) Ex-ante LCA; vi) Circularity analysis; and vii) Multi-Criteria Decision Analysis (MCDA).

In step 1, the unit processes of a novel reference route (RR) for a food product are identified with the RD&I team. When more than one route results in a product with attended quality, their respective unit processes are identified. Moreover, the system boundary (cradle to gate or to grave) and functional unit are established, considering ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

In step 2, RR data on materials proportions, process conditions, feedstock composition, and costs of equipment and inputs are collected. When food residues are used as raw materials, the crop or livestock production that generated them must be considered. As circular food systems develop, residues will increasingly become valuable resources, requiring primary inventory data on their production and processing.

In Step 3, an industrial plant model is developed for each technological route (RRs and their scenarios) using data from the previous step. The framework uses SuperPro Designer® (SPD) (Intelligen, Inc., Freehold, NJ, USA), a reliable tool for industrial-scale biomass process simulation (Tsoy et al., 2020). SPD provides equipment databases and generates mass and energy balances used in techno-economic, environmental, and circularity assessments. Data from Step 2 define unit operations, enabling equipment sizing and industrial-scale material flow estimation (Sulin et al., 2025). Different plant processing capacities and variations in key process parameters (most relevant for yield) are investigated in a sensitivity analysis (Melitos et al., 2025), building different models for each plant size and process condition.

In step 4, a techno-economic is performed to plant models (RRs and their scenarios), considering the following indicators: Minimum Selling Price (MSP), Product Selling Price

(PSP), Discounted Payback Time (DPB), Internal Rate of Return (IRR) and Net Present Value (NPV). With MSP, it is possible to determine the project's breakeven point (NPV = 0) and the most economically efficient one (lowest MSP) (Melitos et al., 2025; Hasanly et al., 2018). Moreover, MSP is a useful economic indicator used to evaluate emerging technologies using TEA, facilitating communication with investors and decision-makers and guiding the definition of a product's selling price (Zhao et al., 2016; Li et al., 2018). The DPB accounts for the time value of money, providing a realistic estimate of investment payback (Ferella et al., 2019; Zhang et al., 2015; Nkambule et al., 2023). The IRR should exceed the Discount Rate (DR) and allows comparison with alternative investments (Nkambule et al., 2023; Towler and Sinnott, 2021; Ortiz, 2020). The PSP reflects project profitability and can be estimated from comparable competitor products (Sulin et al., 2025; Pissinati and Dias, 2022). Due to the study's methodology, the TEA cost estimate has an accuracy of -15% to +20% (optimistic scenario) or -30% to +50% (pessimistic scenario) (AACE, 2020).

Risk analysis is performed for the best plant capacity, using Monte Carlo Simulation (MCS) to assess the impact of variations in the following economic parameters: cost of feedstock and DR. The result of the MCS is a cumulative probability distribution of the economic index (NPV), which allows for the analysis of project risk (Hasanly et al., 2018).

In step 5, the environmental analysis of RR is performed for the plant processing capacity with the best economic viability. An ex-ante Life Cycle Assessment (ex-ante LCA) methodology is applied, following ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b), and the guidelines proposed by Müller-Carneiro et al. (2023). Unlike conventional LCA, ex-ante LCA enables the evaluation of technologies at early development stages (Cucurachi et al., 2018). Impact assessment is performed using the Product Environmental Footprint (PEF) method (Zampori and Pant, 2019). The impact categories representing 80% of the normalized and weighted results are selected as the most relevant for hotspot identification and scenario development, considering circular bioeconomy principles (Stegmann et al., 2020). These scenarios are then modeled at industrial scale (step 3) and assessed economically (step 4) and environmentally (step 5).

In step 6, the circularity analysis is performed for RR and alternative scenarios, generated in step 5. Circularity is measured indirectly, using the Linear Flow Index (LFI), considering production losses (Ellen MacArthur Foundation [EMF] & Granta Design, 2015). LFI depends on the circularity strategy that will be adopted (Vásquez-Cabrera et al., 2025; Rufí-Salís et al., 2021). In this framework, it was used to measure the proportion of material that flows linearly in relation to the total material input of a technological route.

In step 7, the MCDA integrates economic, environmental and circularity indicators to choose the best route or route scenario for advancement on the TRL scale. The Analytic Hierarchy Process (AHP) method (Saaty, 1990) is used because it allows complex decision-making problems to be hierarchically structured (Vaidya and Kumar, 2006). Through pairwise comparisons, the method consistently integrates quantitative technical data and qualitative expert judgments, ensuring a mathematically robust prioritization of alternatives (Abba et al., 2013).

Pairwise comparison assumes that the criteria are independent of each other (Darko et al., 2019). To attend to this criteria, NPV and DPB (obtained using the PSP) are chosen as the economic indices. NPV was chosen due to its ability to synthesize the overall economic viability of the project (Maurer, 2009), allowing for a direct comparison between scenarios of single-product and co-production of by-products. DPB was included to account for the time risk associated with the return on invested capital, considering a minimum acceptable rate of return (DR). The most relevant environmental categories (step 5) and the LFI are maintained as distinct criteria, as they evaluate independent aspects.

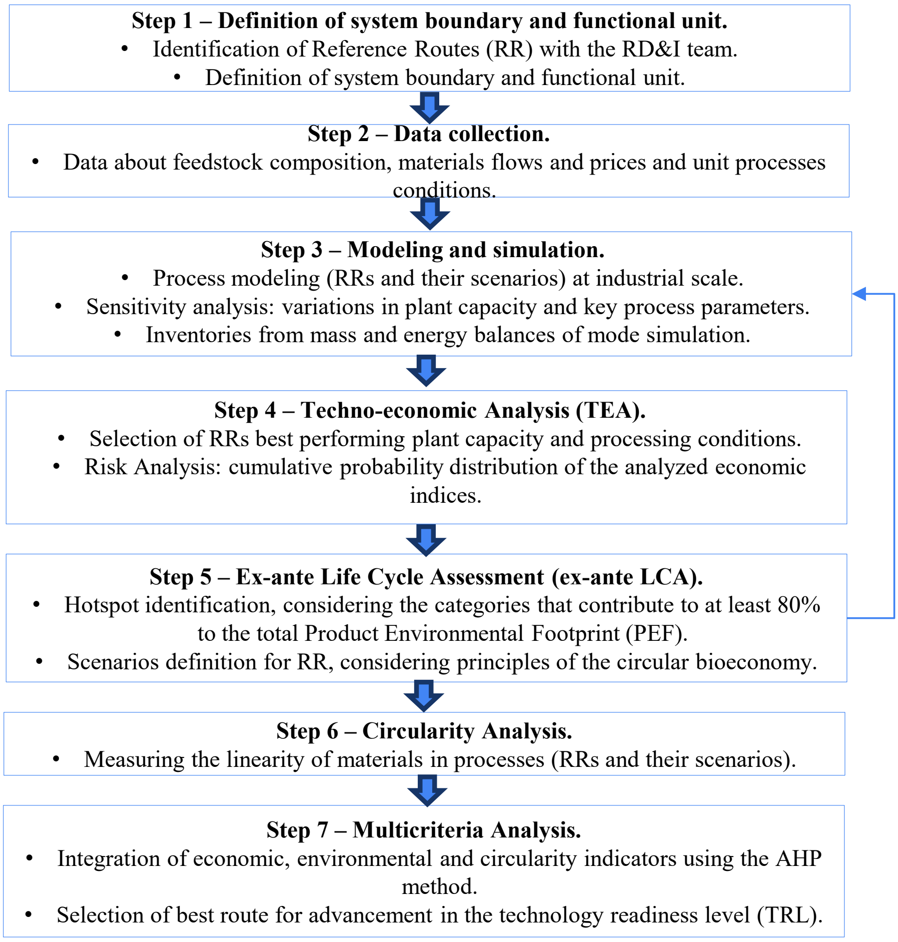


Figure 1. Illustrative flowchart of the steps in the ETECA methodological approach.

2.2. Case study: RPC from dragon fruit

The TEEC was applied to evaluate RR for obtaining RPC from dragon fruit. The RR was proposed by Zocolo et al. (2021) to a novel food colorant at TRL 5, with improved enzymatic and microfiltration conditions established at lab and pilot scales.

2.2.1. Definition of scope, system boundary and functional unit

The system boundary was cradle-to-gate with the use and disposal phases of the RPC being disregarded because of the many possible uses for this colorant. The system boundaries included dragon fruit cultivation, transport from farm to plant, and RPC production (Figure 2). The functional unit was 1 kg of RPC.

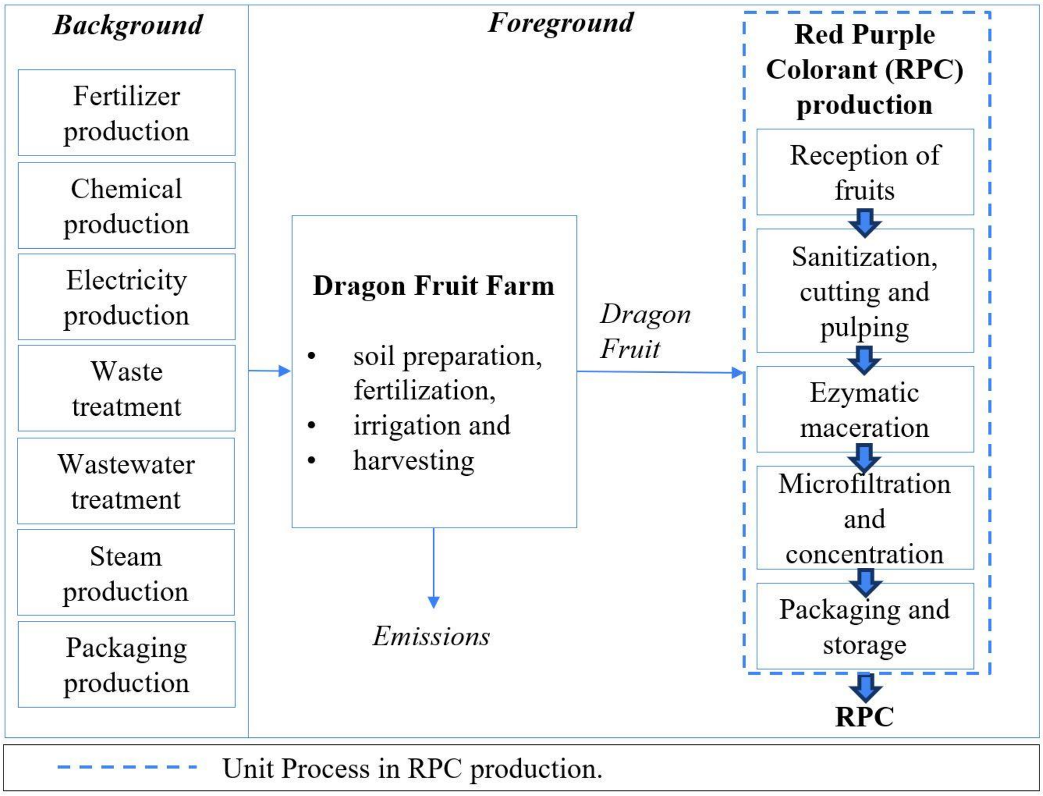


Figure 2. System boundary in the RPC case study.

1.1.1. Primary data collection and inventories

The dragon fruit cultivation inventory (Table 1) was newly developed based on literature data (Almeida et al., 2018; Lone et al., 2020; Gomes Vieira et al., 2022; Dos Santos et al., 2022), considering an orchard lifespan of 25 years. The average values of the inputs were estimated for an orchard with 1,666 plants ha^{-1}, spaced 2 m x 3 m, and an average annual production of 15 t ha^{-1}, starting from the 3rd year of production. The estimation of emissions from the agricultural process was carried out using the BRLUC (Brazilian Land Use Change) method, implemented in the ICVCalc spreadsheet (Matsuura et al., 2022).

Table 1. Inventory of dragon fruit agricultural production.

Inputs and outputs	Substances / Inventories in ecoInvent	Unity	Quantity	Reference
Output				
Dragon fruit		t	15.00	
Inputs				
Water	Water, unspecified natural origin, BR, CE, Metropolitana, Andrade	m^3	152.32	Almeida et al., (2018)
Calcium carbonate ($CaCO_3$)	Soil pH raising agent, as $CaCO_3$ {RoW}| treatment, sludge from pulp and paper production, landfarming | Cut-off, U	kg ha^{-1}	1,800	Lone et al., (2020); Gomes Vieira et al., (2022)
Urea	Urea {RoW}| urea production | Cut-off, U	kg ha^{-1}	286.52	Lone et al., (2020)
Inorganic potassium	Inorganic potassium fertilizer, as K_2O {RoW}| nutrient supply from potassium nitrate | Cut-off, U	kg ha^{-1}	127.65	Lone et al., (2020)
Single superphosphate	Single superphosphate {RoW}| single superphosphate production | Cut-off, U	kg ha^{-1}	580.00	Lone et al., (2020)
Borax	Borax, anhydrous, powder {RoW}| borax production, anhydrous, powder | Cut-off, U	kg ha^{-1}	2.5	Lone et al., (2020)
Glyphosate	Glyphosate {RoW}| glyphosate production | Cut-off, U	kg ha^{-1}	1.4	Dos Santos et al., (2022)
Air emissions				
Carbon dioxide	Carbon dioxide	kg ha^{-1}	209.19	
Ammonia	Ammonia, BR	kg ha^{-1}	23.64	
Dinitrogen monoxide	Dinitrogen monoxide	kg ha^{-1}	6.22	
Nitrogen oxides	Nitrogen oxides, BR	kg ha^{-1}	2.44	
Water emissions				
Nitrate (NO_3^-)	Nitrate, BR	kg ha^{-1}	1427.45	
Cadmium (II)	Cadmium (II)	kg ha^{-1}	4.40E-05	
Copper, ion	Copper, ion	kg ha^{-1}	3.12E-03	
Zinc (II)	Zinc (II)	kg ha^{-1}	1.85E-02	
Lead (II)	Lead (II)	kg ha^{-1}	4.60E-04	
Chromium, ion	Chromium, ion	kg ha^{-1}	1.93E-02	
Soil emissions				

Cadmium (II)	Cadmium (II)	kg ha^{-1}	4.86E-03
Zinc (II)	Zinc (II)	kg ha^{-1}	4.26E-02
Lead (II)	Lead (II)	kg ha^{-1}	4.67E-02
Nickel (II)	Nickel (II)	kg ha^{-1}	8.10E-03
Chromium, ion	Chromium, ion	kg ha^{-1}	1.56E-02
Glyphosate	Glyphosate	kg ha^{-1}	1.11

Regarding RPC production, data was collected at laboratory and pilot plant located at the Brazilian Agricultural Research Corporation (Embrapa), using red dragon fruit supplied by the company FRUTACOR (Vale do Jaguaribe – CE, Brazil). First the fruits were cleaned and sanitized, then peeled and depulped, retaining the seeds in a 1 mm sieve. For enzymatic maceration, 5 kg of dragon fruit pulp were mixed with commercial liquid enzymatic complex. The optimized process conditions for enzymatic maceration were identified at the center point of the central composite rotatable design (CCRD). The complete design is presented in Table S1 (Supplementary Material, SM). Lastly, the pulp was heated to 55 ºC and transferred to the microfiltration system tank (Figure 3).

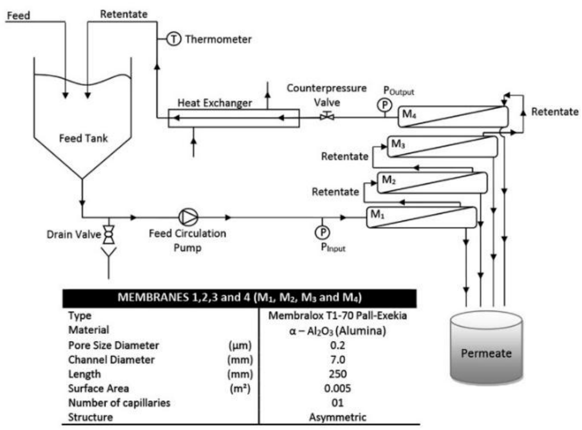


Figure 3. Microfiltration membrane system (adapted from Viana et al., 2021).

The membrane microfiltration system consisted of four tubular aluminum oxide (Al_2O_3) membrane modules, model Membralox, manufactured by PALL (Port Washington, New York, USA). Each module had a surface area of 0.0055 m² and pores with a diameter of 0.2 µm. Pulp recirculation under an average pressure of 2.5 bar was achieved by a positive displacement helical pump.

The procedure lasted a total of 2 hours, with the permeate volume of the four membranes collected for 1 minute every 10 minutes. The final flow rate was obtained by averaging all flow rates over a 10-minute period. The system Permeate Flow (PF) and Volumetric Reduction Ratio (VRR) was determined according to Viana et al., (2021).

The collected permeate was concentrated at 80 °C under vacuum pressure (700 mmHg) until reaching 70 °Brix. Immediately after, the concentrate was packaged in amber glass bottles and stored under refrigeration at 7 °C ± 2 °C. The mass balance (Timmerhaus and West, 2004) was performed at all unit processes of RPC production, considering the input and output of wet mass. The data collected can be found in Table S2.

2.2.2. Plant simulation at industrial scale

Based on the data collected at lab and pilot scales, a model of an industrial plant for the RR (and scenarios) was built using SPD (Figure 4). The plant was designed in batch mode (operation: 330 day a year, 24 hours a day). The RR processing load was set at 500 kg of dragon fruit per batch, with sensitivity analysis considering 1000 kg batch^{-1} to assess potential economies of scale. This upper limit ensures that annual plant demand does not exceed 50% of the projected 2025 dragon fruit production in Ceará (3,200 t), given the fruit's high demand for fresh consumption (Diário do Nordeste, 2026).

The industrial plant model was organized into three stages: "Reception/Washing/Extraction", "Enzymation/Microfiltration/Concentration", and "Packing/Storage". The process begins with the reception and storage of the fruit (P-2), followed by sanitization (P-3) and cutting (P-4). Next, the fruit passes through the expeller pressing (P-5) to remove peels, seeds and mucilage. In the homogenization tank (P-6), an enzymatic complex is added to macerate the pulp, which is then clarified by microfiltration (P-7) and concentrated in the evaporator (P-8). The concentrate is then packaged (P-9), boxed (P-10), and stored under refrigeration (P-11). Table 2 shows the annual input required in the RR.

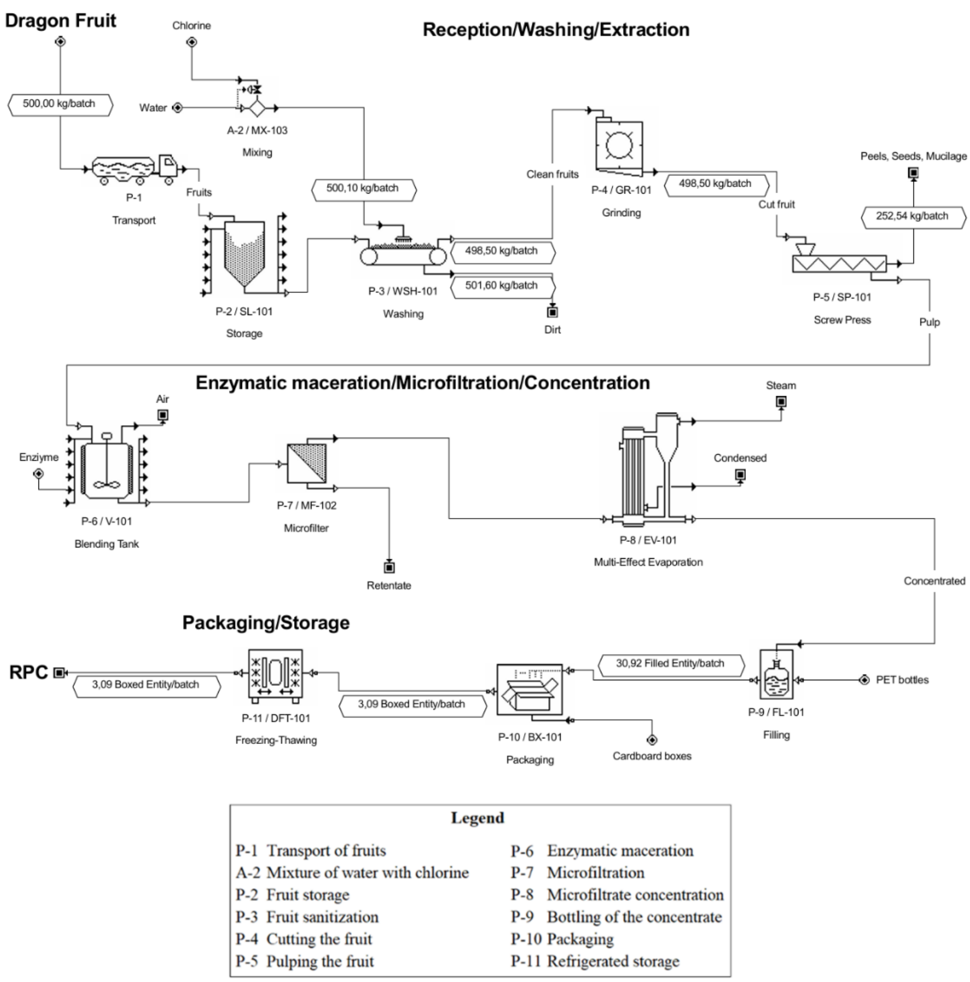


Figure 4. Process flow diagram for obtaining the RPC on the reference route (RR).

Table 2. Inventory of RPC production, processing 500 kg of dragon fruit per batch.

Inputs and outputs	**Substances/Inventories in ecoInvent**	**Unity**	**Annual quantity**
Output			

RPC		t	173.45
Inputs			
Water		m^3	4,772.39
Chlorine	Chlorine, liquid {RoW}| market for chlorine, liquid | Cut-off, U	t	0.13
Corrugated board box	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	t	2.72
Enzymes	Enzymes {GLO}| market for enzymes | Cut-off, U	t	0.65
Dragon fruit	Dragon Fruit Farming	t	1,243.26
Nitric acid	Nitric acid, without water, in 50% solution state {RoW}| market for nitric acid, without water, in 50% solution state | Cut-off, U	t	0.19
PET bottles	Polyethylene terephthalate, granulate, bottle grade {RoW}| polyethylene terephthalate, granulate, bottle grade, recycled to generic market for bottle grade PET granulate | Cut-off, U	t	8.33
Refrigerant R134a	Refrigerant R134a {RER}| refrigerant R134a production | Cut-off, U	t	0.15
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {RoW}| market for sodium hydroxide, without water, in 50% solution state | Cut-off, U	t	1.04
Transport	Transport, freight, lorry 16-32 metric ton, EURO1 {BR}| market for transport, freight, lorry 16-32 metric ton, EURO1 | Cut-off, U	km	10.00
Electricity	Electricity, high voltage {BR-North-eastern grid} | electricity, high voltage, production mix | Cut-off, U	kW h^{-1}	266,632.00
Treatment of biowaste	Biowaste {RoW} Adapted | treatment of biowaste, industrial composting | Cut-off, U	t	650.06
Treatment of wastewater	Wastewater, average {RoW Adapted| treatment of wastewater, average, wastewater treatment | Cut-off, U	t	5142.09

2.2.3.1 Sensitivity analysis

Plant models were built for different plant processing capacities, varying the raw material input from 600 to 1000 kg batch^{-1} in 100 kg increments. These variations will be identified from now on as RRX, where RR represents Route Reference and X represents variation in kg batch^{-1}. Moreover, considering the intrinsic variability of the microfiltration membrane behavior, the PF and VRR parameters were treated as stochastic variables. For incorporation of PF and VRR variations, confidence intervals were defined from distribution percentiles: pessimistic (P5), typical (P50), and optimistic (P95), representing reduced, median, and upper-bound process performance, respectively. In total, 18 models were built for RR, combining different plant capacities, PF and VRR values (see SM, Table S3). Due to industrial confidentiality agreements, specific microfiltration parameters (membrane flux and concentration factor) cannot be disclosed. These values were omitted from Table S3 but do not affect the validity of the analyses presented.

2.2.3. TEA

The MSP was obtained considering a discount rate (DR) of 14.21% and applying a 10% profit margin to estimate the PSP. The DR was the average SELIC (Special System for Settlement and Custody) rate in 2025, which is the base interest rate used in Brazil (Central Bank of Brazil [BCB], 2026a). Table 3 shows the economic parameters and input prices of the project. For this regional case study focused on Brazil, a discount rate of 14.21% per year was adopted, mirroring the country's average basic interest rate (Selic Rate) for 2025 (Central Bank of Brazil, 2026). This selection follows the guideline that the minimum acceptable rate of return should be based on the highest return available on safe investments, such as government bonds (Timmerhaus and West, 2004). Therefore, the Selic rate serves as the contextual risk-free baseline for the local market rather than a mandatory standard.

Table 3. Economic parameters, product, and chemical prices used in TEA.

Economic parameter	Value	Reference
Year of Analysis	2025	
Location	State of Ceará - Brazil	
Project life (year)	25	
Construction period (months)	30	

Start-up period (months)	4	
Income tax rate (%)	25	Contábeis (2025).
Inflation rate (%)	4.26	IBGE (2026)
Depreciation method/ period (year)	Straight line/10	
US$ Exchange to Brazilian Real (R$) exchange rate*	5.59	BCB (2026b)
Red Flesh Dragon fruit (US$ kg^{-1})	1.79	MFRURAL (2025)
Enzyme (US$ L^{-1}) *	126.13	
NaOH (US$ kg^{-1}) *	2.35	
NaClO (US$ kg^{-1}) *	1.80	
HNO3 (US$ kg^{-1}) *	8.01	
PET bottles*	14.61	
Cardboard boxes (kg)*	2.02	
Energy Tariff (kw h^{-1})	0.19	ENEL (2018)
Water tariff (m^3)	7.58	CAGECE (2025)
Operator's working hours (US$ h^{-1})	3.02	MTE (2026)
Supervisor's working hours (US$ h^{-1})	8.01	MTE (2026)

* Prices quoted from local suppliers.

Equipment sizing and mass–energy balances were obtained using SPD. Purchase Equipment Costs were estimated from the SPD database (Russo et al., 2022; Petrides et al., 2000) and updated using the Chemical Engineering Plant Cost Index. Equipment acquisition prices are listed in Table S4.

2.2.3.1. Risk Analysis

To assess the economic risk of the project in the face of market uncertainties, a Monte Carlo simulation with 10,000 iterations was applied. This procedure allowed for probabilistic analysis instead of a deterministic one, quantifying the risk of infeasibility (NPV < 0) under different market variations. The following input variables and distributions were considered in this analysis: i) Raw Material Cost (Dragon Fruit), using a triangular distribution (Asadi et al., 2017) and ii) the Discount Rate (SELIC rate, from 2020 to 2025, according to BCB, 2026a), using a normal distribution (Bruni et al., 1998), reflecting the volatility of the cost of capital. This dual-uncertainty approach provides a robust risk assessment by capturing interactions between raw material price volatility and capital opportunity cost. The values used in these function distributions and the algorithm applied to integrate the input variables in this risk analysis are in SM section 5.

For each of the 10,000 iterations, the Net Present Value (NPV) and Internal Rate of Return (IRR) were automatically recalculated. The analysis was performed for two sales scenarios: the Minimum Selling Price (MSP) and the Price with Profit Margin (PSP). Results were compiled into frequency histograms and cumulative probability curves. Project risk was defined as the relative frequency of iterations in which the NPV showed negative values (US$NPV < 0 US$).

2.2.4. LCA, Circularity and MCDA analysis

The environmental impact assessment was modeled using SimaPro® software (PRé Sustainability, Amersfoort, The Netherlands), v9.5.0.0, and the Ecoinvent database, v3.9.1. Circularity analysis was performed using Microsoft Excel® software. The modified equation is detailed in SM section 5. The MCDA was performed using the 3DM Web software (v.1) developed by Bozza et al., (2020).

3. Results and discussion

3.1. Techno-economic analysis (TEA)

Sensitivity analysis and MCS revealed an inversely proportional correlation between processing scale and economic viability indicators (MSP, PSP, DPB, IRR, and NPV), highlighting gains in economies of scale. In Figure 5, we can see that the reduction in MSP with the increase in load from 500 to 1000 kg batch^{-1} reflects the dilution of production costs over the increase in RPC productivity. It is also observed that the DPB values, when using PSP, decreased to approximately 12.4 years, indicating greater financial robustness compared to MSP (24 years). An acceptable payback period in Brazil is typically around 5 years (Da Silva et al., 2015) or 5–8 years in similar studies (Campos-Ramírez et al., 2020; Canizales et al., 2020). Consequently, the project is highly sensitive to increases in raw material and operational costs.

In Figure 6, we can observe that, while the IRR calculated based on MSP remained constant at 14.21%, the application of PSP raised the IRR to values between 17.08% and 17.68%. This performance is corroborated by the linear growth of the NPV, which reached its highest value in the P95 scenario with a load of 1000 kg (US$ 2,591.00), demonstrating that the increase in production capacity not only reduces the DPB, but also directly increases the absolute value generation of the project. In the Brazilian scenario, this IRR is more attractive than investments in government bonds, since in January 2026, the interest rate in Brazil was 15% (BCB, 2026a). Looking at a scenario beyond the national one, the IRR obtained is within the acceptable range of 16-24% per year for new products or technological processes (Timmerhaus and West, 2004).

It is noted that the low dispersion between the P5, P50, and P95 percentiles suggests that, although the cost of production is sensitive to operational variations, the attractiveness of the investment remains resilient even under pessimistic conditions. These results consolidate the RR1000 scale as the most technically promising configuration to ensure attractiveness to investors and competitiveness in the natural food coloring market. Although the P95 had the lowest production cost, opting for the P50 offers a more conservative parameter for the project, which is essential for subsequent stages.

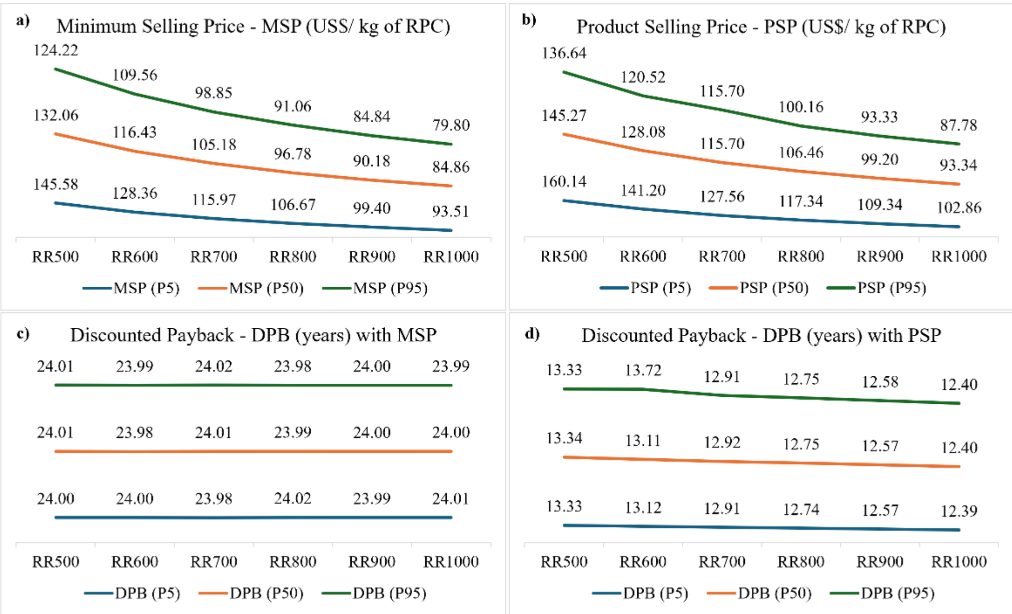


Figure 5. Sensitivity analysis and Monte Carlo simulation for cost and time indicators: (a) Minimum Selling Price (MSP); (b) Product Selling Price (PSP); (c) Discounted Payback Time (DPB) based on MSP; (d) Discounted Payback Time (DPB) based on PSP.

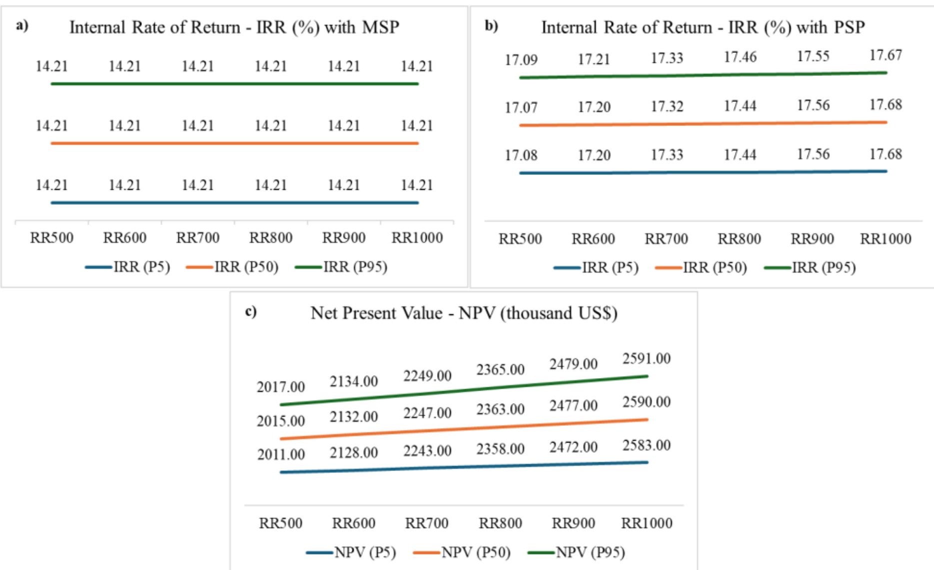


Figure 6. Profitability and investment potential assessment: (a) Internal Rate of Return (IRR) based on MSP; (b) Internal Rate of Return (IRR) based on PSP; (c) Net Present Value (NPV) as a function of raw material load.

Table 4 shows that the CAPEX (Capital Expenditure) and OPEX (Operating Expenditure) values for the P50 case increase with the quantity of fruit processed, due to the increased size of equipment and inputs used in RPC production. RR1000 showed the highest annual demand for pitaya, reaching 1,243.26 t/year, which corresponds to 38.85% of local production. Although local production is sufficient to meet all analyzed capacities, there are risks to consider, such as the seasonality of fruit production, which typically occurs between November and April (Lone et al., 2020). This characteristic indicates the need to establish supply contracts with producers from different regions and maintain refrigerated stocks to ensure continuous supply throughout the year, factors that can increase operational costs.

In this context, it is important to map potential suppliers and establish partnerships with the public sector to provide incentives promoting the expansion of local production. According to De Sá Filho (2026), government policies contribute to overcome barriers and mitigate technological risks associated with the development of new processes. Another strategy to reduce risks is to diversify production by processing additional fruit species, thereby decreasing dependence on a single raw material and a single product, which enhances the plant's financial attractiveness (Zabot and Silva, 2026).

Table 4. Techno-economic results in different plant capacities.

Techno-economic parameters	**RR500**	**RR600**	**RR700**	**RR800**	**RR900**	**RR1000**
CAPEX (million US$)	11.53	11.67	11.80	11.94	12.06	12.17
OPEX (million US$)	3.72	3.99	4.27	4.54	4.81	5.08
Dragon fruit (t year^{-1})	621.63	745.96	870.28	994.61	1,118.93	1,243.26

The economic results of this study are compatible with other works that simulated natural colorant production processes. In the work of Zabot and Silva (2026), who obtained a reddish-orange pigment from Annatto seeds (*Bixa orellana* L.), reported an NPV of US$ 5.8 million at a DR of 7% (half the rate used in this study), an IRR of 19.1%, and a simple payback time (which does not take into account the time value of money) of 3-4 years.

Shofinita et al. (2021) simulated a spray-drying plant to obtain a natural colorant from dragon fruit peel (*Hylocereus undatus*). The authors reported an NPV of US$ 1.98 million, an IRR of 20.6%, and a DPB of 4.3 years. The difference in DPB may be attributed to the complexity of the production steps. Unlike this study, which used pilot-scale data for industrial-scale simulation, the cited works relied on laboratory-scale data for scale-up.

For RR1000, results of the risk analysis showed that when MSP is considered (Figure 7a), the NPV distribution shifts significantly to the positive region of the graph, with a substantial portion of the 10,000 iterations resulting in financial gains (NPV > 0), yielding a project risk of 16.40%. The average NPV value with MSP was US$ 6.38 million, with a standard deviation of US$ 9.40 million. The 16.40% risk represents the project's vulnerability to small fluctuations in the discount rate and raw material costs, especially the cost of dragon fruit. Considering PSP (Figure 7b), the average NPV was US$ 10.63 million, and the standard deviation was US$ 11.87, reducing project risk to 4.24%. It is important to note that the risk observed when the PSP is applied reflects the application of the profit margin.

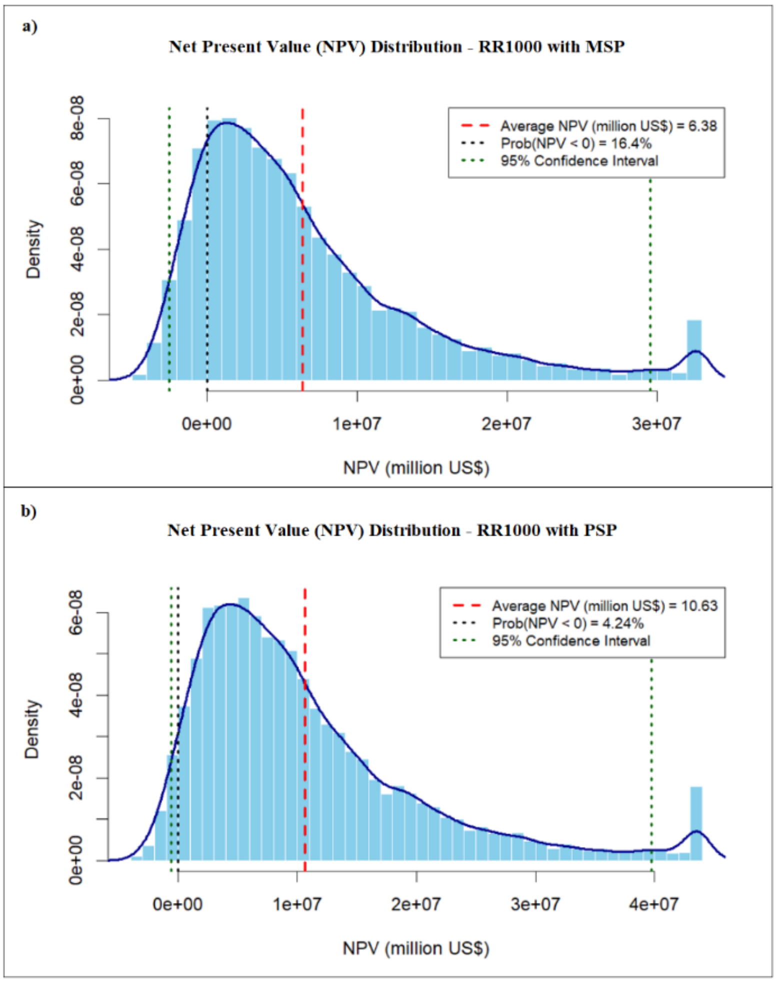


Figure 7. Probability of NPV values from risk analysis for RR1000 with MSP and PSP.

3.2. Life Cycle Assessment

The environmental impact assessment was applied to the chosen plant capacity and operational parameters (RR1000, PP50). The categories which contributed most (83.94%) to the PEF index, selected for contribution analysis, were Eutrophication, marine (EuM) (44.29% of PEF Index), Climate Change (CC) (11.93%), Acidification (AC) (10.60%), Eutrophication, terrestrial (EuT) (8.10%), Human toxicity, non-cancer (HTnc) (5.26%), and Resource use, minerals and metals (RUm) (3.76%). The other categories totaled less than 17% (Figure 8).

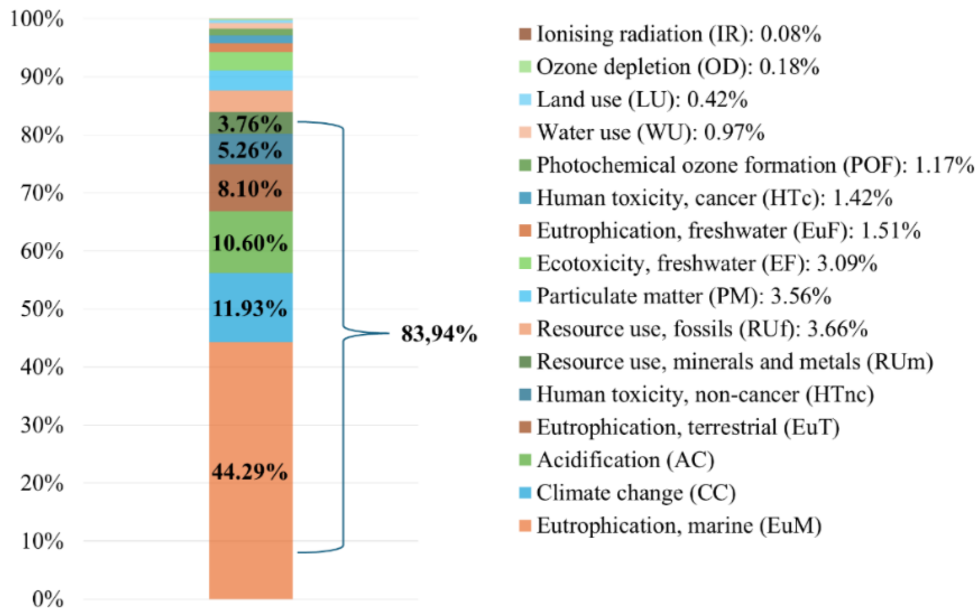


Figure 8. Most relevant categories in the impacts of RPC production at the RR1000 plant. Only the percentages of these categories are represented in the graph. The percentages of the other categories are shown in the legend next to their name.

The contribution analysis showed crop production was the main process in these six categories (Figure 9): EuM (99.16%), CC (69.62%), AC (77.58%), EuT (80.45%), HTnc (97.05%) and RUm (92.56%). RPC production was mostly relevant for CC (30.38%), AC (22.42%) and EuT (19.55. The transportation phase did not contribute to the categories chosen as critical points and was not represented in Figure 9.

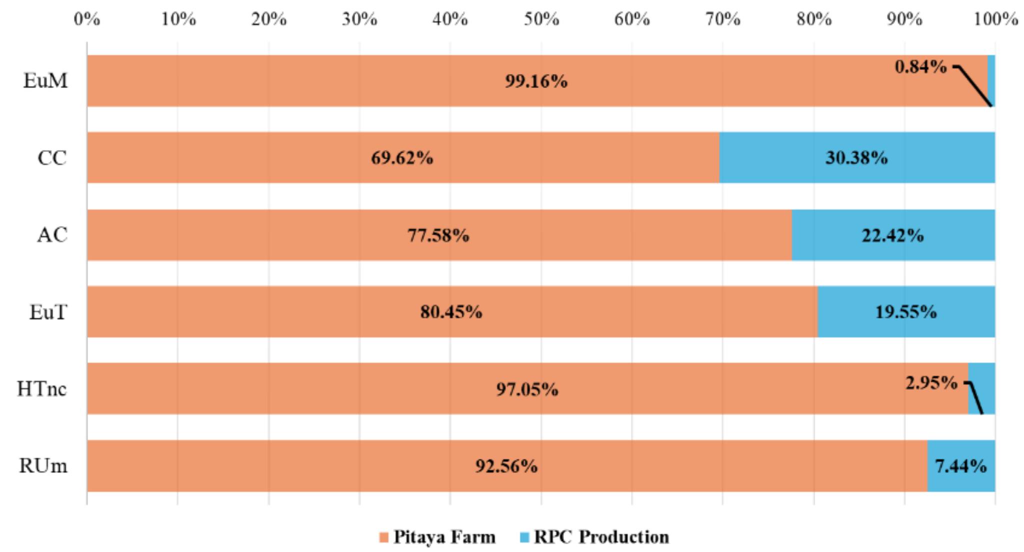


Figure 9. Processes that contributed most to the impact of life cycle of obtaining the RPC.

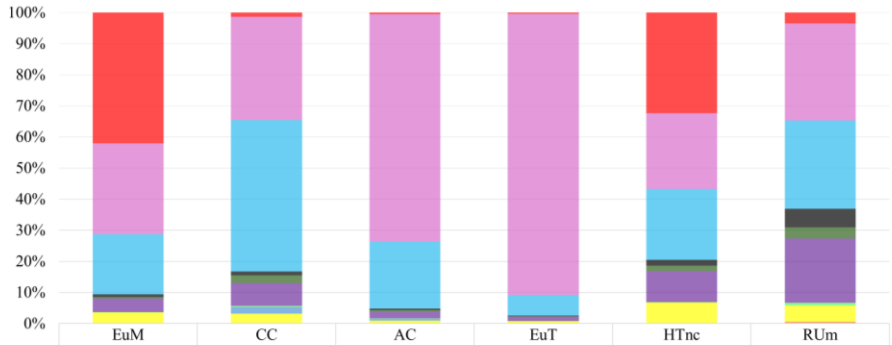
In the agricultural process, the production of fertilizers (Urea, Inorganic potassium and single superphosphate) were the biggest contributors to impacts. Fertilizer production contributes to acidification, mainly due to the emission of NH_3 into the air. Furthermore, nitrogen oxides (NOx) and carbon dioxide (CO_2) are also released during the transportation and production processes of fertilizers. NOx contributes primarily to terrestrial acidification and eutrophication, while CO_2, N_2O and CH_4 from land use change and fertilizers use, to climate change.

The impact network analysis (SM Fig. S1 to S6) demonstrates that the production of anhydrous liquid ammonia represents the main factor associated with the environmental impacts from urea manufacturing. In the production of potassium-based fertilizers, the main contributor to the process is the production of potassium nitrate. Regarding the production of single superphosphates, the main sources of impact are observed to be the processes of obtaining sulfuric acid, organic reagents, and electricity.

Analyzing only the RPC production process (Figure 10), the treatment of biowaste was relevant to all six categories, with a large share in AC (73.13%) and EuT (90.44%). The impact network of these categories (SM, Figs. S7 and S8) showed the composting process and the use of diesel and electricity during treatment were the main contributors to the environmental impact of waste treatment.

Wastewater treatment contributes mainly to the categories of EuM (42.04%) and HTnc (32.38%). The impact network of these categories (SM, Fig. S9 and S10) revealed that the formation of sewage sludge is the main source of environmental impact from this process. This byproduct is characterized by high levels of organic matter, nutrients, pathogens, and toxic substances, including organic contaminants and heavy metals, representing one of the main sources of impact from this process (Di Costanzo et al., 2021).

Electricity production has its largest contribution in CC (48.73%), although the Brazilian electricity mix is predominantly renewable. The impact network analysis (SM, Fig. S11) identified natural gas and heavy fuel oil as the main causes of the environmental impact in the electricity generation used in the simulated RR1000 power plant. The use of this source causes CO_2 and NOx emissions, directly influencing the categories of acidification and climate change.



	EuM	CC	AC	EuT	HTnc	RUm
Treatment of wastewater	42.04%	1.37%	0.47%	0.41%	32.38%	3.47%
Treatment of biowaste	29.30%	33.18%	73.13%	90.44%	24.42%	31.23%
Electricity Production	19.33%	48.73%	21.65%	6.62%	22.74%	28.44%
Sodium hydroxide Production	0.76%	1.28%	0.42%	0.25%	1.82%	5.99%
Refrigerant Production	0.49%	2.48%	0.49%	0.17%	1.79%	3.61%
PET Production	4.44%	7.34%	2.16%	1.26%	9.98%	20.62%
Nitric acid Production	0.08%	0.31%	0.10%	0.10%	0.15%	0.87%
Enzymes Production	0.00%	2.19%	0.65%	0.00%	0.00%	0.00%
Corrugated board box Production	3.49%	3.01%	0.88%	0.72%	6.56%	5.23%
Chlorine Production	0.07%	0.12%	0.04%	0.02%	0.17%	0.55%

Figure 10: RPC processes that contributed most to the impact categories.

The results of the critical point analysis show the importance of characterizing waste (liquid and solid) during the development phase, so that new opportunities can be identified for the valorization of these wastes. Furthermore, the results suggest the search for a new energy mix is important to reduce the impact on CC.

Comparing the environmental results obtained with studies employing similar methodologies, it is observed that Arias et al. (2025), when evaluating the extraction of R-phycoerythrin in various LCA scenarios, identified that the most promising scenario (aqueous extraction and enzymatic digestion) was the one that presented energy consumption (electricity and steam) as the main environmental critical point. Although they did not use LCA, Zabot and Silva (2026) highlighted the importance of minimizing waste generation. These studies reinforce that efficient waste management, and the use of renewable energies are essential challenges in novel processes for the bioeconomy.

3.3. Scenario development and analysis

From the hotspot analysis of RPC production process, five alternative scenarios were built, observing the principles of circular bioeconomy (Table 5). SC1 proposes reuse of the fruit washing water (P-3, Figure 4). SC2 valorizes peels and mucilage from pitaya pulping by incorporating them in RPC production process through adding a pasteurization step. SC3 uses microfiltration residue to produce powdered colorant, although this option still requires further residue characterization. SC4 replaces the hydroelectric energy mix with a photovoltaic system, a renewable power source available close to pitaya producing regions in Brazil. The assumptions adopted for constructing the scenarios and the process flow diagrams for these scenarios in SPD are provided in Table S5 and Figures S12-S16 of the SM, respectively.

Table 5. Scenarios Developed Based on the Principles of the Circular Bioeconomy.

Environmental hotspots	Principles of the circular bioeconomy	Improvement	Scenarios
Wastewater treatment	Use of waste and residues as a resource	Wastewater utilization	Scenario 1 (SC1)
Biowaste treatment.	Resource Efficiency	Peels and mucilage utilization in production of RPC.	Scenario 2 (SC2)
Biowaste treatment.	Resource Efficiency	Retentate of microfilter.	Scenario 3 (SC3)
Electricity production	Resource Efficiency	Use of photovoltaic energy mix for equipment operation	Scenario 4 (SC4)
		Scenario 5 encompasses all the measures from the previous scenarios.	Scenario 5 (SC5)

The environmental and economic results of these scenarios were compared to the results of RR1000 (P50). Regarding the environmental results (Figs. 11a, 11b, 11c, 11d, 11e, and 11f), SC2 showed the largest reductions in all six environmental impact categories analyzed, ranging from 63 to 68%, according to the category. These results highlight the importance of using peels and mucilage, besides pitaya pulp, as raw material for RPC, increasing the efficiency of the RPC production process.

The water reuse scenario (SC1) did not change impact values in the main categories, while energy mix substitution (SC4) did not result in reductions in all impact categories. In SC4, there was a 9.90% decrease in total CC value, a category in which electricity use made the greatest contribution. However, there was an increase (43.57%) in the RUm category caused by using solar panels (Stolz et al., 2017).

In SC3, the impacts rose by more than 65% in all categories because unit operations were added to produce a by-product. However, all categories decreased in SC 5, suggesting that concurrent mitigation of these effects may be possible with advancements in both solid waste management and wastewater treatment.

Regarding the economic analysis (Figs. 12a, 12b, 12c), the best results were also for SC2 that presented the lowest MSP and PSP values. These reduced values results are explained from better utilization of dragon fruit in the RPC process. The other economic indicators (IRR and DPB) in SC2 remained similar to those of RR1000.

In SC1, the equipment required for water reuse and recovering the vapor stream from the evaporation step increased operating costs to US$ 5,159,699.00 (1.42%). This rise elevated the MSP and led to an increase in the NPV to US$ 2,647,053.00 (2.14%).

In contrast, SC3 presented the highest MSP and PSP values, mainly due to the increase in operational costs resulting from the inclusion of new unit operations. Even with the inclusion of a byproduct with an estimated PSP of US$ 3.60 kg^{-1}, the NPV of US$ 2,813,729 (8.65% higher than that obtained in RR1000) was only about 1.8% higher than the value obtained in SC2 (US$ 2,764,000). The CAPEX of SC3, which includes the acquisition of new equipment, increased 13.32% (US$14,426,126) in relation to CAPEX of RR1000 (US$12,816,000). The OPEX of SC3 also increased from US$ 5,084,841.00 (RR1000) to US$5,463,250.00 (7,44%).

In SC4, the NPV decreased by 0.35%, associated with reduced costs (due to the lower photovoltaic energy price). However, this also resulted in lower revenue, MSP and PSP values.

In SC5, there was a 13.03% increase in NPV compared to RR1000, however there was a 26.96% increase in CAPEX and a 9.31% increase in OPEX.

Considering the PSP, the risk analysis showed all IRRs exceeded the adopted DR (14.21%), reducing the project risk: 4.42% (SC1), 4.16% (SC2), 4.47% (SC3), 4.24% (SC4) and 4.94% (SC5) (Fig. S17 to S21). However, as discussed earlier, an IRR greater than the DR does not eliminate market uncertainties. This aspect becomes more critical given the DPB exceeded 10 years in all scenarios, exposing the projects to a prolonged period of uncertainty.

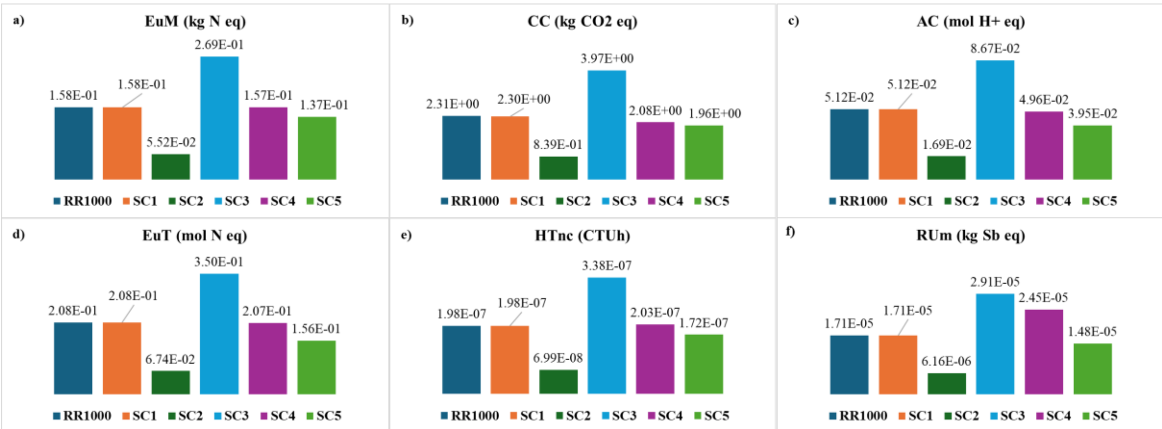


Figure 11: Comparison of the environmental results of RR100 and the developed scenarios.

Figure 12: Comparison of the economic results of RR1000 and the developed scenarios.

3.4. Circularity Analysis

The circularity analysis was performed for RR1000 and proposed scenarios. The comparative analysis of the LFI showed RR1000 was a highly linear system (97.36%), with a significant fraction of the raw material, mainly peels and mucilage, being discarded (Table 6).

The implementation of water reuse (SC1) and recovery of the microfiltration retentate (SC3) resulted in only slight reductions in LFI, reaching 95.26% and 95.31%, respectively. The most significant improvement was observed in SC2, in which dragon fruit peels and mucilage were incorporated into the RPC production process. This strategy reduced LFI to 83.61%, highlighting that maximizing raw material utilization is the main driver for improving process circularity.

In contrast, SC4 presented the same LFI as RR1000 (97.36%). This occured because the LFI only accounts for material flows. Therefore, replacing grid electricity with photovoltaic energy, although important for decarbonization, does not affect the mass balance of the RPC production process.

In the SC5 system, the integration of water reuse and byproduct processing (retentate) systems resulted in high water consumption for equipment washing, which influenced the LFI of this scenario.

From a CE perspective, quantifying process linearity helps identify material inefficiencies and highlights opportunities for process optimization (Rizwan et al., 2025). Reducing these losses contributes to a more efficient resource cycle, resulting in lower LFI values and potential economic and environmental benefits.

Table 6. Linear Flow Index (LFI) of RR1000 and scenarios.

Component	**RR1000**	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**
LFI (%)	97.36	91.06	83.61	95.31	97.36	87.12
V' (t/year)	7,269.63	4,176.51	6,217.87	6,304.73	7,269.63	6,233.06
W' (t/year)	6,885.48	3,429.86	4,179.88	5,713.64	6,885.48	4,627.08
2*M' (t/year)	14,539.26	8,353.02	12,435.68	12,609.45	14,539.26	12,466.12

3.5. Multi-Criteria Decision Analysis

The AHP method (Table 7) indicated that SC2 achieved the highest score (0.3336). This strategy increased the material circularity (LFI = 83.61%) without requiring the extensive addition of new equipment, as observed in SC3 (0.0952) and SC5 (0.1600). These differences directly affected both CAPEX and OPEX, making SC2 the scenario that best balanced technical, economic, and environmental performance. Under the current industrial configuration, pursuing full residue utilization (total circularity) introduced economic trade-offs that reduced project attractiveness, especially when compared with the more targeted intervention represented by SC2. The economic summary for RR1000 and all scenarios is in Table S6.

Table 7. Values of the weights calculated by AHP.

Alternative	Score obtained
SC2	0.3336
SC5	0.1600
SC1	0.1380
RR1000	0,1366
SC4	0,1365
SC3	0.0952

SC2 benefited from presenting better environmental results, since experts assigned greater weight to environmental categories compared to other indices (Table 8). This choice is based on the premise that mitigating the environmental impacts indicated by LCA has immediate priority over the other indices.

When comparing economic criteria, although the DPB is complementary to the NPV (Bhandari, 1989), the expert assigned moderate importance (3 = Moderate importance) to the NPV in relation to the DPB. Thus, prioritizing the NPV considers that the project involves a long-term investment (25 years) and that the total value of the wealth generated throughout the project exceeds the need for immediate recovery of the invested value.

The robustness of the judgments was confirmed by the Consistency Ratio (CR) of 0.0876, a value significantly lower than the limit of 0.10 proposed by the AHP method (Saaty, 1990). This index ensures that the pairwise judgments performed maintained acceptable logical consistency, validating the use of AHP for decision-making regarding the best route in this study.

Table 8. Criteria comparison Matrix.

	AC	CC	EuM	EuT	HTnc	RUM	LFI	NPV	DPB
AC	1	1/2	1/5	2	3	4	1	3	3
CC	2	1	1/5	2	3	4	1	3	3
EuM	5	5	1	5	6	7	1	3	3
EuT	1/2	1/2	1/5	1	1	3	1	2	2
HTnc	1/3	1/3	1/6	1	1	1	1	2	2
RUm	1/4	1/4	1/7	1/3	1	1	1	2	2
LFI	1	1	1	1	1	1	1	1	3
NPV	1/3	1/3	1/3	1/2	1/2	1/2	1	1	3
DPB	1/3	1/3	1/3	1/2	1/2	1/2	1/3	1/3	1

Note: 1 = Equal importance, 2 = Weak or slight, 3 = Moderate importance, 4 = Moderate plus, 5 = Strong importance, 6 = Strong plus, 7 = Very strong or demonstrated importance, 8 = Very, very strong, 9 = Extreme importance, according to Saaty (1990).

3.6. Limitations and recommendations

Despite the contributions of this study to the evaluation of technologies in early stages of development, some limitations should be noted. Regarding the economic feasibility analysis, the absence of a demand analysis of the RPC was overcome through sensitivity analyses on MSP and PSP, allowing the identification of the project's viability limit. Nevertheless, a comprehensive market analysis is necessary to quantify the real demand for natural food colorants. According to Aranda-Barradas et al. (2025), market analysis generates data that are crucial for establishing realistic profit margins.

Therefore, it is recommended that the RD&I team conduct a market survey to identify the price that food industries are willing to pay for natural colorants as a substitute for synthetic ones. Furthermore, to reduce the uncertainties of the assessment, future risk analyses should incorporate the fluctuations of other project variables, such as the costs of energy, water, enzymes, and labor, which were maintained as deterministic in this study.

Moreover, scenario 3 (SC3) was modeled prospectively using literature data (De Lima et al., 2020; De Sousa Silva et al., 2024) to estimate the composition of RPC and enable the full utilization of residues generated during the microfiltration process. Although these previous studies indicated that this extraction residue contains carbohydrates, fiber, and minerals, the absence of a specific physicochemical characterization for the residue produced in this route limits the accuracy of its potential application and, consequently, the estimation of its market value.

To address this limitation, future work should include a detailed physicochemical characterization of this residue, including proximate composition, fiber content, and thermal stability. Such analysis will allow a more accurate technical specification of this co-product and support its position within the functional colorant market.

Finally, the LCA showed crop production as the main source of impacts categories. As the inventory of pitaya production was built from literature data, considering a monocropping system, future analysis should collect primary data and expanded analysis to other production systems. This will reduce uncertainty in this process and allow the assessment of opportunities to reduce impacts.

4. Conclusions

This study presented the novel TEEC framework to robustly assess the techno-economic, environmental and circularity performance of food colorants with technological routes at low maturity level. This framework was structured in seven steps and successfully applied to assess the sustainability of RPC; a food colorant obtained from dragon fruit.

The techno-economic analysis indicated that the Discounted Payback Period (DPB) exceeds the desirable investment recovery horizon of five years, although the project presents a positive Net Present Value (NPV) and an Internal Rate of Return (IRR) above the discount rate. This result shows that the project may suffer from market variations. The risk analysis of the reference route (RR1000) indicated that, when Minimum Selling Price (MSP) was practiced, 16.40% of the ten thousand NPV simulations were negative. With Product Selling Price (PSP) practice, the risk fell to 4.24%.

The LCA analysis via the Product Environmental Footprint (PEF) method identified crop production as the primary impact driver, contributing over 90% to marine eutrophication and human toxicity due to the use of fertilizers (urea, inorganic potassium and single superphosphate). In the industrial phase, electricity consumption and the treatment of solid waste and effluents emerged as the most critical impact categories.

Circularity analysis showed that SC2 and SC5 had the lowest Linear Flow Index (LFI), with a value of 83.61% and 87.12%, respectively. This value indicates that the process efficiency is still very low and suggests the need to implement more efficient measures to promote process circularity.

MCDA identified scenario SC2, processing 1000 kg batch^{-1}, as the most suitable for advancing to the maturity scale. Although SC2 is economically viable (NPV of US$ 2.76 million and IRR of 17.70%, higher than the discount rate), the long payback period (12.36 years) indicates market risks that need to be mitigated in the future.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Gemini by Google to enhance readability of complex sentence structures. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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5. CONSIDERAÇÕES FINAIS

Esta tese propôs, aplicou e validou o framework TEEC (Análise Técnico-Econômica, Ambiental e de Circularidade) para apoio à tomada de decisão no escalonamento industrial de tecnologias alimentares em estágios iniciais de desenvolvimento (TRL 4-5). As evidências discutidas ao longo deste trabalho confirmam o caráter inovador desse **Framework TEEC que traz uma contribuição metodológica original**. Diferente das ferramentas descritas na literatura corrente, o framework rompe com a linearidade das avaliações convencionais ao estabelecer uma convergência dinâmica entre TEA, ACV *ex-ante* e LFI. Sua inovação teórica está na capacidade de revelar *trade-offs* e sinergias ocultas durante a transição da escala laboratorial para a escala piloto. Ao integrar os resultados da TEA — única etapa em que foi aplicada a Simulação de Monte Carlo — juntamente com a ACV *ex-ante* e o LFI ao método AHP, o framework conseguiu converter resultados multidimensionais em vetores de priorização consistentes, aumentando a robustez matemática do processo decisório e reduzindo a subjetividade inerente ao julgamento dos tomadores de decisão. O ineditismo prático foi ratificado ao provar, quantitativamente, que agendas de transição energética e de eficiência material operam sob dinâmicas independentes, transformando o TEEC em um instrumento indispensável de ecodesign e de inteligência decisória para a bioeconomia alimentar. Assim, o objetivo geral foi plenamente alcançado, consolidando um framework robusto e replicável para guiar a transição de modelos lineares para a bioeconomia circular.

O framework proposto fundamenta-se em:

- **Integração multidimensional:** A integração da Análise Técnico-Econômica (TEA), Avaliação do Ciclo de Vida (ACV) *ex-ante* e métricas de circularidade apoia a seleção fundamentada de processos e escalas ótimas antes da transição do ambiente piloto para o industrial.
- **Mitigação antecipada de riscos:** A integração dessas avaliações na fase de Pesquisa e Desenvolvimento e Inovação (PD&I) permite identificar gargalos técnicos, econômicos e ambientais de forma precoce, reduzindo riscos econômicos e ambientais antes da construção da infraestrutura física.
- **Direcionamento para o ecodesign:** A mensuração da circularidade em fases iniciais do projeto aumenta a probabilidade de a planta industrial ser implementada sob um modelo circular, evitando custos futuros de readequação de processos lineares.

- **Equilíbrio sistêmico:** A modelagem integrada previne que a otimização isolada de um vetor (como o econômico) resulte na degradação involuntária de outro (como o ambiental), preservando a harmonia entre os eixos.

A validação da metodologia ocorreu por meio de dois estudos de caso complementares. No primeiro, focado na valorização de resíduos agroindustriais, avaliou-se a produção de Fibra de Caju Desidratada (FCD) a partir do bagaço do pseudofruto. A análise multicritério (AHP) identificou que a secagem em estufa (6 toneladas batelada^{-1}) alimentada por energia solar fotovoltaica (Cenário SC3-RR1-6T) representou a configuração mais equilibrada. No segundo, direcionado à obtenção de Corante Vermelho-Púrpura a partir da pitaya, o cenário ótimo (SC2; 1.000 kg batelada^{-1}) destacou-se ao maximizar a circularidade pelo aproveitamento integral da polpa, cascas e mucilagem, elevando a eficiência material do processo.

A estrutura geral do framework TEEC (Análise Técnico-Econômica, Ambiental e de Circularidade) foi aplicada de forma idêntica através de sete etapas sequenciais em ambos os estudos. As sete etapas padronizadas foram: (1) definição do escopo, (2) coleta de dados, (3) modelagem e simulação em escala industrial, (4) Análise Técnico-Econômica (TEA), (5) Avaliação de Ciclo de Vida ex-ante (LCA), (6) análise de circularidade e (7) análise de decisão multicritério. Apesar de usar a mesma estrutura, o passo a passo dentro de algumas etapas sofreu adaptações específicas para lidar com as características únicas de cada matéria-prima e processo tecnológico. As principais diferenças na aplicação do framework foram:

- **Definição do Escopo (Etapa 1):** No estudo da Fibra de Caju (DCF), a etapa inicial partiu da comparação direta entre **duas rotas tecnológicas de referência distintas** (secagem em estufa de circulação de ar forçado vs. liofilização). Já no estudo do Corante de Pitaya), o escopo foi direcionado a uma **única rota de referência** (maceramento enzimático e microfiltração).
- **Modelagem de Incertezas Operacionais (Etapa 3):** Em ambos os trabalhos, a Simulação de Monte Carlo foi utilizada nesta etapa para gerar cenários operacionais discretos baseados em percentis: pessimistas, típicos e otimistas (P5, P50 e P95). A diferença consistiu nas variáveis estocásticas avaliadas: no processo do caju, a incerteza modelada foi a **umidade experimental da FCD** durante a secagem; no processo da pitaya, a incerteza recaiu sobre o **fluxo de permeado e a taxa de redução volumétrica** da membrana de microfiltração.

- **Análise de Risco Econômico (Etapa 4):** Para prever o risco financeiro de o projeto obter um Valor Presente Líquido (VPL) negativo, o estudo do caju aplicou a simulação de Monte Carlo variando **apenas a taxa de desconto de capital (Taxa Selic)**. O estudo da pitaya adotou uma abordagem de "dupla incerteza" nesta etapa, variando simultaneamente **a taxa de desconto e a volatilidade do custo da matéria-prima** (o preço de compra da pitaya fresca).
- **Ponderação na Decisão Multicritério (Etapa 7):** Embora ambos tenham utilizado o método AHP (Processo Analítico Hierárquico) para selecionar o melhor cenário para o avanço da tecnologia, os julgamentos dos especialistas sobre os pesos dos critérios variaram. No caso do caju, o critério ambiental foi julgado apenas "levemente mais importante" (nível 2 na escala de Saaty) que o critério econômico. Na pitaya, o especialista atribuiu um "peso maior" às categorias ambientais e definiu uma importância moderada do VPL sobre o Tempo de Retorno Descontado (DPBT).

5.1. Conclusões de cada objetivo específico

- **Simular os balanços de massa, energia e custos operacionais de rotas tecnológicas emergentes em escala industrial, gerando os inventários base para as avaliações de sustentabilidade:** O uso de modelagem computacional permitiu o escalonamento da escala piloto para a escala industrial. Para a Fibra de Caju Desidratada (FCD), foram gerados inventários e balanços detalhados para duas rotas (secagem em estufa e liofilização). Para o Corante de Pitaya, simulou-se a rota com capacidade ótima de 1000 kg por batelada (RR1000). Esses balanços gerados serviram como base essencial e robusta para viabilizar as avaliações de viabilidade técnico-econômica e impacto ambiental subsequentes nos dois estudos.
- **Determinar a viabilidade econômica dos cenários de referência por meio de indicadores financeiros, tais como o Preço Mínimo de Venda (PMV), Retorno Sobre o Investimento (ROI), Taxa Interna de Retorno (TIR), Valor Presente Líquido (VPL) e Tempo de Retorno Descontado:** Ambas as tecnologias provaram ser viáveis. No Artigo 1, a secagem em estufa a 6 toneladas por batelada (RR1-6T) obteve um Valor Presente Líquido (VPL) de US$ 1,75 milhões. No Artigo 2, a rota da pitaya alcançou um VPL de US$ 2,76 milhões. Contudo, ambas enfrentam um longo Tempo de Retorno Descontado (de 16,24 anos para a FCD e 12,36 anos para a pitaya), o que supera a margem de 5 anos de agentes de fomento nacionais (como o BNDES).

- **Avaliar os impactos ambientais ex-ante das rotas propostas, identificando os principais gargalos (*hotspots*) ao longo do ciclo de vida do processo:** A Avaliação do Ciclo de Vida (ACV) ex-ante localizou pontos críticos ambientais distintos entre os dois estudos de caso. Para a FCD, os maiores impactos incidiram na etapa industrial, dominados pelo consumo da rede elétrica (hidrelétrica) e pelo uso de vapor para aquecimento dos equipamentos, afetando drasticamente as categorias de Mudanças Climáticas e Uso de Recursos Fósseis. Já no caso do corante de pitaya, a fase agrícola despontou como o ponto crítico central em virtude do uso de fertilizantes químicos sintéticos (ureia, potássio, superfosfato simples), impulsionando mais de 90% das emissões nas categorias de eutrofização marinha e toxicidade humana.
- **Mensurar o desempenho circular das rotas tecnológicas por meio de indicadores de fluxo de massa, quantificando o potencial de valorização e reinserção de subprodutos no sistema:** No estudo da FCD, a recuperação da água de lavagem para a criação de um concentrado rico em carotenoides reduziu o Índice de Fluxo Linear (LFI) de 83,27% para aproximadamente 52%. Na produção da pitaya, a estratégia circular mais eficiente para diminuir a linearidade (reduzindo o LFI de 97,36% para 83,61%) foi o aproveitamento integral e reinserção das cascas e mucilagem para maximizar a extração do corante. A aplicação do LFI nos dois estudos de caso evidenciou benefícios importantes para avaliar a eficiência de materiais, mas também revelou limitações significativas na mensuração de estratégias exclusivamente energéticas. Em ambos os casos, a circularidade de materiais captada pelo LFI representou apenas uma das dimensões da bioeconomia circular. Embora essencial para identificar ineficiências na valorização de massa e na redução de perdas, o LFI não quantifica medidas de mitigação ambiental que não envolvem fluxos materiais.
- **Modelar a variabilidade dos parâmetros operacionais da escala piloto e as volatilidades de mercado via Simulação de Monte Carlo, estabelecendo perfis probabilísticos de risco para o VPL e para os impactos ambientais:** A aplicação da Simulação de Monte Carlo atestou a resiliência dos projetos contra volatilidades. No Artigo 1, modelando variações da taxa Selic e flutuações de umidade da desidratação (percentis P5, P50 e P95), o risco financeiro de perda (VPL < 0) da Rota 1 operando no limite de custo base ficou em 29,77% (RR1-6T) e 29,70% (RR2-9T), diminuindo para 23,92% (RR1-6T) e 24,37% (RR2-9T) ao praticar o Preço de Venda do Produto (PVP). No Artigo 2, o estudo de "dupla incerteza" (custo da pitaya e volatilidade da taxa de juros) demonstrou um risco inicial de 16,40% no PMV, mitigado expressivamente para

apenas 4,24% de chance de o projeto se tornar inviável quando praticado uma margem de 10% sobre o PMV.

- **Propor e avaliar cenários alternativos de bioeconomia circular direcionados à mitigação dos *hotspots* ambientais previamente identificados:** Os cenários gerados mostraram grandes eficiências, mas revelaram importantes *trade-offs* das tecnologias emergentes sustentáveis estudadas. Ao alimentar o processo da FCD (Artigo 1) com eletricidade 100% fotovoltaica para operação e aquecimento (Cenário 3), houve o declínio de mais de 45% nos impactos climáticos e fósseis; no entanto, o Uso de Recursos Minerais e Metálicos subiu expressivamente (mais de 1.600%) devido aos minérios demandados pelos painéis solares. Já para o caso do corante da pitaya (Artigo 2), a circularidade das cascas/mucilagem gerou redução profunda, de 63% a 68%, em todas as seis frentes de impacto ambiental crítico do ciclo.
- **Integrar e priorizar os indicadores multidimensionais (TEA-ACV-Circularidade) por meio do método AHP, consolidando uma estrutura:** A integração via o método AHP permitiu indicar com sucesso e de forma confiável a melhor rota para avanço na escala TRL. Para a FCD, a alternativa escolhida como mais equilibrada (pontuação de 0,1761) foi a Secagem em Estufa de 6 toneladas batelada^{-1} totalmente movida a painéis solares fotovoltaicos (SC3-RR1-6T), por unir o VPL viável às maiores reduções de Mudanças Climáticas. No processamento da pitaya, o melhor equilíbrio (score 0,3336) deu-se no Cenário 2 (processamento agregado com cascas e mucilagem), por alcançar a maior agregação circular (redução de perdas de massa) atrelada à ótima rentabilidade (TIR de 17,70%), descartando equipamentos superdimensionados ou de baixa recuperação de custo.

5.2.Limitações do Framework TEEC e sugestões para trabalhos futuros

Não obstante o alcance dos objetivos propostos, é imperativo pontuar as limitações metodológicas e arquiteturais que delimitam o escopo deste estudo e do próprio framework desenvolvido:

- **Abstração de Critérios Sociais (Escopo do Framework):** Sob a perspectiva de engenharia de sistemas e sustentabilidade holística, o Framework TEEC limitou-se às dimensões econômica, ambiental e material. A desconsideração de critérios sociais e de governança (como a avaliação de ciclo de vida social - ACV-S ou métricas de impacto na agricultura familiar local) configura uma limitação conceitual da estrutura atual, necessária para manter a parcimônia matemática do modelo inicial.

- **Sensibilidade à Incerteza de Dados Secundários (*Up-scaling*):** Sendo um modelo aplicado em fases TRL 4-5, a modelagem de processos dependeu substancialmente de dados secundários oriundos de patentes, simuladores de processos (como Aspen Plus) e bases de dados eco-inventariais internacionais. Embora a Simulação de Monte Carlo mitigue o impacto dessa variabilidade, o nível de incerteza intrínseco a coeficientes estequiométricos escalonados teoricamente representa uma limitação metodológica em comparação com plantas piloto operando em regime permanente estável.
- **Limitações do Indicador Material Adoptado (LFI):** O Índice de Fluxo Linear (LFI), escolhido pela sua clareza matemática e replicabilidade, concentra-se estritamente na massa física. Ele falha em capturar aspectos qualitativos da circularidade, tais como a degradabilidade biológica dos fluxos de resíduos, o nível de toxicidade dos compostos reciclados e a degradação da qualidade (entropia) dos materiais ao longo de sucessivos loops de reciclagem na cadeia de alimentos.
- **Coleta de Dados Primários Restrita:** Para a validação dos estudos de caso, os dados primários de laboratório (fornecidos pela Embrapa Agroindústria Tropical) refletiram condições experimentais controladas. A ausência de séries temporais longas com repetições sazonais sistemáticas nos dados de entrada limita a captura de variações reais de composição físico-química da matéria-prima vegetal, cujas flutuações fenotípicas foram tratadas apenas por aproximações de distribuições de probabilidade estatística.
- **Falta de análises abrangentes de mercado:** A ausência de pesquisas sobre a elasticidade de preços e a disposição do consumidor a pagar por novos ingredientes de base biológica dificulta a definição de margens de lucro comerciais mais precisas e realistas.

5.2.1. Limitações no Estudo de Caso 1 (Fibra de Caju Desidratada - FCD):

- **Tempo de Retorno de Capital elevado:** Mesmo após a aplicação da margem de 10% sobre o preço mínimo de venda, o projeto resultou em um Tempo de Retorno Descontado (DPBT), de aproximadamente 16,24 anos. Esse tempo representa uma barreira, pois supera o limite de 5 anos geralmente exigido por agências de fomento brasileiras, como o BNDES.
- **Transferência de Carga Ambiental:** Embora o Cenário 3 tenha sido a melhor estratégia contra as Mudanças Climáticas. O impacto na categoria de Uso de Recursos Minerais e Metálicos teve um aumento de 1.662,18% devido ao uso de metais

necessários para a fabricação dos painéis solares.

5.2.2. Limitações no Estudo de Caso 2 (Corante Vermelho-Púrpura de Pitaya):

- **Incertezas nos Dados do Cultivo Agrícola:** A Avaliação do Ciclo de Vida indicou que o cultivo da pitaya é a principal fonte de impacto ambiental. No entanto, o inventário para essa etapa foi construído com base em dados de literatura (focados em regime de monocultura) em vez de dados primários coletados em campo, o que aumenta o grau de incerteza dos impactos e limita a precisão para se propor novas reduções de impacto na agricultura.
- **Restrições na Análise de Risco:** A Simulação de Monte Carlo limitou as flutuações apenas aos preços da matéria-prima e à taxa de juros (Selic). Custos operacionais essenciais, como os de energia, água, complexos enzimáticos e mão de obra, foram mantidos como fixos (determinísticos).
- **Falta de Caracterização de Coproduto (Cenário 3):** O cenário que propôs a recuperação do retido da microfiltração para gerar um corante em pó secundário foi modelado de forma prospectiva, embasado apenas em literatura. A ausência de uma caracterização físico-química e de estabilidade térmica do resíduo limita a precisão de sua aplicação potencial, bem como a estimativa do seu valor no mercado.

5.2.3. Desafios críticos de implementação industrial das tecnologias avaliadas

- **Ponto de vista econômico:** Ambos os projetos apresentaram um longo Tempo de Retorno Descontado (DPB). Mesmo sob cenários otimizados com aplicação de margem de lucro sobre o Preço Mínimo de Venda (PMV), o tempo de recuperação de capital foi estimado em 16,24 anos para a fibra desidratada e 12,36 anos para o corante natural de pitaya. Estes tempos superam o limite padrão de 5 anos frequentemente exigido por agentes financiadores nacionais, como o BNDES, evidenciando o risco temporal dos investimentos.
- **Do ponto de vista ambiental:** A transição para sistemas renováveis e circulares revelou impactos negativos. No caso da fibra de caju, a descarbonização da matriz energética através do uso de energia fotovoltaica reduziu as emissões de gases de efeito estufa, mas gerou um incremento superior a 1.600% na categoria de uso de recursos minerais e metálicos. No caso do corante de pitaya, a fase agrícola configurou-se como

o gargalo central, respondendo por mais de 90% dos impactos de eutrofização marinha e toxicidade humana devido ao uso intensivo de fertilizantes nitrogenados.

5.2.4. Sugestões para investigações futuras

- **Caracterização físico-química e mercadológica dos coprodutos:** Avaliar as propriedades funcionais dos resíduos geradas nos cenários propostos, com ênfase no retido da microfiltração da pitaya e nas frações líquida e sólida oriundas da prensagem do bagaço de caju.
- **Análises de mercado e necessidade de demanda:** Conduzir estudos sobre a real necessidade do mercado por ingredientes sustentáveis, e consequentemente mapear a disposição do mercado em pagar por produtos naturais de alto valor agregado.
- **Refinamento dos inventários agrícolas:** Coletar dados primários de sistemas de cultivo em campo (com foco na cultura da pitaya), explorando modelos que reduzam a dependência de fertilizantes químicos sintéticos.
- **Mitigação de Impactos de Infraestruturas Renováveis:** Desenvolver pesquisas focadas na reciclagem em fim de vida de equipamentos solares, explorando tipos de manufatura circular e políticas públicas capazes de atenuar o intenso *trade-off* de uso de recursos minerais e metais causados pela implementação de matrizes fotovoltaicas nas plantas industriais analisadas.

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APÊNDICES

APÊNDICE A – MATERIAL SUPLEMENTAR DO ARTIGO 1

1. Descrição das condições de processamento para extração do suco de caju

O processamento dos pedúnculos de caju envolve lavagem e sanitização por imersão, seguidas de lavagem por aspersão, ambas utilizando água ozonizada (0,2 µL L-1). Imediatamente após, realiza-se uma seleção manual dos pseudofrutos na linha de produção para remover os frutos danificados ou estragados, seguida de uma etapa de lavagem e sanitização por aspersão. Em seguida, os pedúnculos são triturados em moinhos de lâminas para extração em máquinas de polpação equipadas com peneiras de 2,0 mm e refinadores equipados com peneiras de 0,8 mm para obtenção da polpa de caju refinada. O bagaço resultante dos processos de polpação e refino é então prensado em prensas tipo extrusora (rosca sem fim) para extrair a polpa residual, resultando no bagaço de caju industrial.

2. Descrição das condições de processamento para obtenção de fibra desidratada de caju (FCD) em planta piloto.

O bagaço de caju (BC) embalado e congelado foi adquirido de uma indústria de processamento. Após o descongelamento em câmara fria (5 °C), o BC foi pesado e água potável a 100 °C (BC:água, 1:2, m/m) foi adicionada à massa resultante em um tanque de agitação de aço inoxidável de 40 L. A mistura permaneceu sob agitação. Em seguida, o BC hidratado foi levado a uma prensa extrusora, onde foi prensado e pesado novamente. O processo de secagem em estufa foi realizado a 50 °C por 6 horas, utilizando um secador de bandejas com circulação de ar forçada (modelo SL-102/1980, marca Solab). Para a liofilização, a fibra de caju tratada foi primeiro congelada em um ultracongelador a -80 °C e, em seguida, transferida para um liofilizador piloto (Liobrás LP510). Os dois produtos obtidos, fibra de caju seca em estufa e fibra de caju liofilizada, foram moídos separadamente em um moinho (modelo 400-8D, marca Fritsch) e posteriormente embalados em sacos plásticos e armazenados à temperatura ambiente.

3. Dados sobre a produção de FCD coletados em uma planta piloto

Tabela S1: Balanço de massa em escala piloto do processo de produção de DCF

Etapas	**Massa (kg)**
Bagaço de Caju (BC)	9,40
Água	18,80
SUBTOTAL	28,20
Peso do BC após a imersão	27,42
Água evaporada após a imersão	0,78
Efluente da prensagem	15,51
Resíduos sólidos da prensagem	0,39
Resíduo retido dentro da prensa expeller (volume morto estimado)	2,04
Peso final do bagaço	9,48

4. Descrição do processo em escala piloto

Em ambas as rotas (Figuras S1 e S2), o processo inicia-se com a lavagem do bagaço (P-1/V-101) seguida da prensagem (P-2/SP-101). Após a prensagem, a fibra é desidratada. Na rota 1, foi utilizado o equipamento mostrado na Figura S1 (P-5/RDR-101). Para a rota 2, foi utilizado o equipamento (FDR-101) mostrado na Figura S2. Após a desidratação, a fibra é moída (GR-101), embalada em sacos plásticos (FL-101) e armazenada em caixas de papelão (BX-101).

Figura S1. Diagrama do processo da RR1-9T.

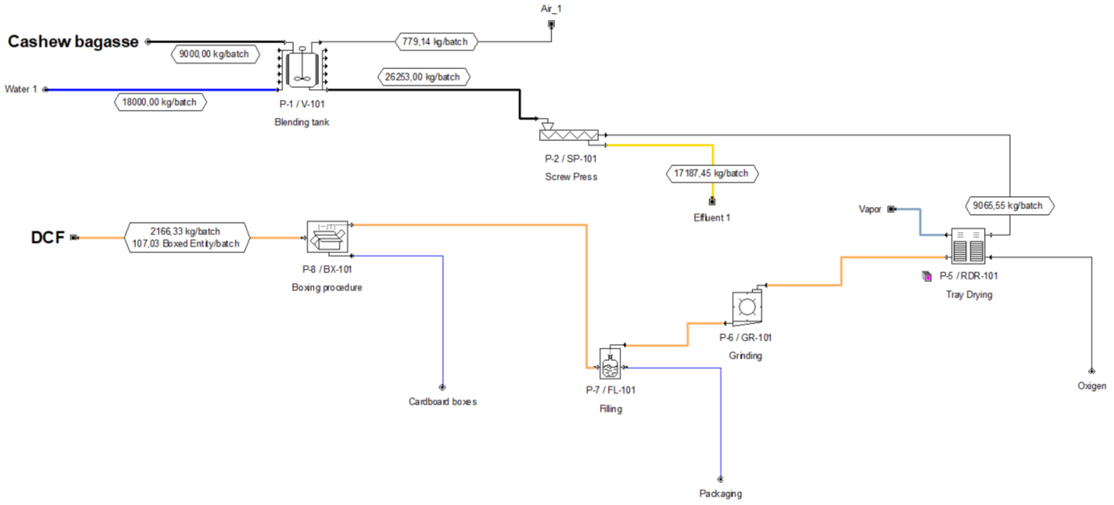
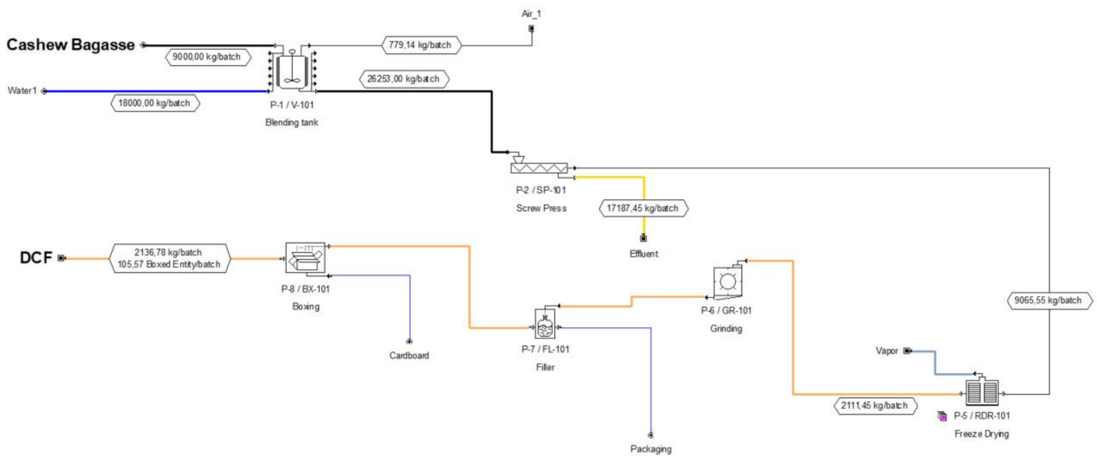


Figure S2. Diagrama do processo da RR2-9T.



5. Inventário da produção em escala industrial da FCD (Análise de Cenários)

Tabela S2: Inventário da extração anual de DCF em escala industrial de diferentes cenários.

Entrada e saídas	**Inventários do ecoinvent v. 3.9.1**	**Unidade**	**Quantidade anual**					
			SC1-RR1-6T	SC2-RR1-6T	SC3-RR1-6T	SC1-RR2-9T	SC2-RR2-9T	SC3-RR2-9T
Saída do produto								
FCD		t	170,42	291,13	291,13	252,04	325,16	325,16
Líquido concentrado		t	80,58			120,87		
Entradas								

Bagaço de caju	Cashew pulp production	ton.	708,08	1.224	1.224	720	1.386	1.386
Caixas de papelão	Corrugated board box {RoW}| market for corrugated board box | Cut-off, U	ton.	1,68	2,91	2,91	1,69	3,25	3,25
Embalagens plásticas	Polyethylene terephthalate, granulate, bottle grade {RoW}| polyethylene terephthalate, granulate, bottle grade, recycled to generic market for bottle grade PET granulate | Cut-off, U	ton.	1,89	0,58	0,58	1,92	0,65	0,65
Cloro	Chlorine, liquid {RoW}| market for chlorine, liquid | Cut-off, U	ton.	0,29	3,41	3,41	0,20	2,95	2,95
Água		m^3	1.775,58	3.130,74	3.130,74	1.713,30	3.361,99	3.361,99
Eletricidade	Electricity, high voltage {BR-North-eastern grid} | market for electricity, high voltage | Cut-off, U	$kW.h^{-1}$	96.581.000	1.669.520	1.970.498	81.215	3.367.389	3.708.203
Vapor	Steam, in chemical industry {RoW}| market for steam, in chemical industry | Cut-off, U	t	1.310	411	0.00	2.446	466	0.00
Água e emissões para tratamento								
Resíduo sólido	Biowaste {RoW} Modified | treatment of biowaste, industrial composting | Cut-off, U	ton.	29.39	52.34	52.34	29.89	59.27	59.27
Resíduo líquido	Wastewater, average {RoW} Modified| treatment of wastewater, average, wastewater treatment | Cut-off, U	m^3	383,23	2.446,87	2.446,87	317,43	2.771,06	2.771,06

6. Fluxogramas e inventários de todos os cenários

Figura S3. Cenário SC1-RR1-6T.

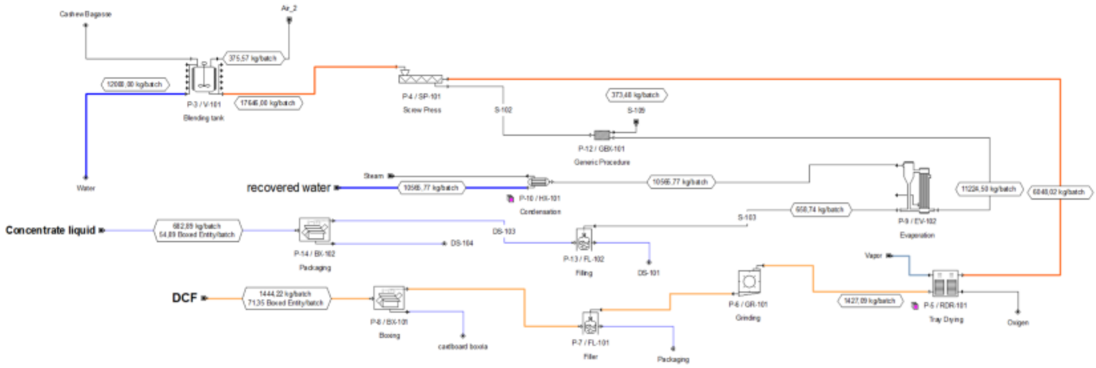
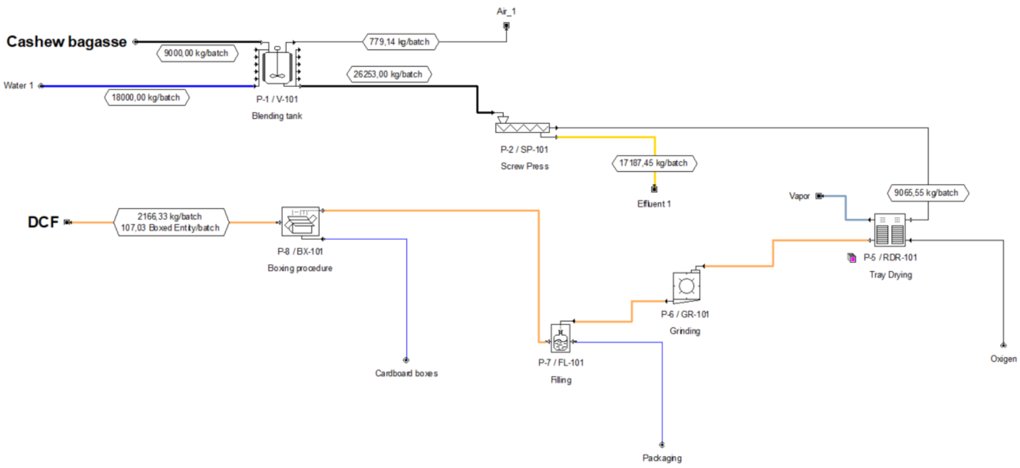


Figura S4. Cenário SC2-RR1-6T e SC3-RR1-6T.



Os diagramas para os cenários SC1 e SC2 são idênticos aos do RR1-6T, visto que a alteração da matriz energética ocorreu na configuração do software. A matriz fotovoltaica não existe no banco de dados do SuperPro Designer. Portanto, apenas o valor em kW/h foi alterado.

Figura S5. Cenário SC1-RR2-9T.

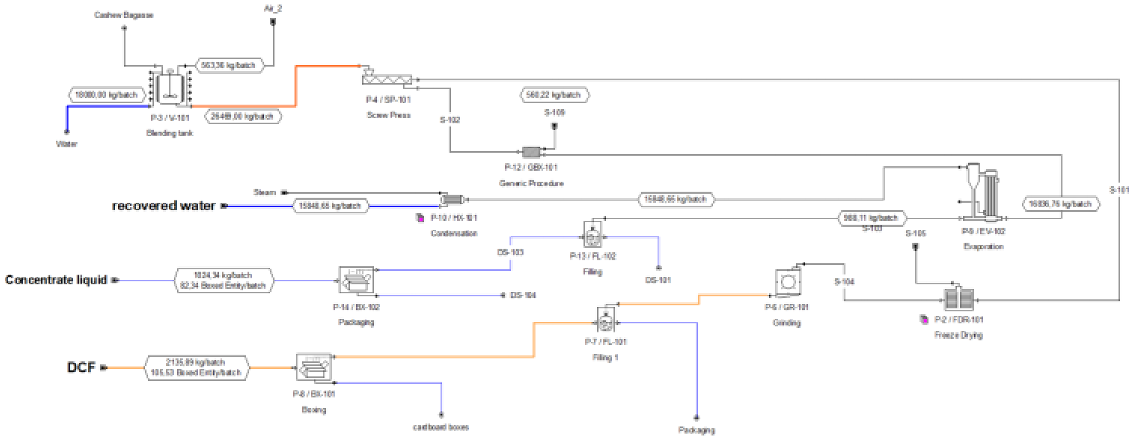
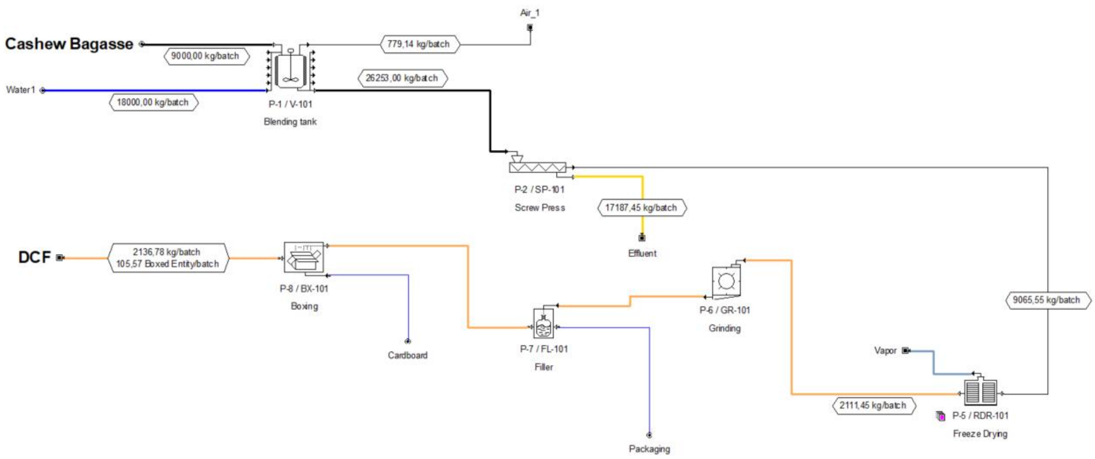


Figura S6. Cenário SC2-RR2-9T e SC3-RR2-9T.



Os diagramas para os cenários SC1 e SC2 são idênticos aos do RR2-9T, visto que a alteração da matriz energética ocorreu na configuração do software. A matriz fotovoltaica não existe no banco de dados do SuperPro Designer. Portanto, apenas o valor em kW/h foi alterado.

7. Rede de impactos dos três processos principais da produção da FCD

Estas imagens mostram a rede de impactos dos três principais processos: cultivo do caju, produção de suco e produção de FCD. As imagens foram geradas utilizando o software SIMAPRO versão 10.2.0. Banco de dados: ecoinvent 3.9.1.

Figura S7. Categoria “Acidification” (RR1-6T)

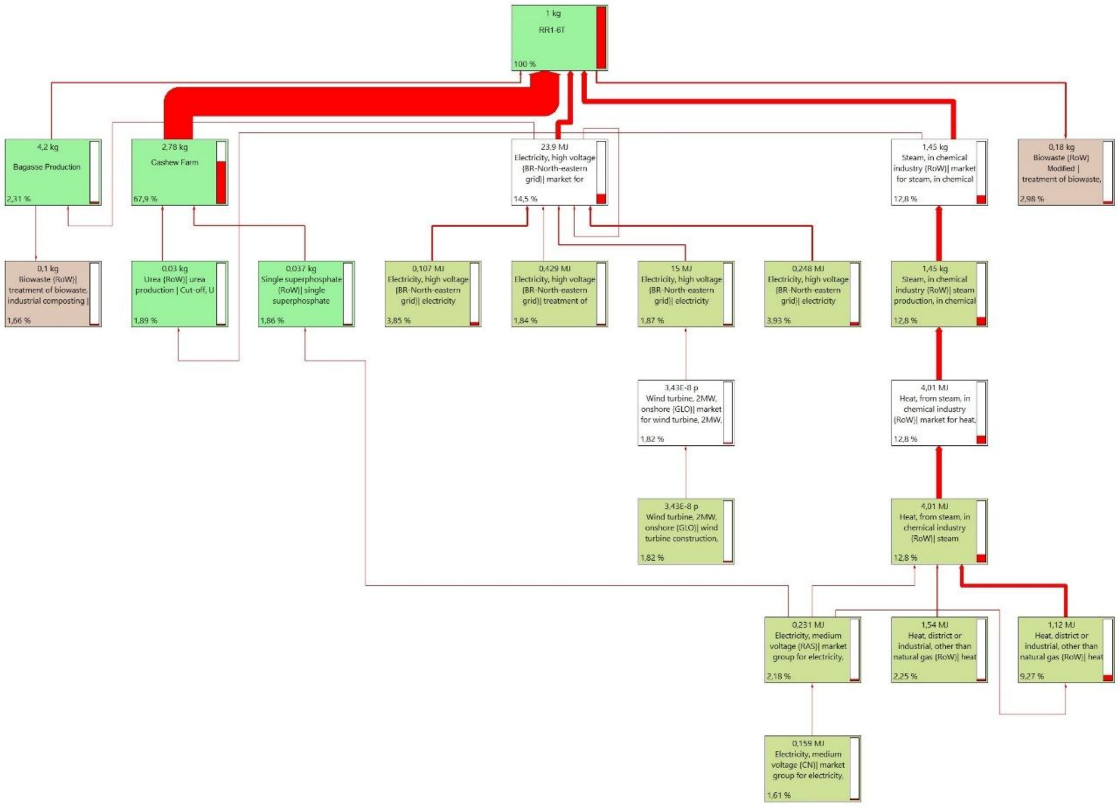


Figura S8. Categoria “Climate Changes” (RR1-6T)

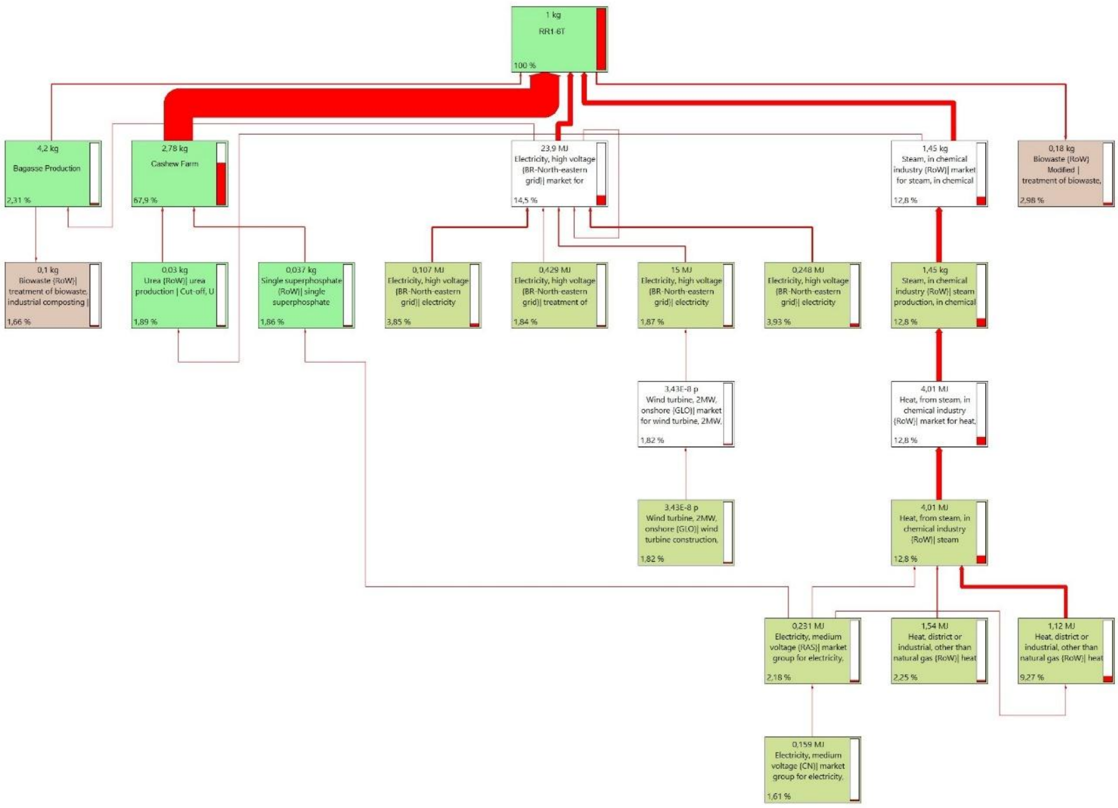


Figura S9. Categoria "Particulate matter" (RR1-6T)

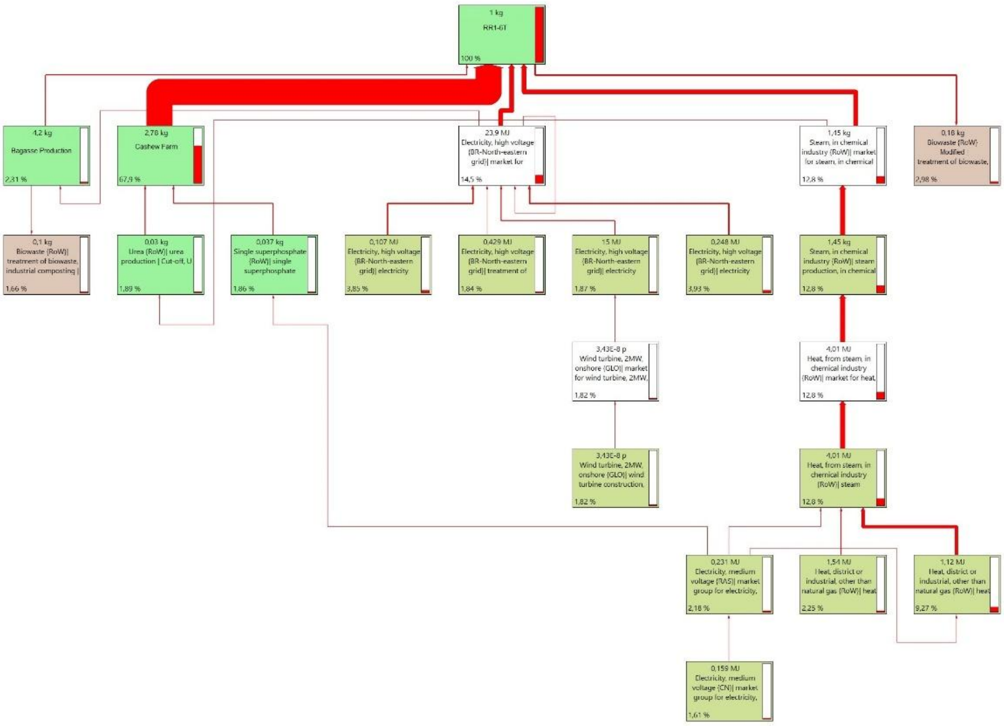


Figura S10. Categoria "Eutrophication, terrestrial" (RR1-6T)

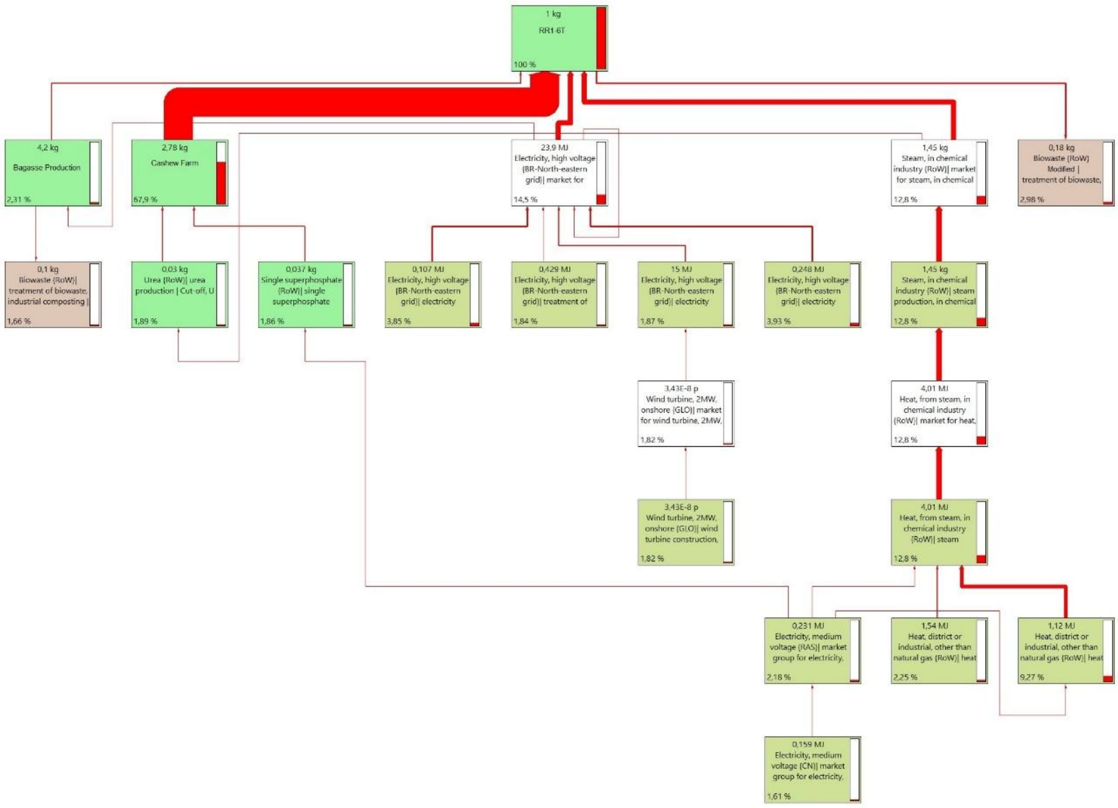


Figura S11. Categoria "Resource use, fossils" (RR1-6T)

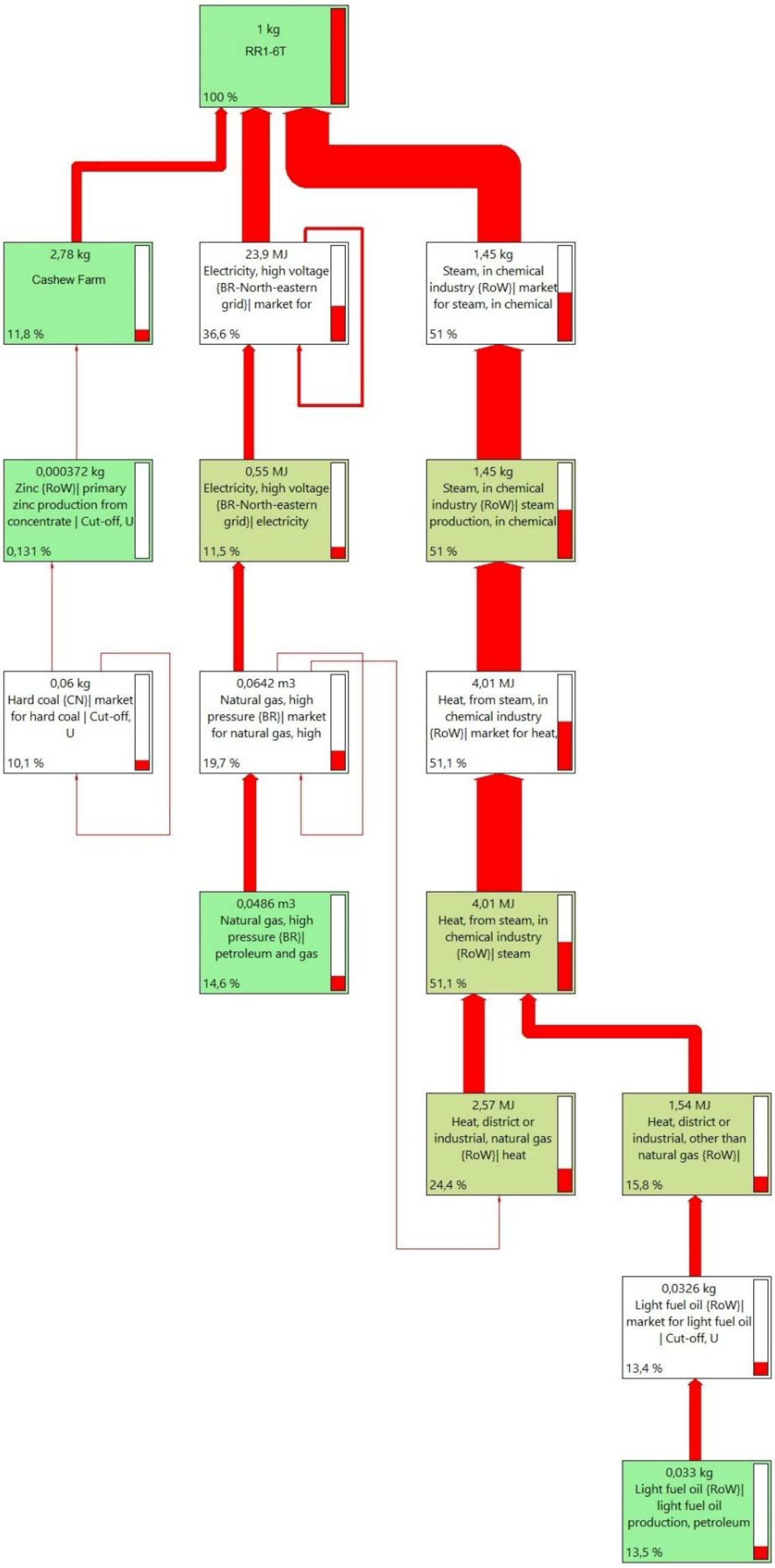


Figura S12. Categoria “Resource use, minerals and metals” (RR1-6T)

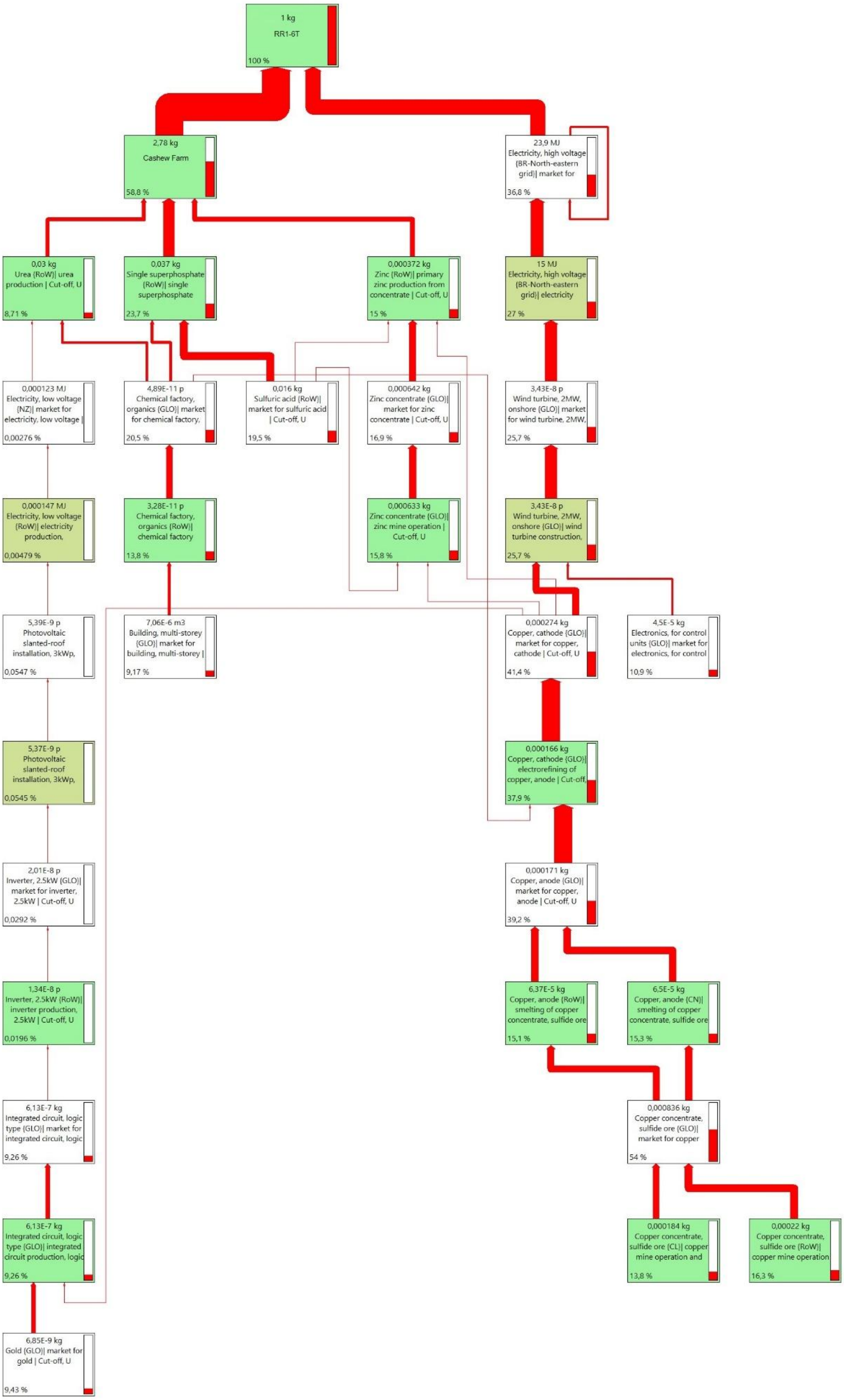


Figura S13. Categoria “Acidification” (RR2-9T)

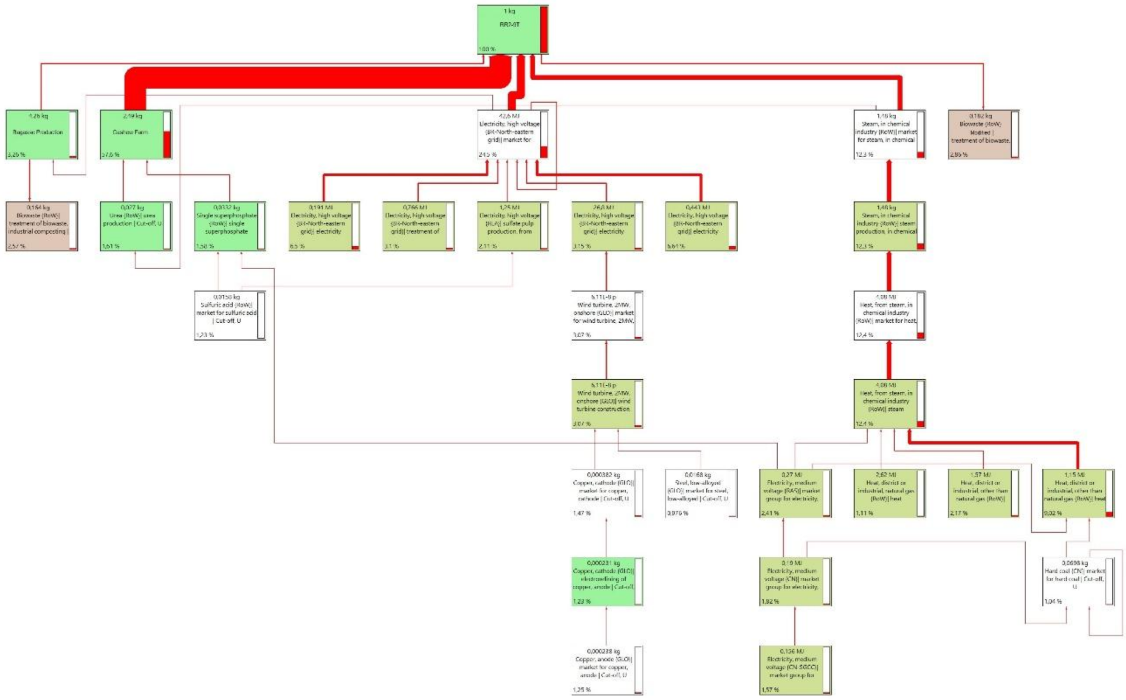


Figura S14. Categoria “Climate Changes” (RR2-9T)

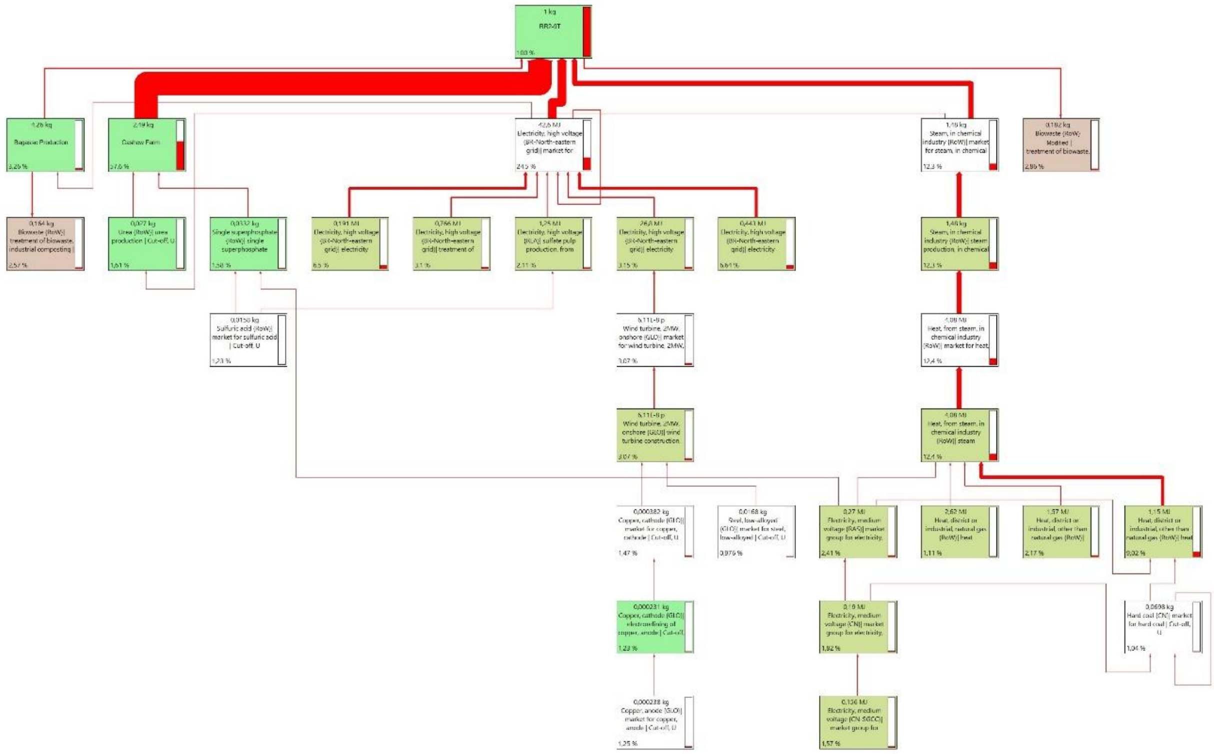


Figura S15. Categoria "Particulate matter" (RR2-9T)

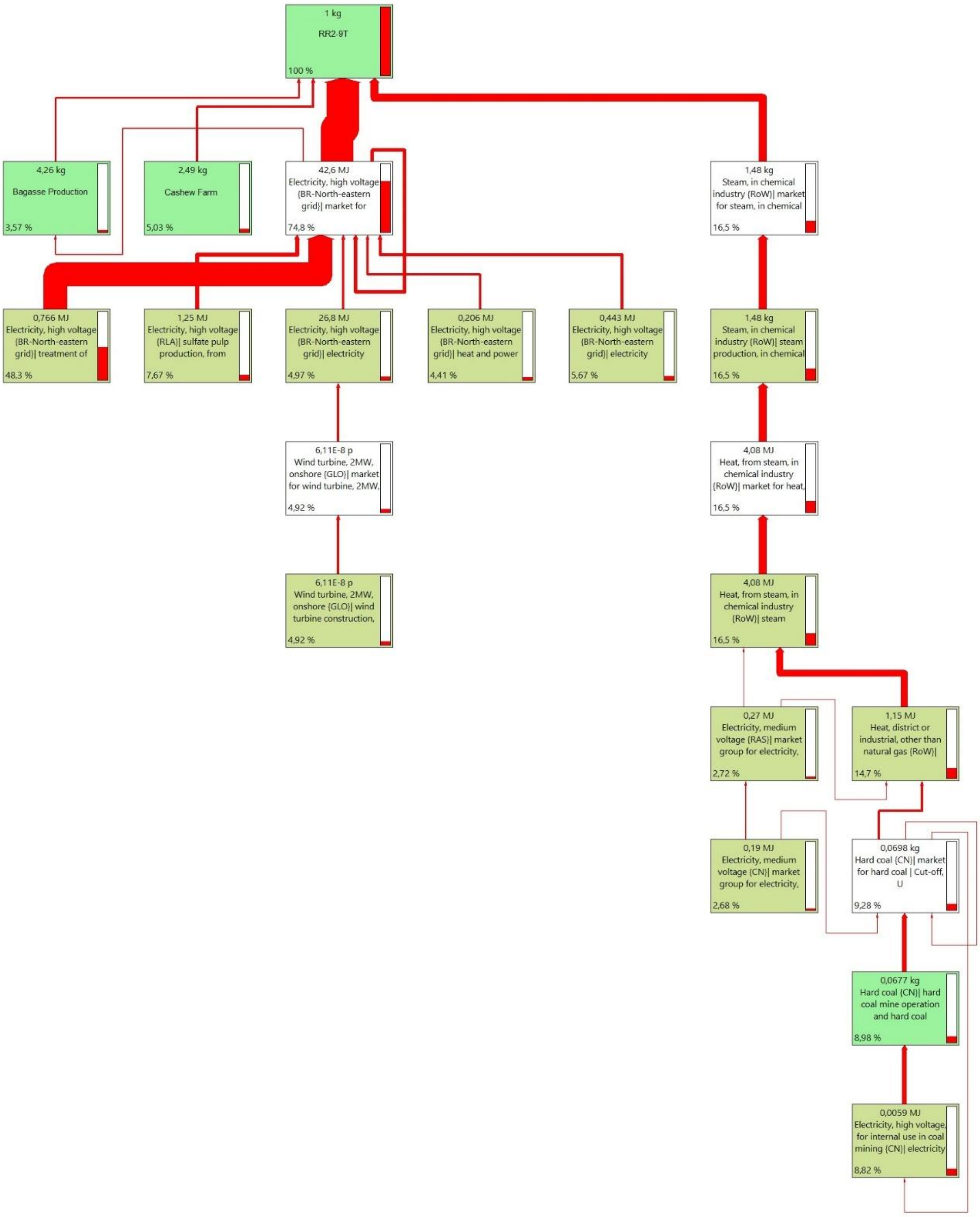


Figura S16. Categoria “Eutrophication, terrestrial” (RR2-9T)

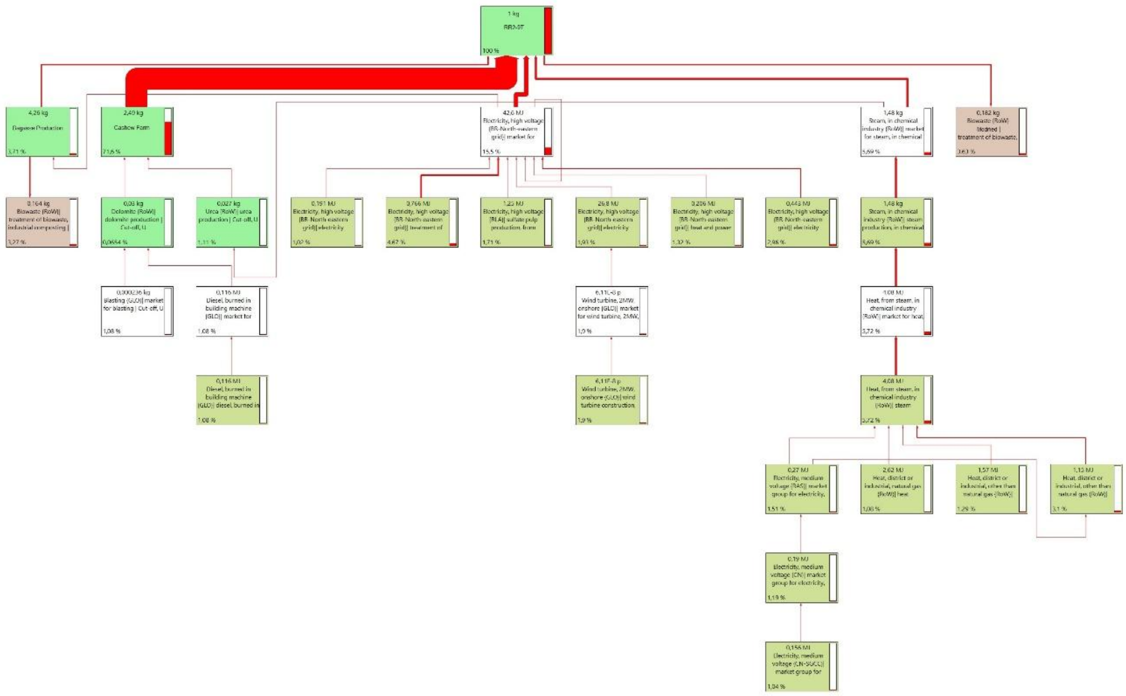


Figura S17. Categoria “Resource use, fossils” (RR2-9T)

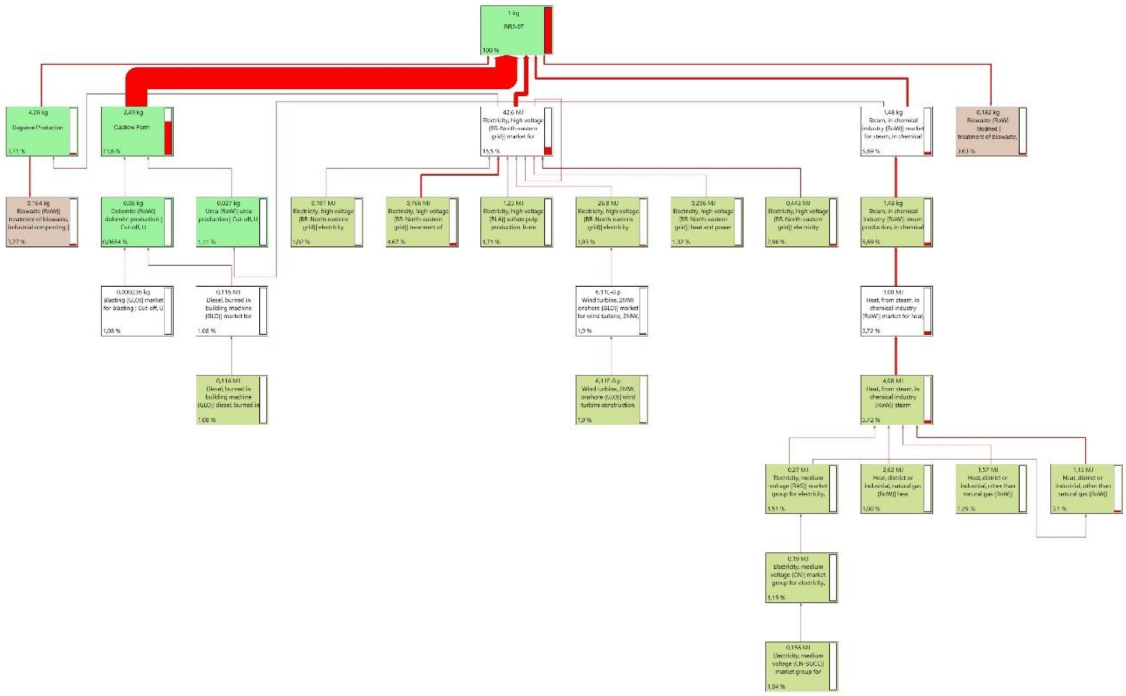
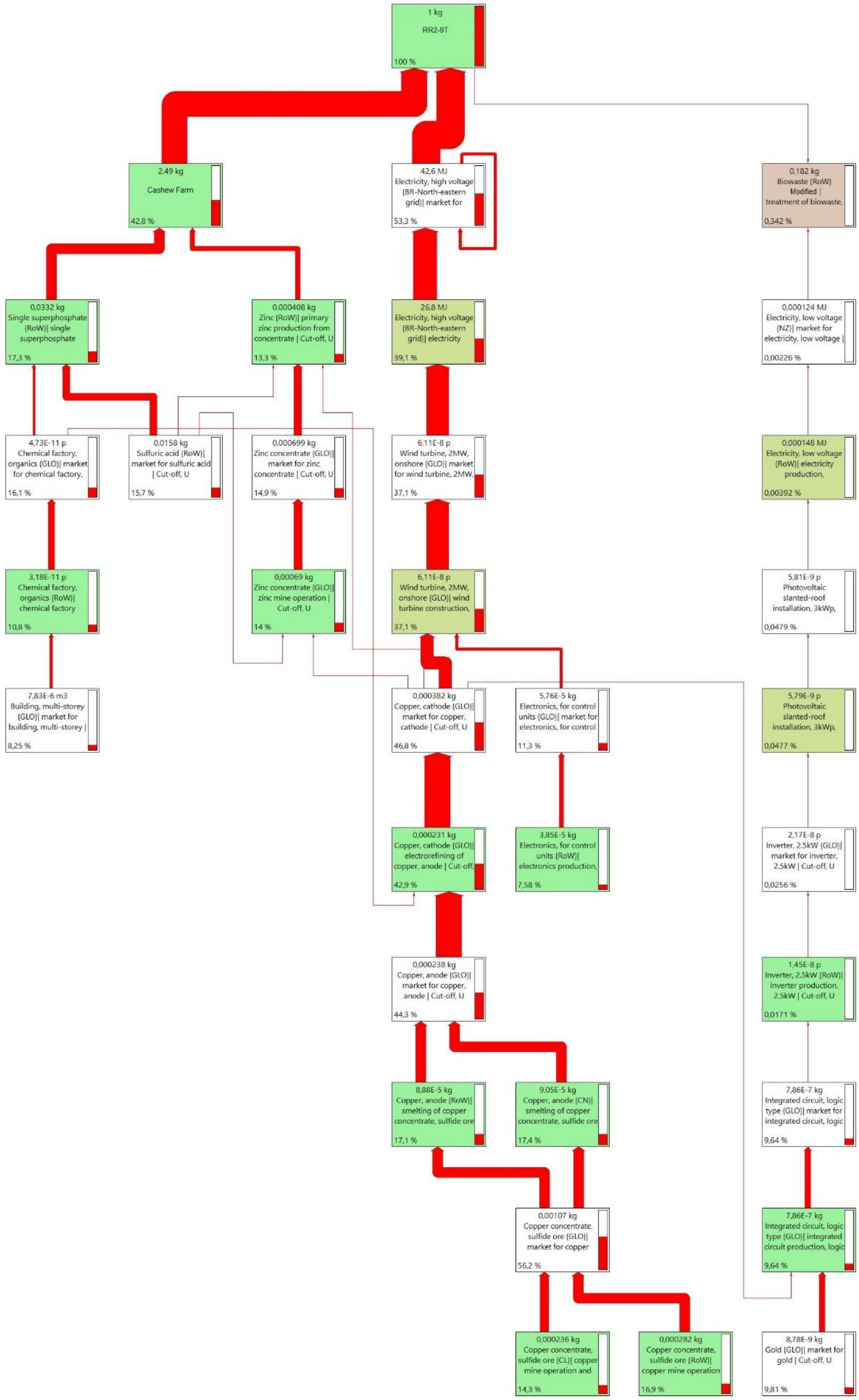


Figura S18. Categoria "Resource use, minerals and metals" (RR2-9T)



8. Rede de impactos do processo industrial de obtenção da FCD

Estas imagens mostram a rede de impactos da produção de DCF. As imagens foram geradas usando o software SIMAPRO V.10.2.0. Banco de dados: ecoinvent 3.9.1.

Figura S19. Categoria “Acidification” (RR1-6T)

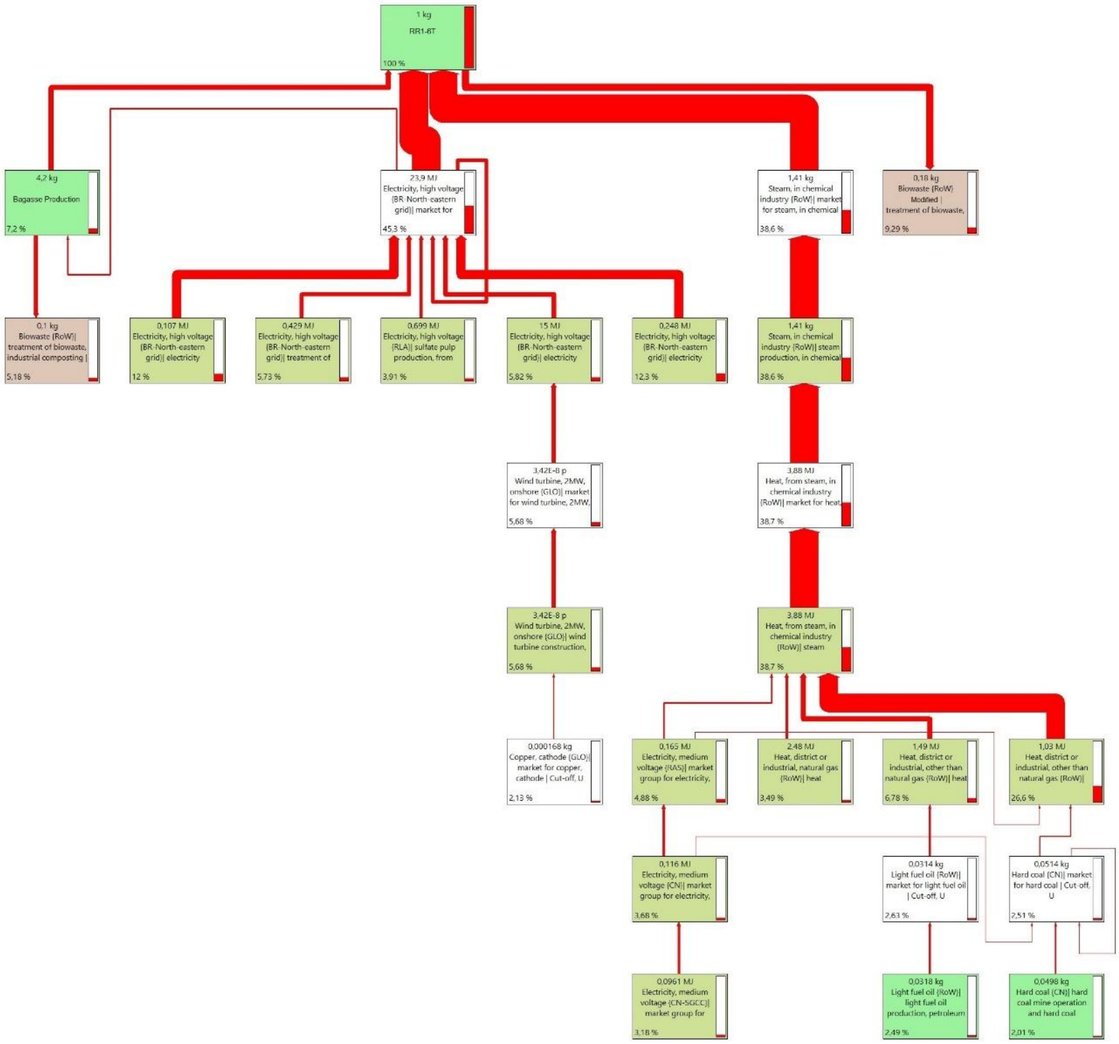


Figura S20. Categoria "Climate Changes" (RR1-6T)

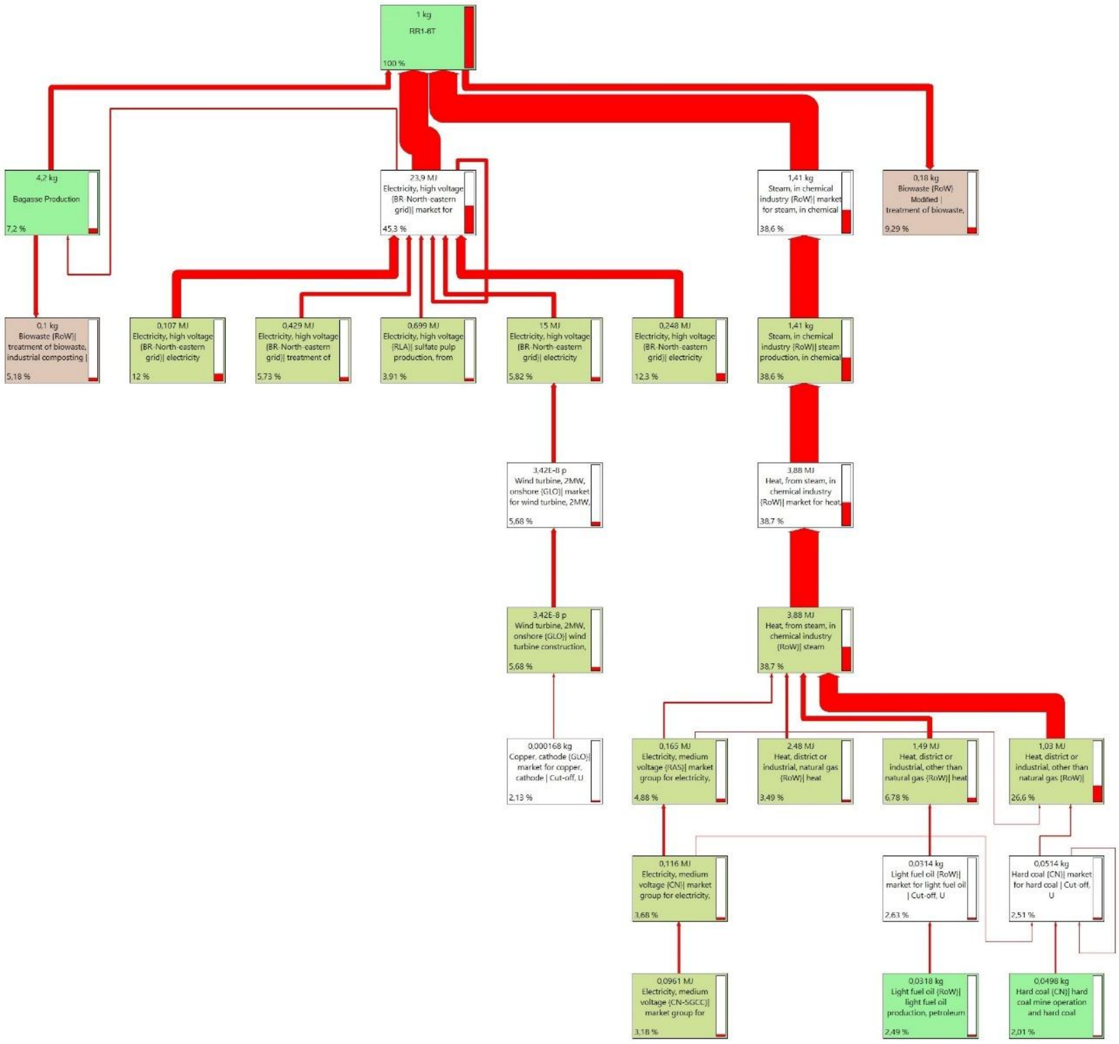


Figura S21. Categoria “Particulate matter” (RR1-6T)

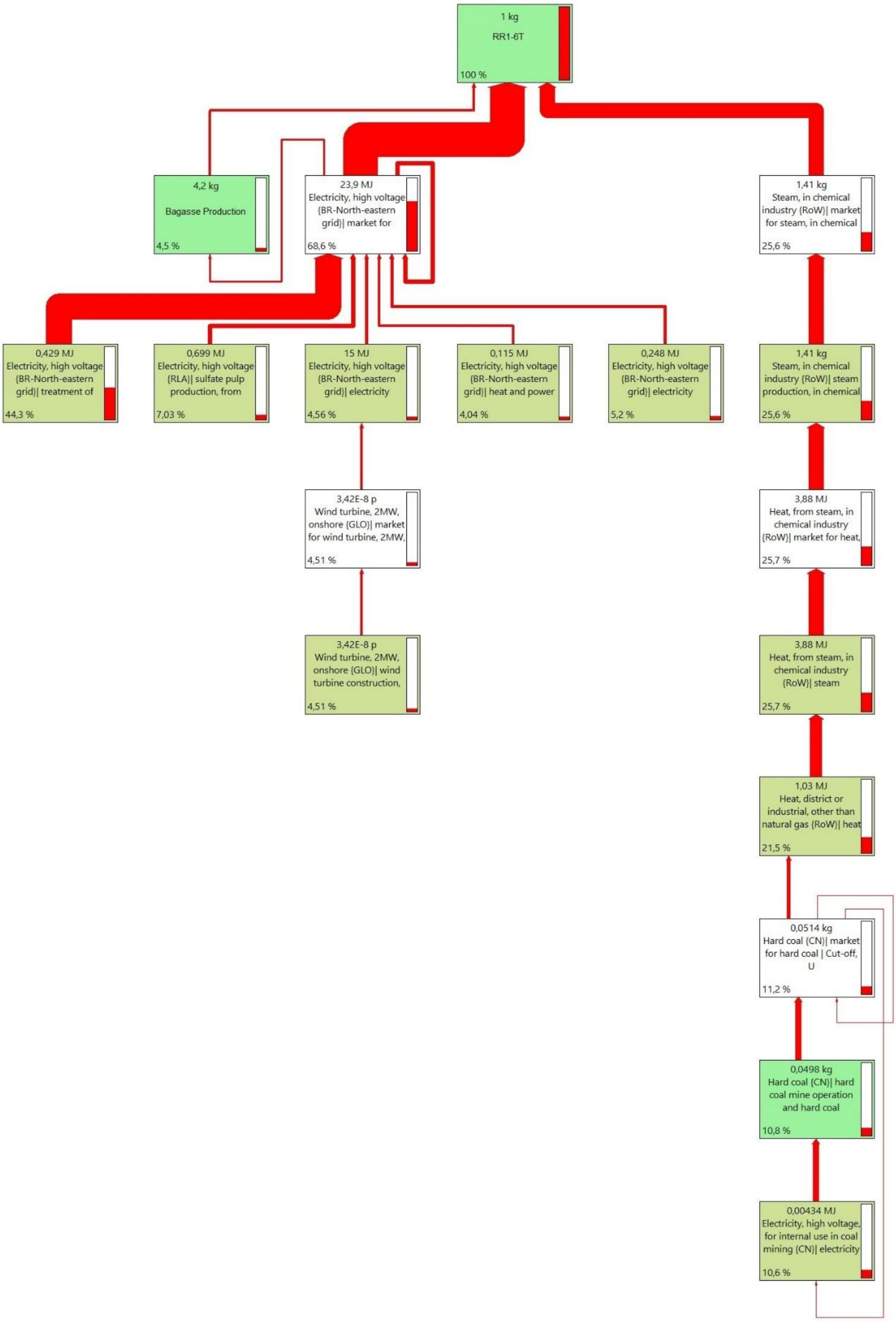


Figura S22. Categoria "Eutrophication, terrestrial" (RR1-6T)

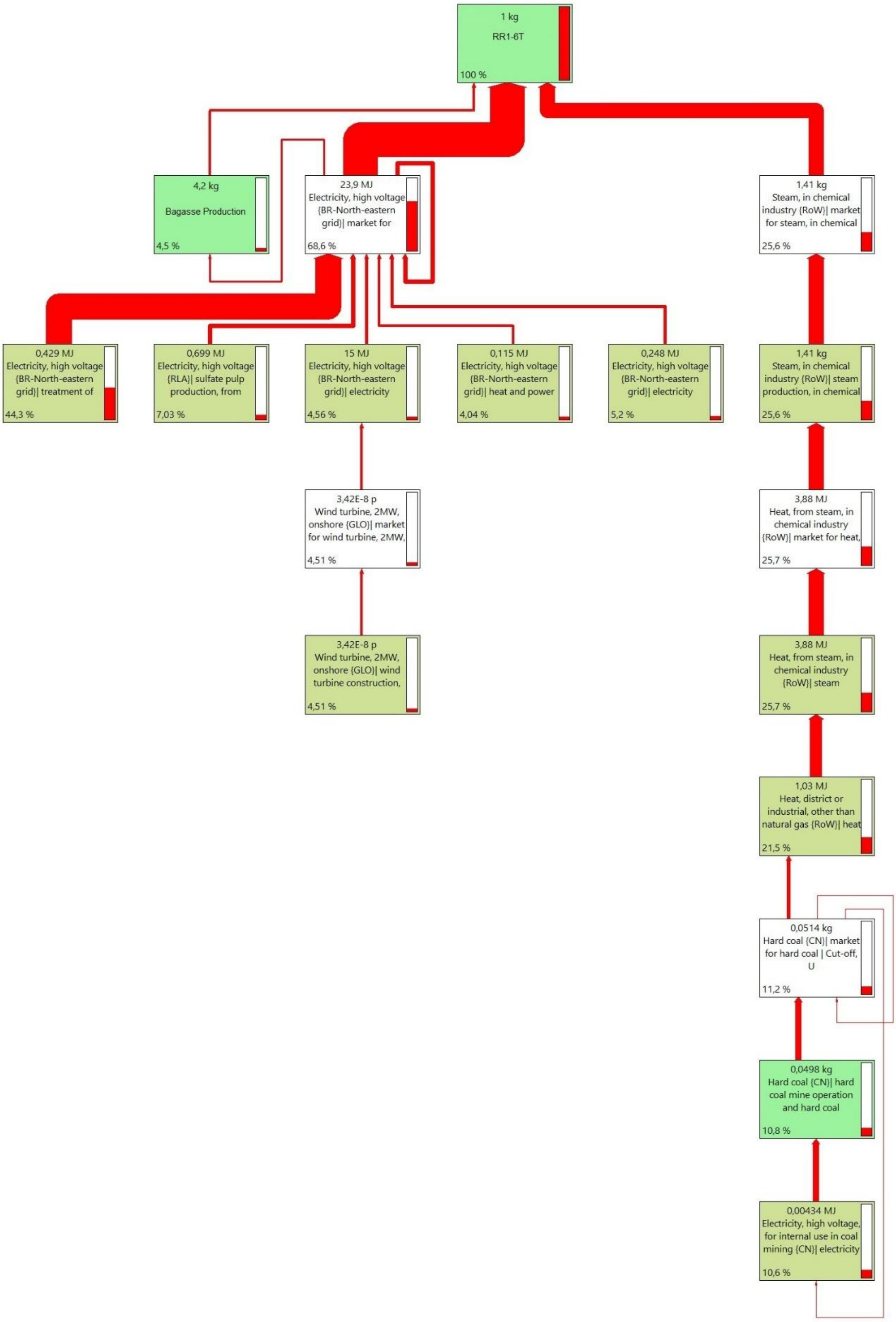


Figura S23. Categoria "Resource use, fossils" (RR1-6T)

Figura S24. Categoria "Resource use, minerals and metals" (RR1-6T)

Figura S25. Categoria “Acidification” (RR2-9T)

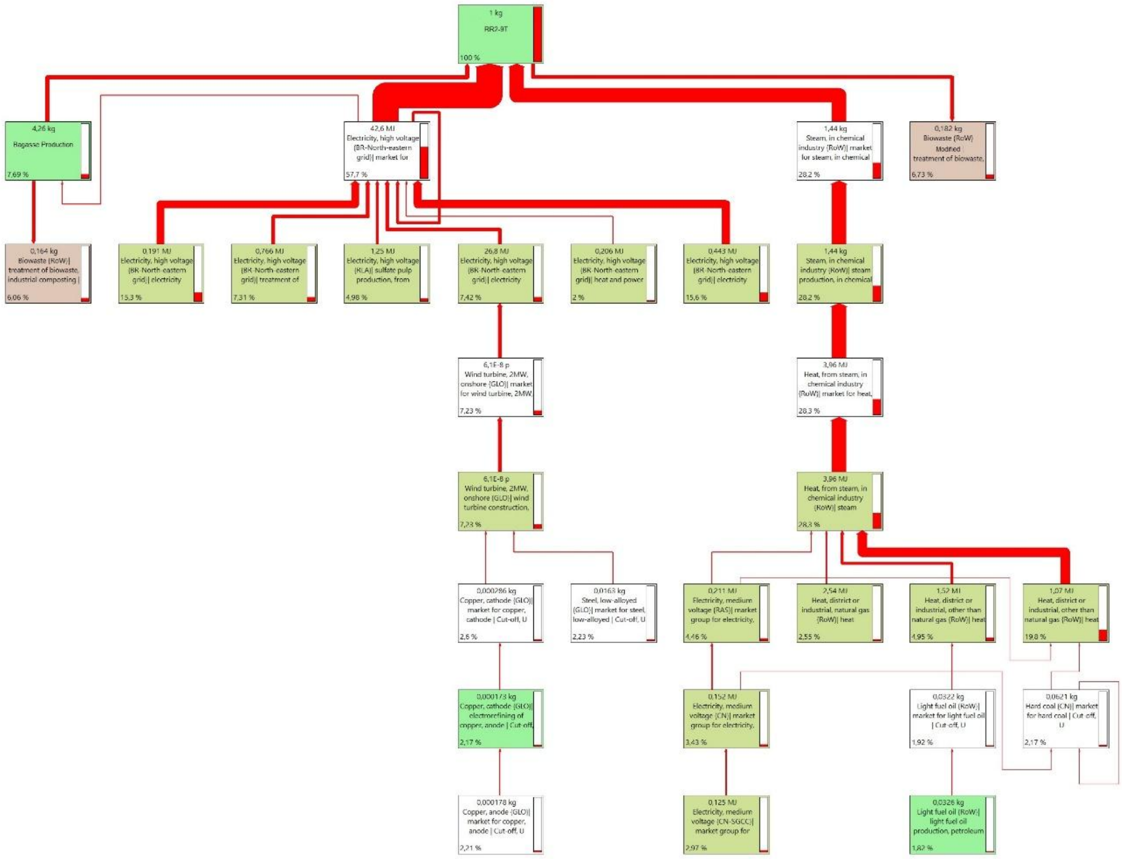


Figura S26. Categoria "Climate Changes" (RR2-9T)

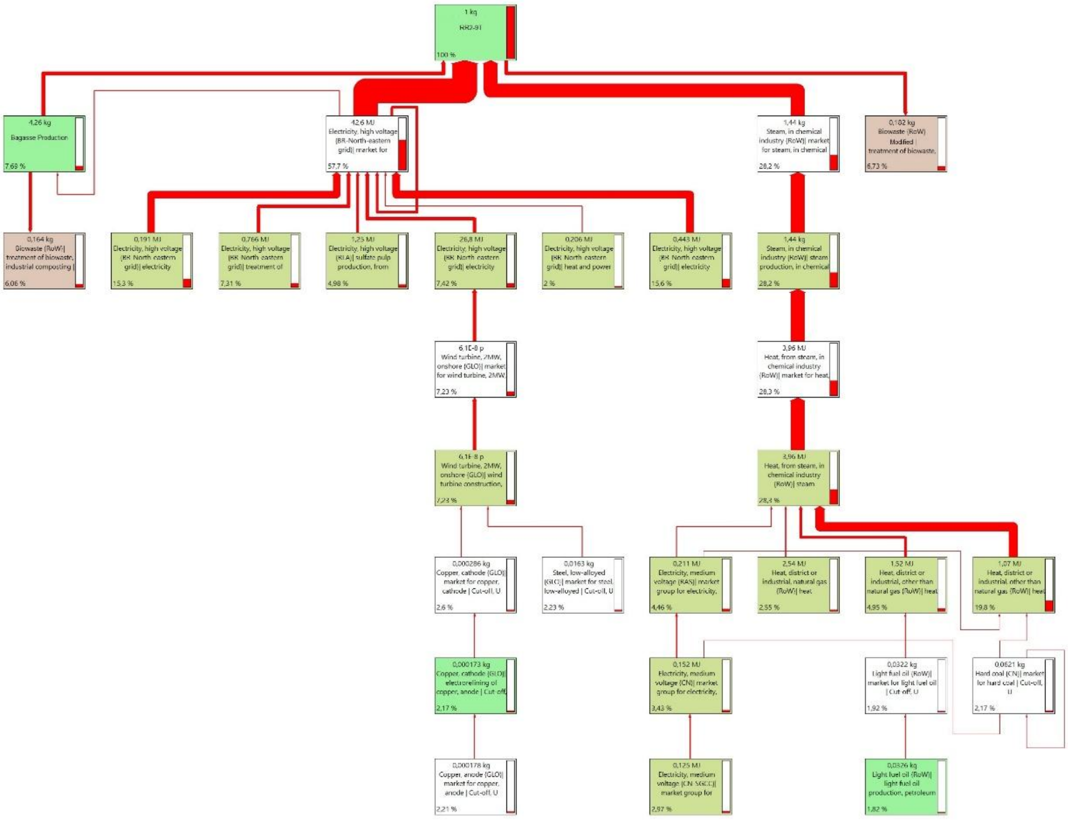


Figura S27. Categoria "Particulate matter" (RR2-9T)

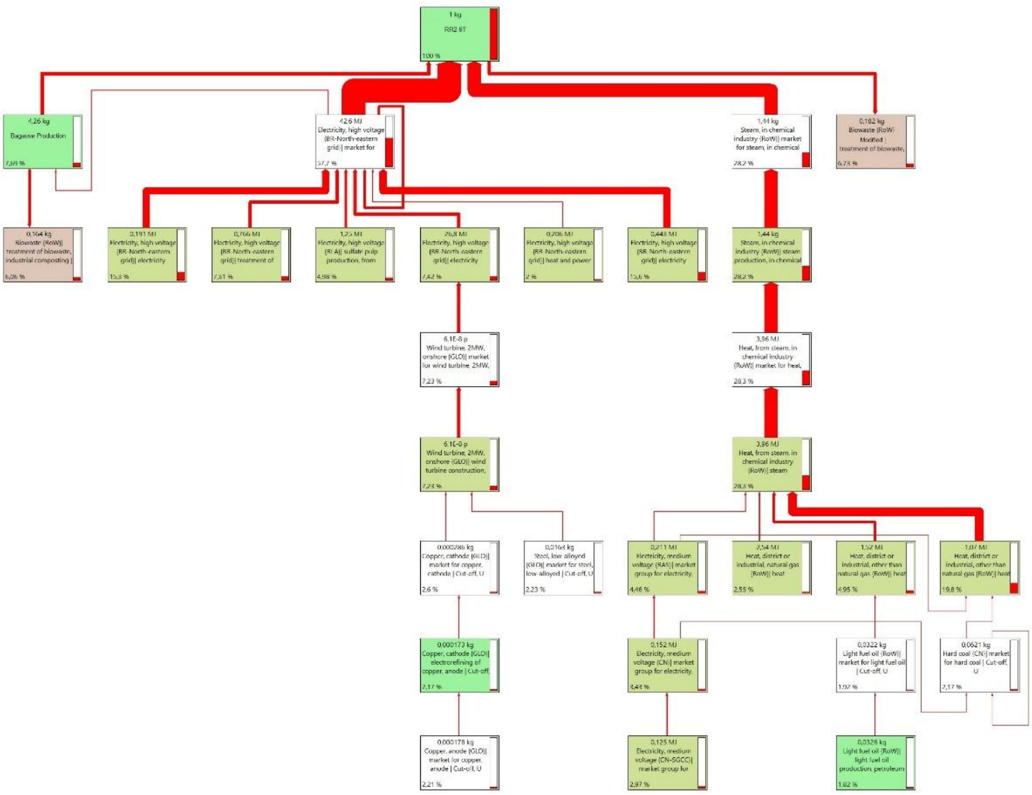


Figura S28. Categoria “Eutrophication, terrestrial” (RR2-9T)

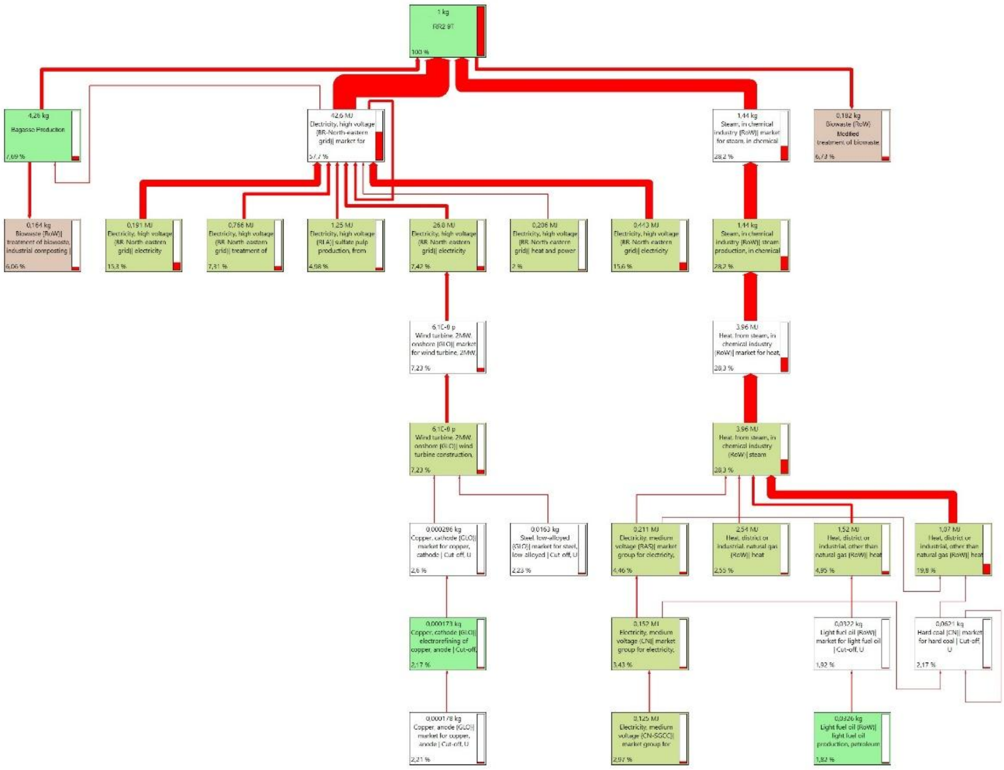


Figura S29. Categoria “Resource use, fossils” (RR2-9T)

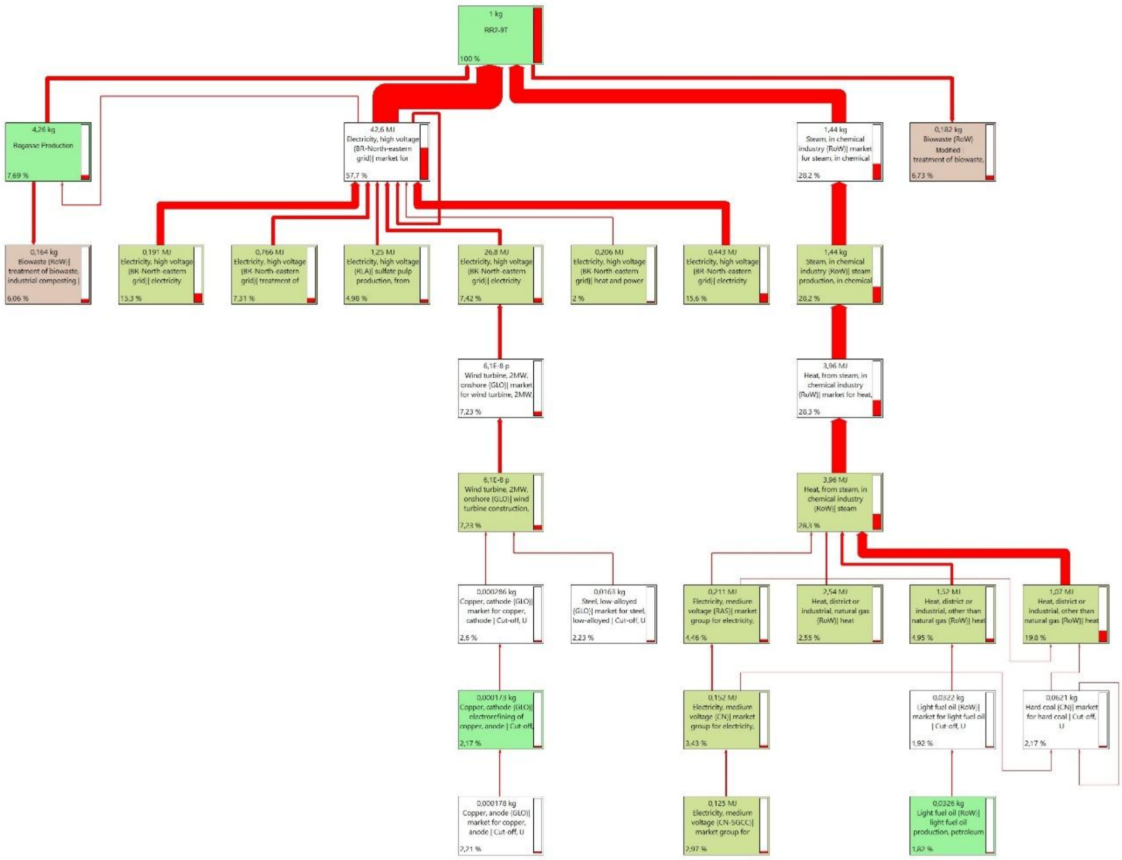
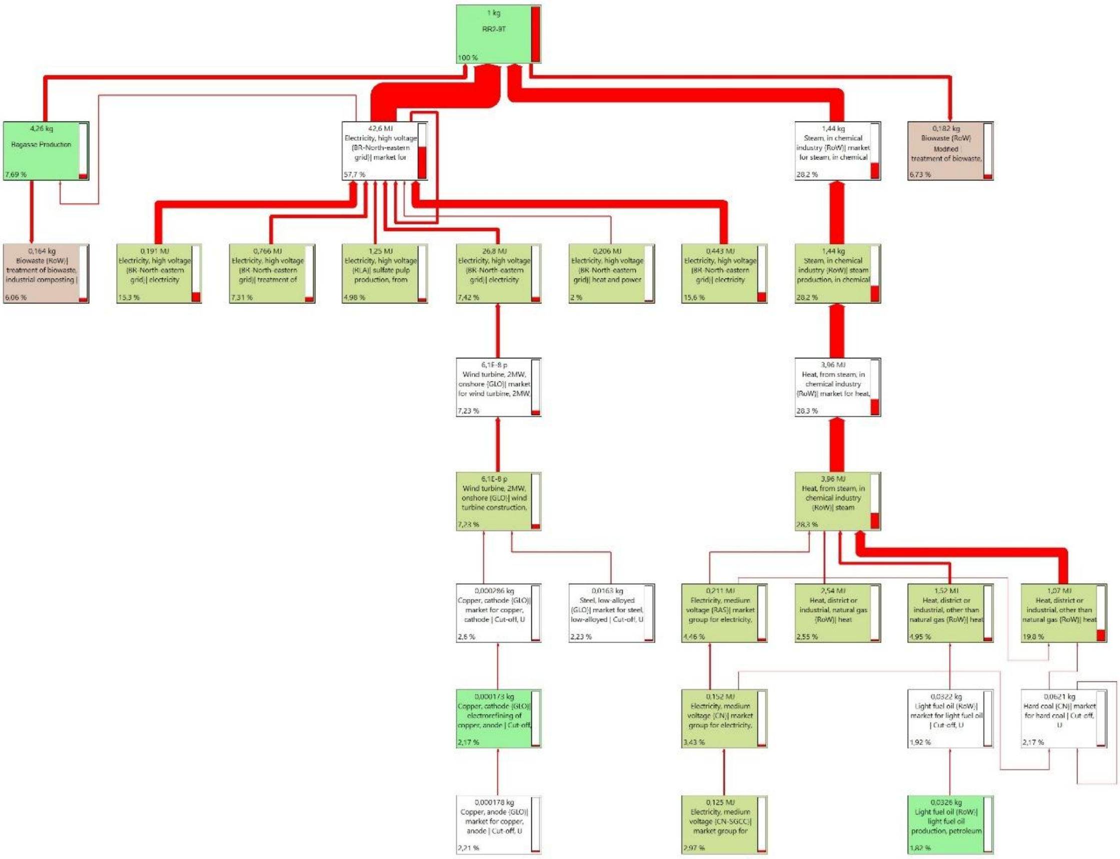


Figura S30. Categoria “Resource use, minerals and metals” (RR2-9T)



9. Tabela de preços dos equipamentos utilizados na modelagem no SuperPro Designer

Tabela S3: Preços de compra do equipamento RR1-9T.

Quantidade	**Código**	**Descrição**	**Característica**	**Custo (US$)**
1	SP-101	Screw Press	Throughput = 26253,00 kg h^{-1}	694,000.00
1	V-101	Blending Tank	Vessel Volume = 30.003,82 L	389,000.00
9	RDR-101	Tray Dryer	Tray Area = 75,61 m^2	1,476,000.00
1	GR-101	Grinder	Rated Throughput = 2.140,64 kg h^{-1}	99,000.00
1	FL-101	Filler	Discrete Throughput = 214,06 entities h^{-1}	10,000.00
1	BX-101	Packer	Discrete Throughput = 107,03 entities h^{-1}	6,000.00
		Unlisted equipment		518,000.00
		Total		3,191,000.00

Tabela S4: Preços de compra do equipamento RR2-9T.

Quantidade	Código	Descrição	Característica	Custo (US$)
1	SP-101	Screw Press	Throughput = 26253,00 kg h^{-1}	694,000.00
6	V-101	Blending Tank	Vessel Volume = 30.003,82 L	389,000.00
1	RDR-101	Freeze Dryer	Sublimation Capacity = 579,51 kg	5,484,000.00
1	GR-101	Grinder	Rated Throughput = 2.111,45 kg h^{-1}	99,000.00
1	FL-101	Filler	Discrete Throughput = 211,14 entities h^{-1}	10,000.00
1	BX-101	Packer	Discrete Throughput = 105,57 entities h^{-1}	5,000.00
		Unlisted equipment		1,520,000.00
		Total		8,201,000.00

10. Resultados Econômicos dos cenários

Tabela S5. Resultados Econômicos dos cenários

Índice econômico	SC1-RR1-6T	SC2-RR1-6T	SC3-RR1-6T	SC1-RR2-9T	SC2-RR2-9T	SC3-RR2-9T
MSP (US$ kg^{-1})	12.17	11.69	11.75	40.47	39.61	39.67
ROI (%)	14.15	14.16	14.16	14.16	14.17	14.17
DPBT (anos)	23.99	24.01	23.99	24	24	24
NPV (US$)	0	0	0	0	0	0
PSP (US$ kg^{-1})	13.38	12.86	12.92	44.52	43.57	43.63
ROI (%)	16.11	16.12	16.12	15.88	16.06	16.07
DPBT (anos)	16.22	16.27	16.24	16.59	16.39	16.39
NPV (milhões US$)	1.999	1.745	1.754	4.305	6.606	6.616

11. Dados utilizados no método AHP

Tabela S6. Valores quantitativos usados no método AHP.

Rotas / Cenários	Categorias de Impactos Ambientais							Indicadores econômicos	
	AC (mol H+ eq)	CC (kg CO_2 eq kg^{-1})	PM (disease increase)	EUT (mol N eq)	RUF (Mj)	RUMM (kg Sb eq.)	LFI (%)	VPL (milhões US$)	DPBT (anos)
RR1-6T	4.33E-03	9.82E-01	8.08E-08	9.90E-03	1.11E+01	1.93E-06	83.27%	1,82	16.09
SC1-RR1-6T (DCF – Alocação de massa)	8.03E-03	2.15E+00	1.18E-07	1.48E-02	2.64E+01	1.73E-06	52.08%	2,00	16.22

SC2-RR1-6T	5.63E-03	9.48E-01	5.60E-08	1.08E-02	1.19E+01	2.90E-05	83.27%	1,75	16.27
SC3-RR1-6T	4.52E-03	5.32E-01	4.02E-08	9.07E-03	6.55E+00	3.41E-05	83.27%	1,75	16.25
RR2-9T	6.06E-03	1.36E+00	1.25E-07	1.40E-02	1.49E+01	3.31E-06	83.27%	6,75	16.30
SC1-RR2-9T (DCF – Alocação de massa)	8.32E-03	2.32E+00	1.03E-07	1.44E-02	2.94E+01	7.59E-07	52.03%	4,31	16.60
SC2-RR2-9T	8.29E-03	1.27E+00	7.90E-08	1.55E-02	1.59E+01	5.22E-05	83.27%	6,61	16.40
SC3-RR2-9T	7.23E-03	8.66E-01	6.39E-08	1.38E-02	1.07E+01	5.73E-05	83.27%	6,62	16.39

Legenda: AC- Acidification, CC – Climate Changes, PM – Particulate Matter, EUT - Eutrophication terrestrial, RUF - Resource use, fossils, RUM - Resource use, minerals and metals; LFI – Linear Flow Index, VPL – Valor Presente Líquido, DPBT – Tempo de retorno descontado.

Table S7. Criteria comparison Matrix (Saaty Matrix)

Critérios	**AC**	**CC**	**PM**	**EUT**	**RUF**	**RUM**	**LFI**	**NPB**	**DPBT**
AC	1	1/3	2	3	4	5	1	2	2
CC	3	1	4	4	4	4	1	3	3
PM	1/2	1/4	1	2	2	2	1	2	2
EUT	1/3	1/4	1/2	1	1	2	1	2	2
RUF	1/4	1/4	1/2	1	1	2	1	2	2
RUM	1/5	1/4	1/2	1/2	1/2	1	1	2	2
LFI	1	1	1	1	1	1	1	2	2
VPL	1/2	1/3	1/2	1/2	1/2	1/2	1/2	1	2
DPBT	1/2	1/3	1/2	1/2	1/2	1/2	1/2	1/2	1

Table captions: AC- Acidification, CC – Climate Changes, PM – Particulate Matter, EUT - Eutrophication terrestrial, RUF - Resource use, fossils, RUM - Resource use, minerals and metals; LFI – Linear Flow Index, VPL – Valor Presente Líquido, DPBT – Tempo de retorno descontado.

APÊNDICE B – MATERIAL SUPLEMENTAR DO ARTIGO 2

1. Delineamento Experimental

A Tabela S1 apresenta os dados codificados para o Delineamento Composto Central Rotacional (DCCR). Os valores reais foram omitidos para proteger dados sensíveis do projeto.

Tabela S1: Matriz de planejamento experimental DCCR para maceração enzimática com valores codificados para os fatores analisados.

Experimento	**X_1 - tempo (min.)**	**X_2 - (Enzima, % v/v) ***
1	-1	-1
2	1	-1
3	-1	1
4	1	1
5	0	0
6	0	0
7	0	0
8	-1.41	0
9	1.41	0
10	0	-1.41
11	0	1.41

*Percentagem relativa ao volume inicial do substrato (150 mL).

2. Parâmetros coletados em escala piloto

Tabela S2: Balanço de massa do processo em escala piloto.

Etapa	Entrada (kg)	Saída (kg)	Resíduo (%)	Resíduo (kg)	Rendimento %
Lavagem das pitayas	26.61	26.60	0.04	0.01	99.96
Remoção das cascas	26.60	20.02	24.74	6.58	75.26
Despolpa	20.02	15.75	21.33	4.27	78.67
Maceração enzimática*	15.75	15.64	0.70	0.11	99.30
Microfiltração*	15.64	10.90	30.31	4.74	69.69
Evaporação*	10.90	1.74	84.04	9.16	15.96

*Nessas etapas, lotes de 5 kg foram separados.

3. Análise de incerteza dos parâmetros da membrana de microfiltração

Os parâmetros técnicos da membrana de microfiltração, fluxo de permeado (PF) e taxa de redução volumétrica (VRR), foram tratados como variáveis estocásticas devido à variabilidade intrínseca do processo. Com base em dados experimentais obtidos em escala piloto, foi realizada uma simulação de Monte Carlo (10.000 iterações) no MS Excel, da qual foram extraídos três cenários probabilísticos:

Cenário pessimista (P5): Correspondente ao 5º percentil, representando condições de baixa eficiência operacional.

Cenário típico (P50): Correspondente ao 50º percentil (Mediana), representando o desempenho central e mais provável do processo.

Cenário Otimista (P95): Correspondente ao percentil 95, representando o fluxo máximo observado e o potencial de recuperação.

Definição de variáveis de entrada e distribuições:

- Fluxo de permeado (PF) e taxa de redução volumétrica (VRR): Modelados usando uma distribuição normal, refletindo a variabilidade dessas variáveis de processo.

Estrutura do algoritmo no Microsoft Excel

- A função RAND() foi usada em conjunto com funções de probabilidade inversa (=INV.NORM.N(RAND();AVERAGE; STDEV.P())) para gerar 10,000 valores aleatórios para o PF. Onde, AVERAGE = média dos valores de PF, e STDEV.P() = desvio padrão dos valores. Ambos os valores obtidos na escala piloto.

- A função RAND() foi usada em conjunto com funções de probabilidade inversa (=INV.NORM.N(RAND();AVERAGE; STDEV.P())) para gerar 10,000 valores aleatórios para o VRR. AVERAGE = média dos valores de VRR, e STDEV.P() = desvio padrão dos valores. Ambos os valores obtidos na escala piloto.

Os valores das variáveis (PF e VRR) foram omitidos para proteger dados sensíveis do projeto.

Tabela S3: Parâmetros técnicos da membrana de microfiltração.

Percentis de Simulação de Monte Carlo	Parâmetros operacionais	500 kg batelada^{-1}	600 kg batelada^{-1}	700 kg batelada^{-1}	800 kg batelada^{-1}	900 kg batelada^{-1}	1000 kg batelada^{-1}
P5	Fluxo do permeado (L/m^{2}h)	-	-	-	-	-	-
	Taxa de redução volumétrica	-	-	-	-	-	-
P50	Fluxo do permeado (L/m^{2}h)	-	-	-	-	-	-
	Taxa de redução volumétrica	-	-	-	-	-	-
P95	Fluxo do permeado (L/m^{2}h)	-	-	-	-	-	-
	Taxa de redução volumétrica	-	-	-	-	-	-

Nota: Os parâmetros de microfiltração (fluxo de membrana e fator de concentração) não foram divulgados devido a acordos de confidencialidade industrial.

4. Lista de preços de compra de todos os equipamentos utilizados no SuperPro Designer.

Tabela S4: Equipamento registrado no SuperPro Designer (SPD) RR500.

Código do equipamento	Equipamento	Quantidade	dolares (mil US$)
DFT-101	FREEZE-THAW	1	797.00
V-101	BLENDING TANK	1	206.00
EV-101	MULTI-EFFECT EVAPORATOR	1	140.00
GR-101	GRINDER	1	96.00
SL-101	SILO	1	90.00
BX-101	PACKER	1	81.00
SP-101	SCREW PRESS	1	54.00

MF-102	MICROFILTER	1	33.00
FL-101	FILLER	3	18.00
WSH-101	WASHER	1	18.00
SCR-101	STATIONARY SCREEN	1	2.00
MX-103 (RA_1 2X)	MIXER	1	2.00
Unlisted equipment			384.00
Total			1,920

5. Incerteza estocástica e avaliação de risco (Simulação de Monte Carlo)

Risco econômico do projeto.

Para avaliar o risco econômico do projeto diante das incertezas do mercado, foi aplicada uma simulação de Monte Carlo com 10.000 iterações. Esse procedimento permitiu uma análise probabilística em vez de uma determinística, quantificando o risco de inviabilidade (VPL < 0) sob diferentes variações de mercado. A simulação passo a passo foi estruturada da seguinte forma:

Definição de variáveis de entrada e distribuições:

- Custo da matéria-prima (pitaya): Modelado usando uma distribuição triangular, com base nos valores mínimo, médio e máximo coletados em pesquisas históricas de preços.
- A taxa de desconto (SELIC): modelada usando uma distribuição normal, refletindo a volatilidade do custo de capital.

Estruturando o algoritmo no Excel:

- Foi utilizada a função de distribuição triangular.: =IF(RAND()<((H3-G3)/(F3-G3));G3+SQRT(RAND()*(F3-G3)*(H3-G3)); F3-SQRT((1-RAND())*(F3-G3)*(F3-H3))) para gerar 10.000 valores aleatórios para o custo da pitaya. Onde F3 = custo máximo; G3 = custo mínimo; H3 = custo médio.
- A função RAND() foi usada em conjunto com a função de probabilidade inversa (=INV.NORM.N(RAND();AVERAGE; STDEV.P())) para gerar 10.000 valores aleatórios para a taxa SELIC. AVERAGE = média da taxa Selic, e STDEV.P() = desvio padrão.

Cálculo dos Indicadores de Desempenho:

- Para cada uma das 10.000 iterações, o Valor Presente Líquido (VPL) e a Taxa Interna de Retorno (TIR) foram recalculados automaticamente.
- A análise foi realizada para dois cenários de vendas: o Preço Mínimo de Venda (PMV) e o Preço de Venda do Produto (PVP).

Análise estatística dos resultados:

- Os resultados foram compilados em histogramas de frequência e curvas de probabilidade cumulativa. O risco do projeto foi definido como a frequência relativa de iterações em que o VPL apresentou valores negativos (VPL < 0 US$).

6. Análise de Circularidade

A metodologia original do Indicador de Circularidade de Materiais (MCI), desenvolvida pela Fundação Ellen MacArthur e pela Granta Design, quantifica a proporção de material que flui linearmente em um sistema usando o Índice de Fluxo Linear (LFI). A equação padrão para o índice é definida como:

$$LFI = \frac{V + W}{2M}$$

Onde V é a massa do material virgem, W é o resíduo não recuperado e M é a massa do produto final.

Neste trabalho, a equação foi ajustada de acordo com o Apêndice A da mesma metodologia.

$$LFI = \frac{V' + W'}{2M'}$$

Onde V' é a massa virgem ajustada (assumindo-se V' = M'), W' é o resíduo não recuperável ajustado e M' é a massa total de entrada.

7. Rede de impactos da produção do corante de pitaya

Figura S1. Rede de impacto da produção do corante (categoria Acidificação).

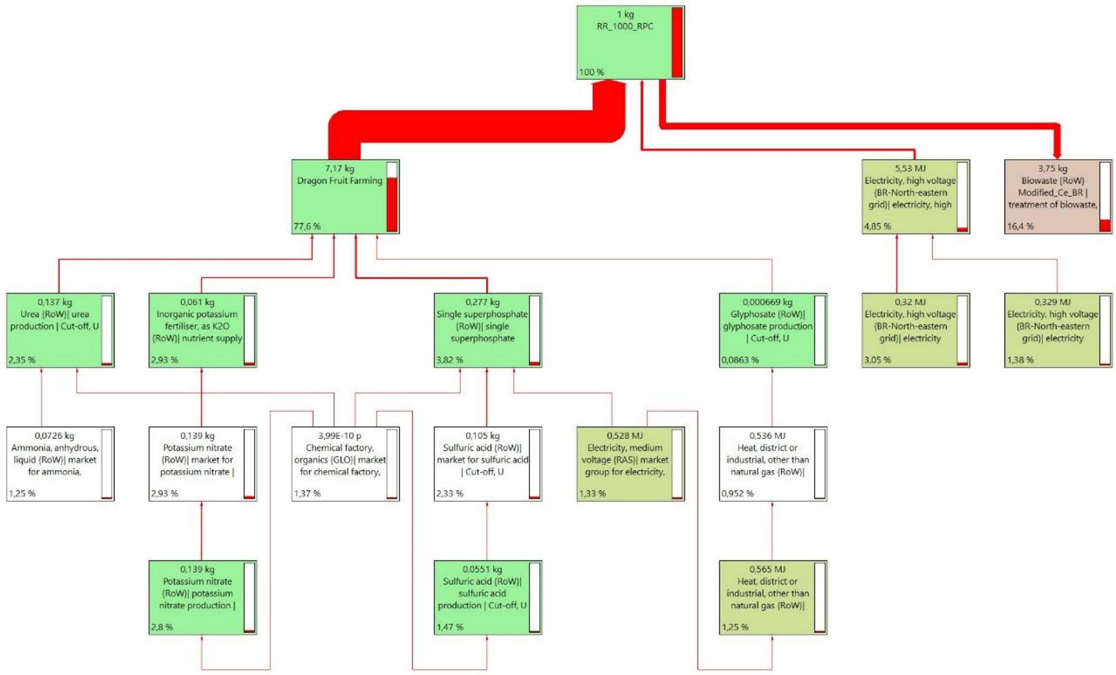


Figura S2. Rede de impacto da produção do corante (categoria Mudanças Climáticas).

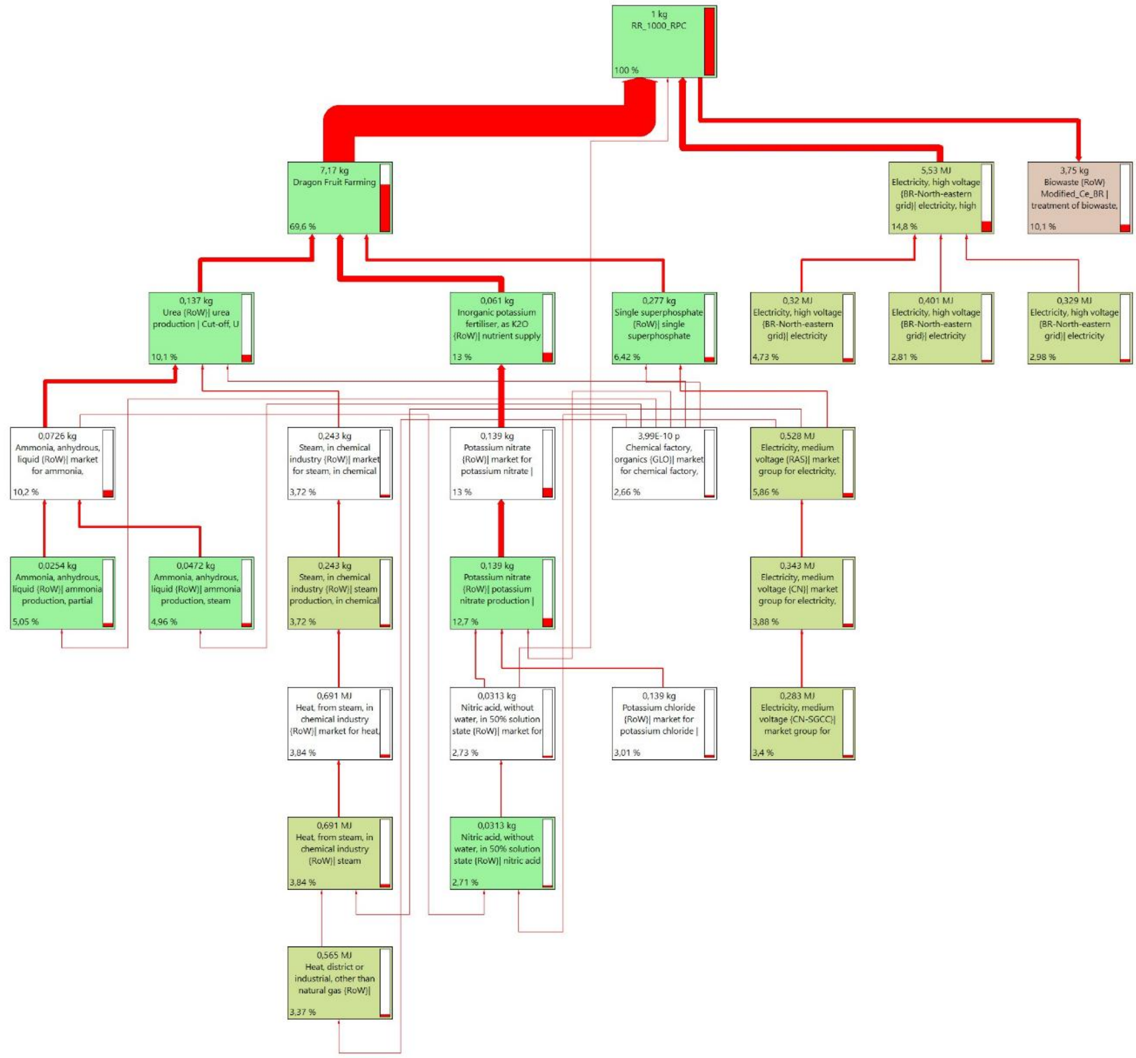


Figura S3. Rede de impacto da produção do corante (Categoria Eutrofização marinha).

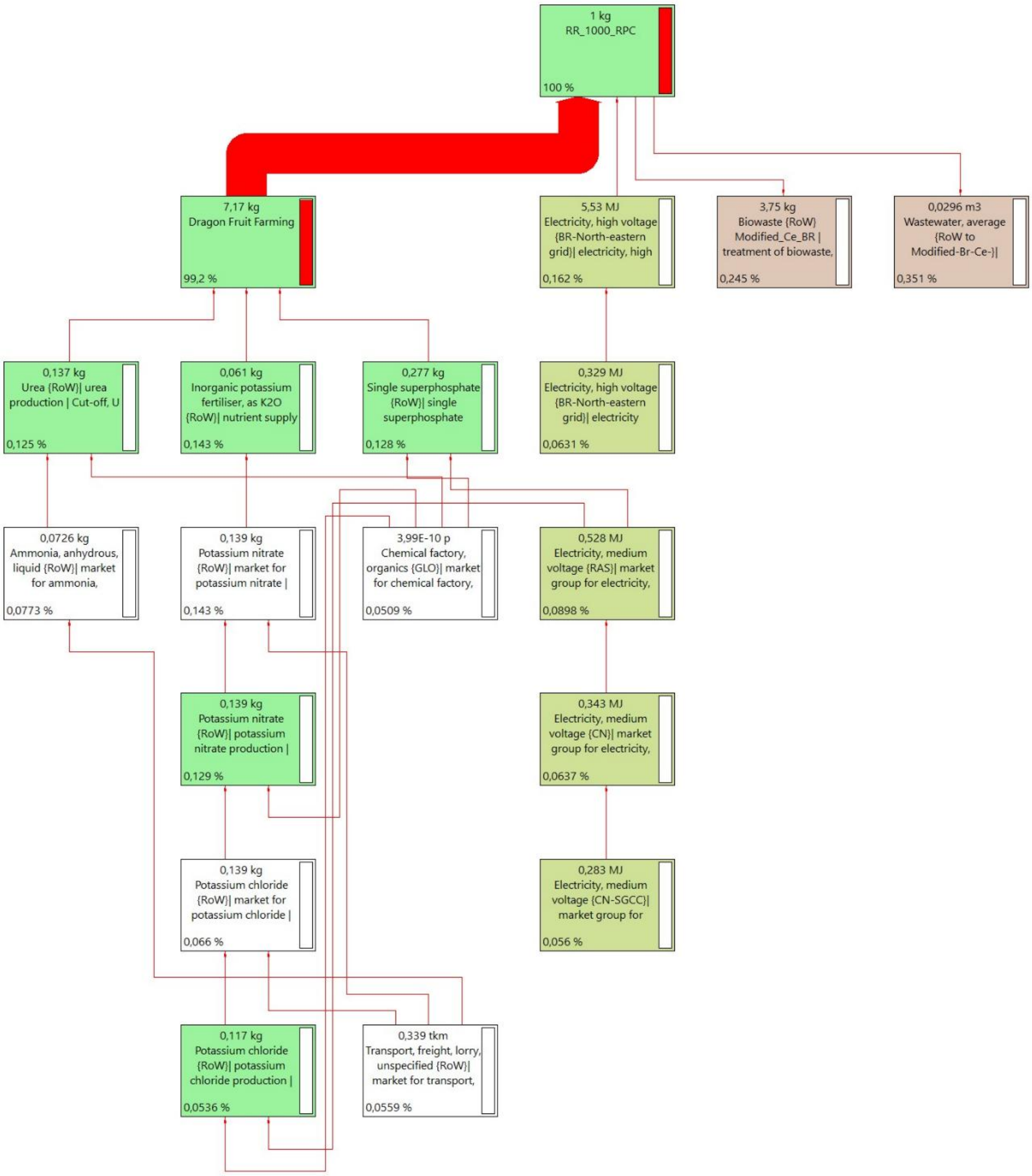


Figura S4. Rede de impacto da produção do corante (Categoria de Eutrofização terrestre).

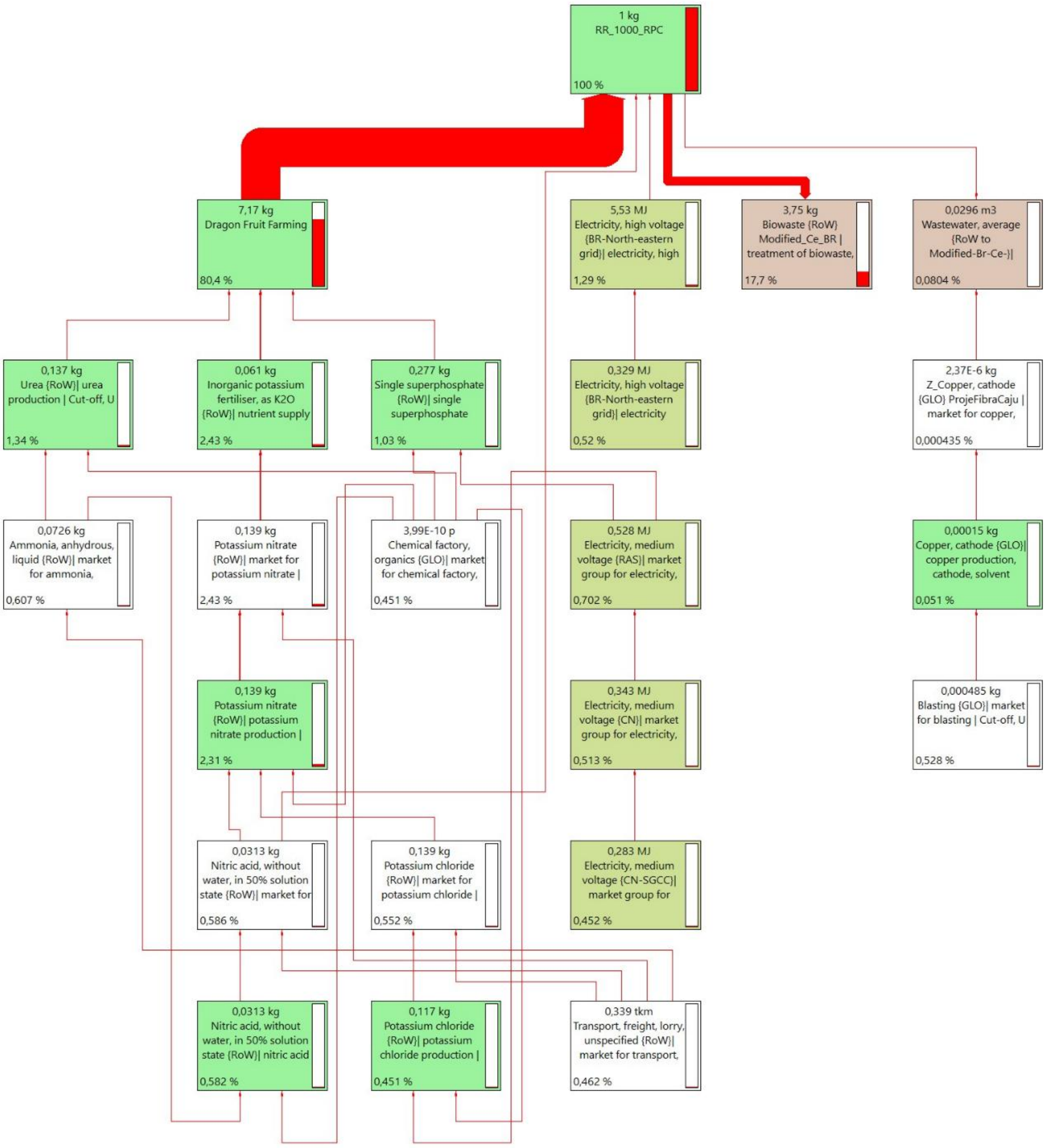


Figura S5. Rede de impacto da produção do corante (Categoria de Toxicidade humana, não cancerígena).

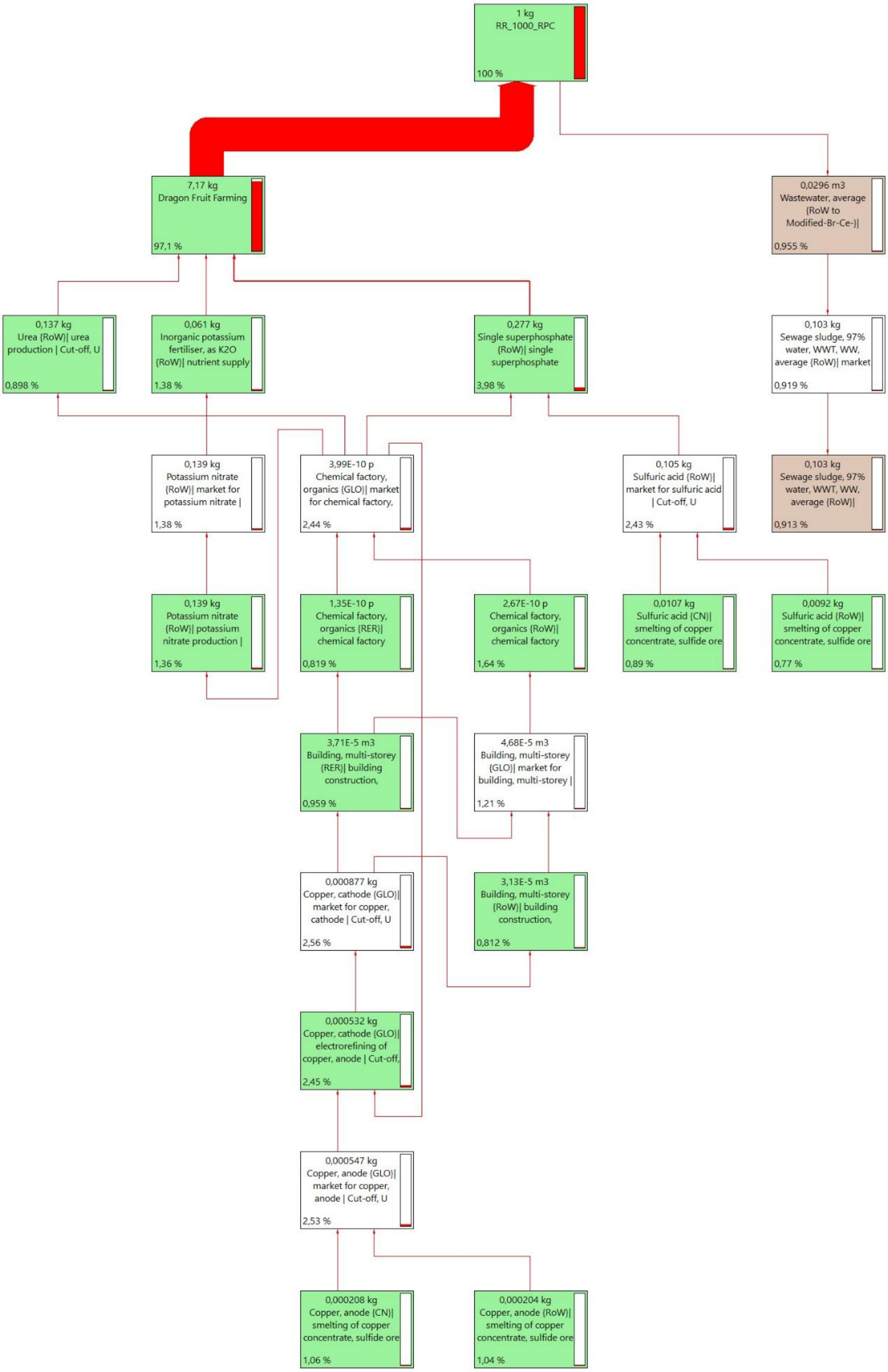


Figura S6. Rede de impacto da produção do corante (Categoria de Uso de Recursos minerais e metais).

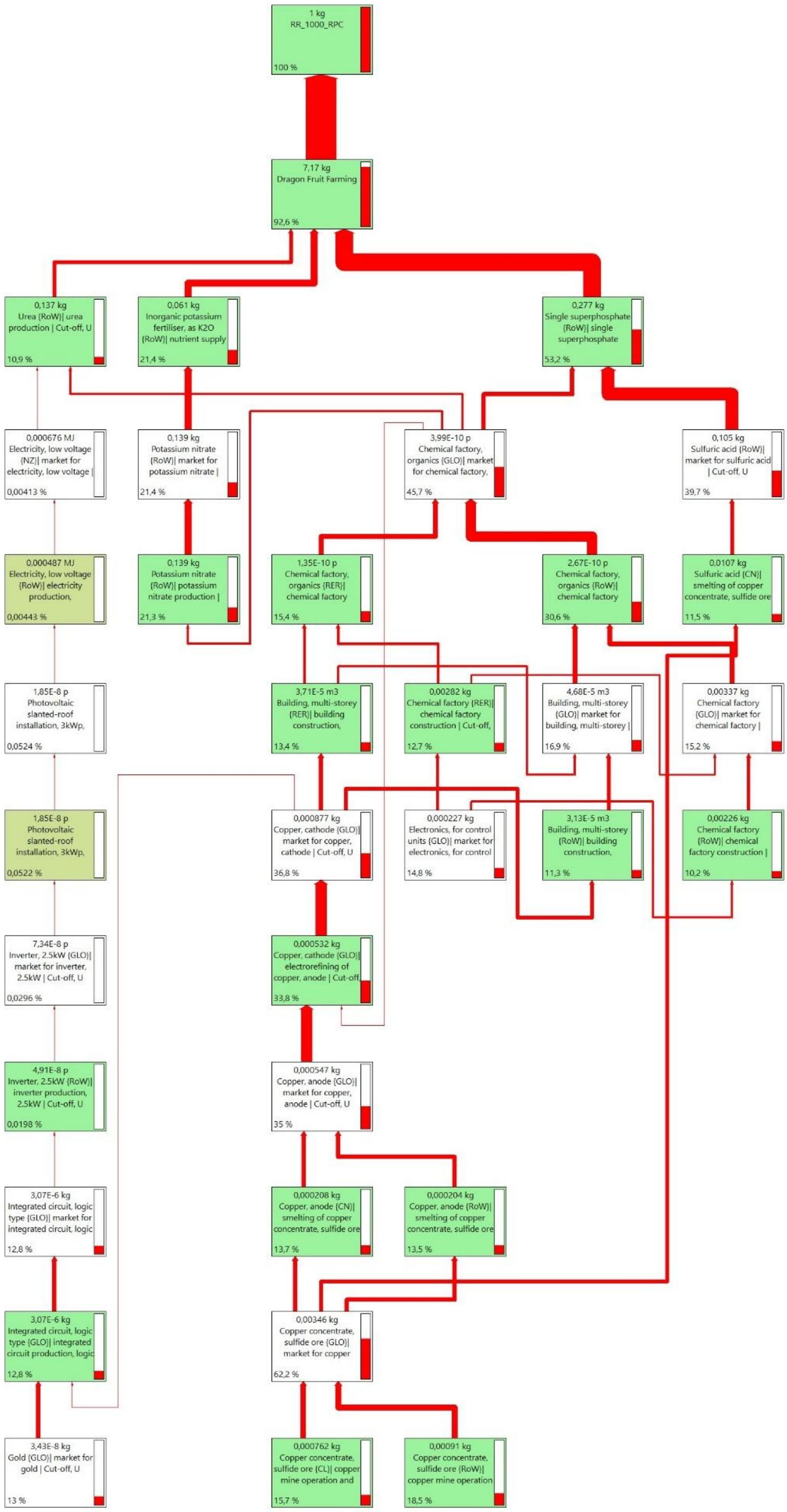


Figura S7. Rede de impacto da do processo industrial do corante de pitaya (Categoria de Acidificação).

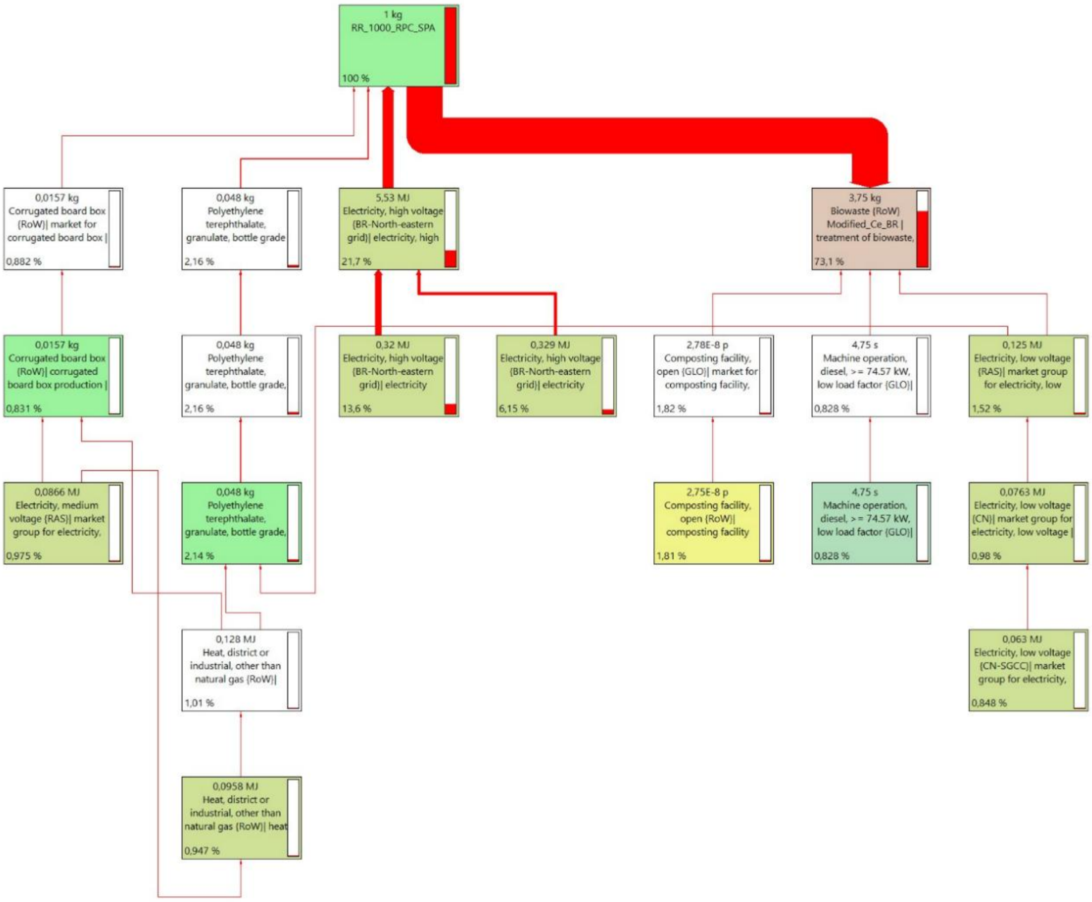


Figura S8. Rede de impacto da do processo industrial do corante de pitaya (Categoria Eutrofização, terrestre).

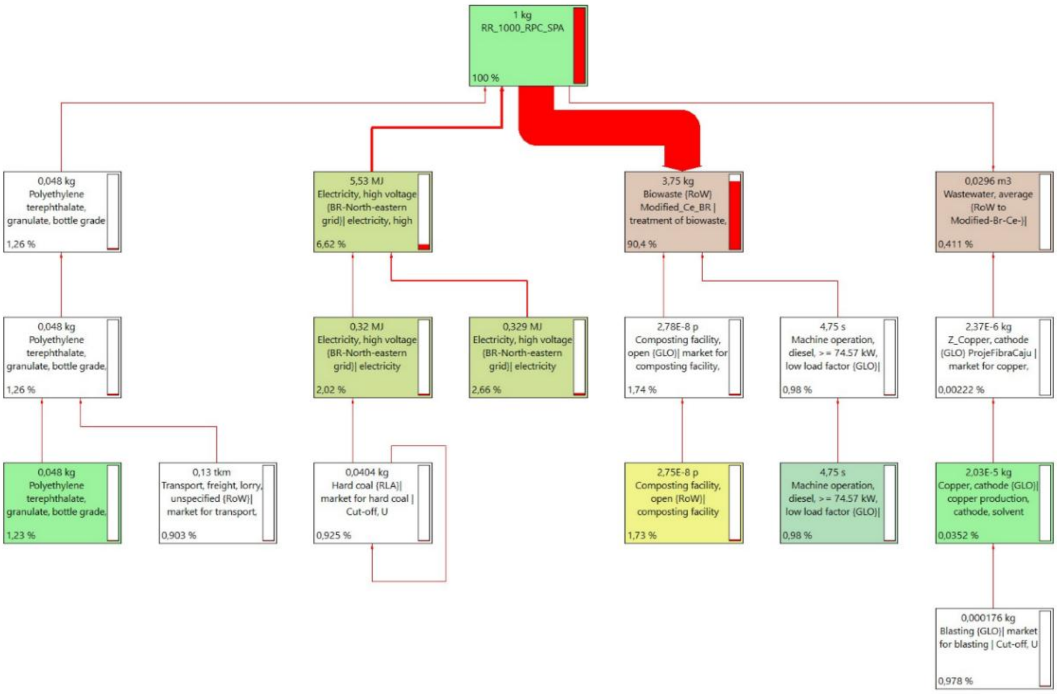


Figura S9. Rede de impacto da do processo industrial do corante de pitaya (Categoria de Eutrofização, marinha).

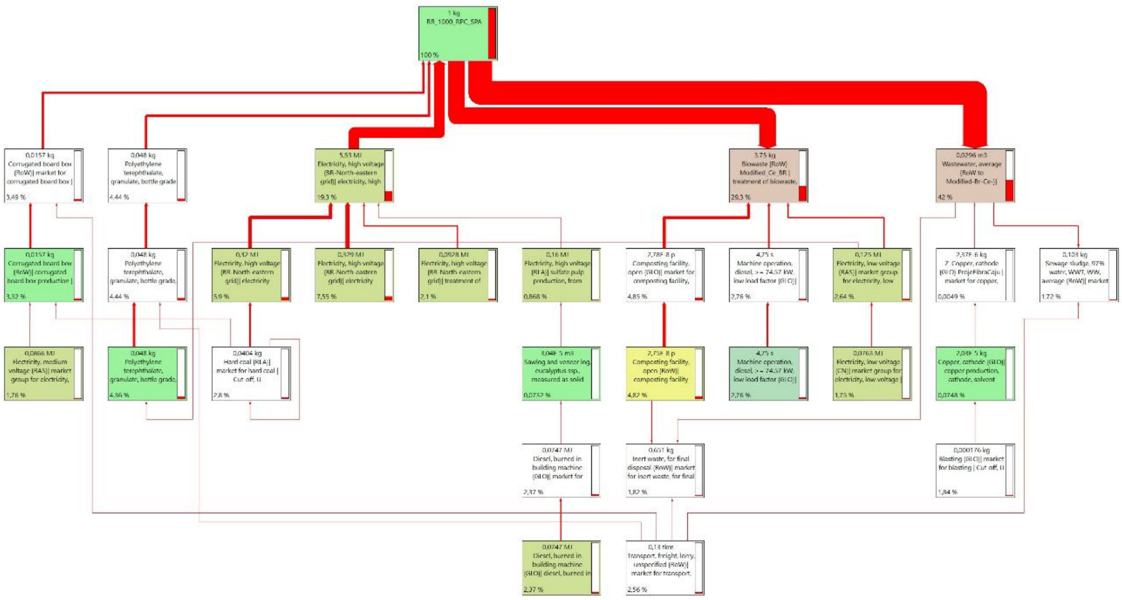


Figura S10. Rede de impacto da do processo industrial do corante de pitaya (Categoria de Toxicidade humana, não cancerígena).

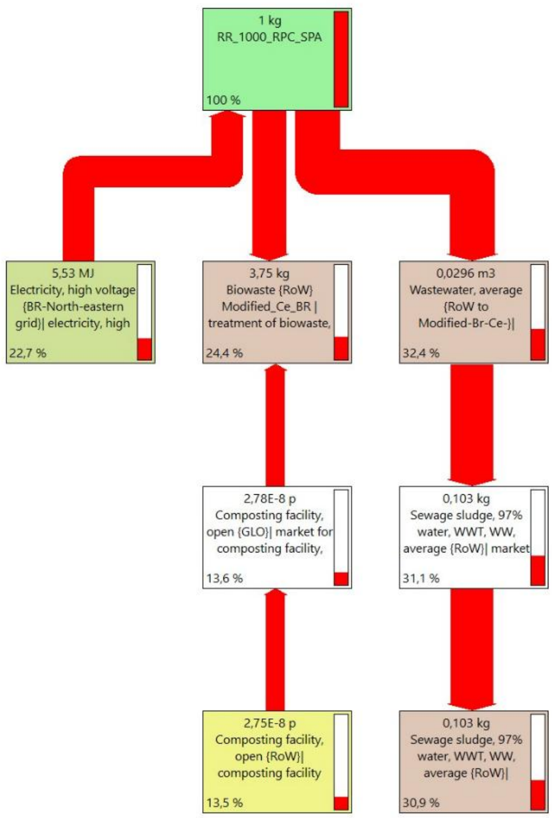
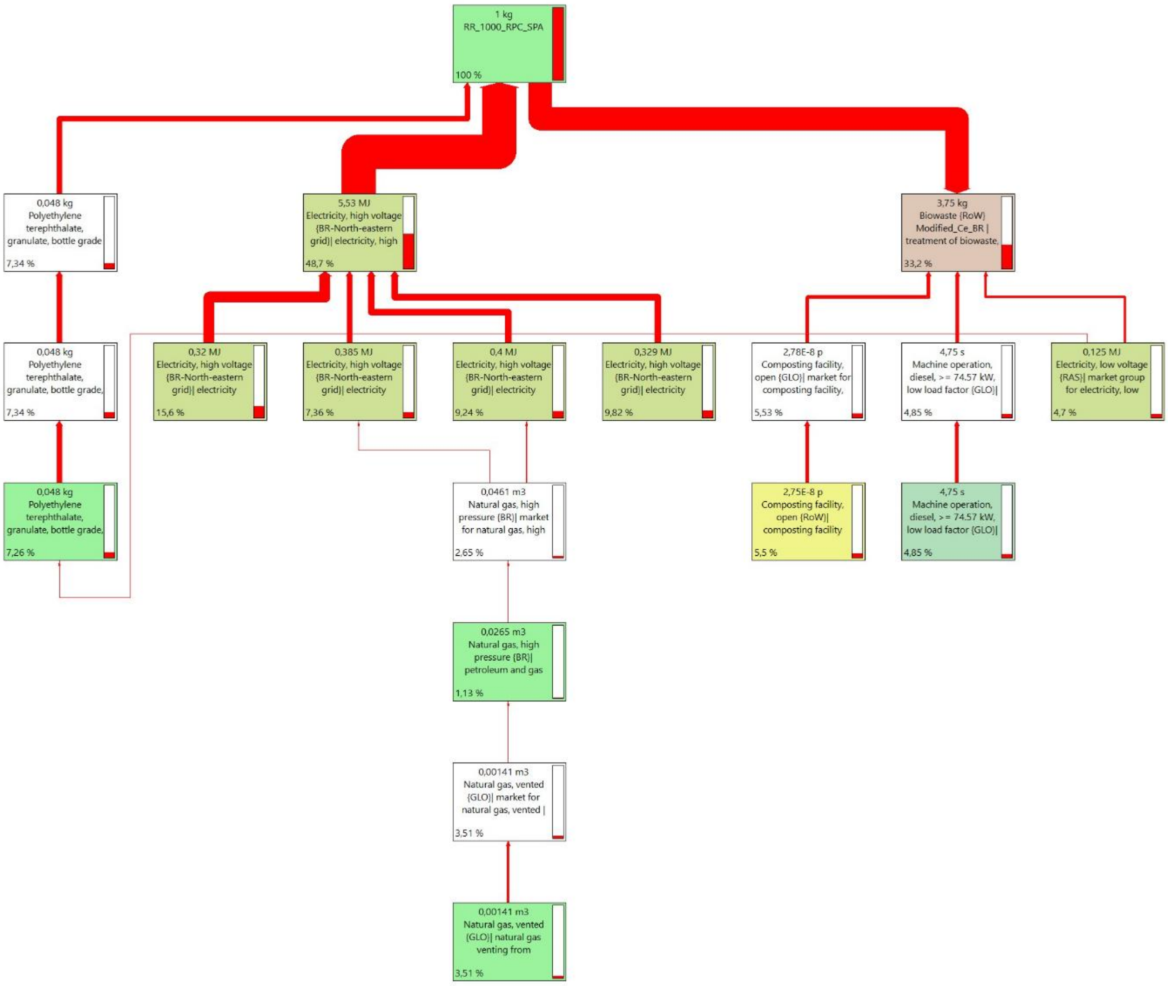


Figura S11. Rede de impacto da do processo industrial do corante de pitaya (Categoria de Mudanças Climáticas).



8. Diagrama de fluxo do processo para todos os cenários

Em todas as rotas (Figuras S13, S14, S15, S16 e S17), o processo inicia-se com a recepção e o armazenamento das pitayas (P-1 e P2). Na rota SC1, o fluxo de água proveniente da lavagem das frutas (P-3) é direcionado para um separador (A-1) que remove impurezas; o fluxo de água segue então para a mistura com a entrada principal de água (A-2) e a adição de cloro (A-3). Além disso, na rota SC1, o vapor do evaporador (P-10) foi reutilizado no trocador de calor (P-8). Na rota SC2, a modificação envolveu a utilização da casca da pitaya, que foi moída juntamente com a polpa (P-4) e posteriormente pasteurizada (P-6). Na rota SC3, o resíduo da microfiltração (P-8) foi seco (P-13), moído (P-14) e embalado (P-15) como subproduto (corante em pó). Este subproduto não possui caracterização química. A SC4 segue a mesma descrição da RR1000 (descrita no texto principal). No cenário 5, todas as estratégias (SC1 a SC4) operam simultaneamente. As figuras foram obtidas do *software* SuperPro Designer.

Tabela S5: Pressupostos feitos na modelagem de cenários.

Cenário	Descrição	Suposições feitas na modelagem (SuperPro Designer)
SC1	Reuso da água da lavagem dos frutos	1. As águas residuais da etapa de lavagem apresentam qualidade físico-química adequada (ou requerem tratamento leve) para serem reintroduzidas no processo.
SC2	Valorizando as cascas da pitaya	1. As cascas são processadas simultaneamente com a polpa, partindo do pressuposto de que contêm quantidade de betalaínas que justificam a extração (De Sousa Silva et al., 2024).
SC3	Recuperação do retentado da microfiltração	1. Cenário teórico (especulativo) de viabilidade, baseado na literatura (De Lima et al., 2020; De Sousa Silva et al., 2024) que sugere que o retido da microfiltração contém fibras e carboidratos.
SC4	Integração de energia fotovoltaica	1. A transição energética ocorre por meio de um modelo de negócios de Geração Distribuída ou um Mercado de Energia Livre (por exemplo, assinatura de energia), eliminando a necessidade de investimento em maquinário (CAPEX) para painéis solares na usina. 2. Essa premissa se reflete na mudança da tarifa de energia elétrica (custo do kWh no SuperPro Designer) e na matriz de emissões associada ao consumo de eletricidade.
SC5	Biorrefinaria Integrada (Cenário Otimizado)	1. Pressupõe-se a viabilidade técnica da sinergia entre todas as estratégias (SC1 a SC4) operando simultaneamente.

Figura S12. Diagrama do processo SC1.

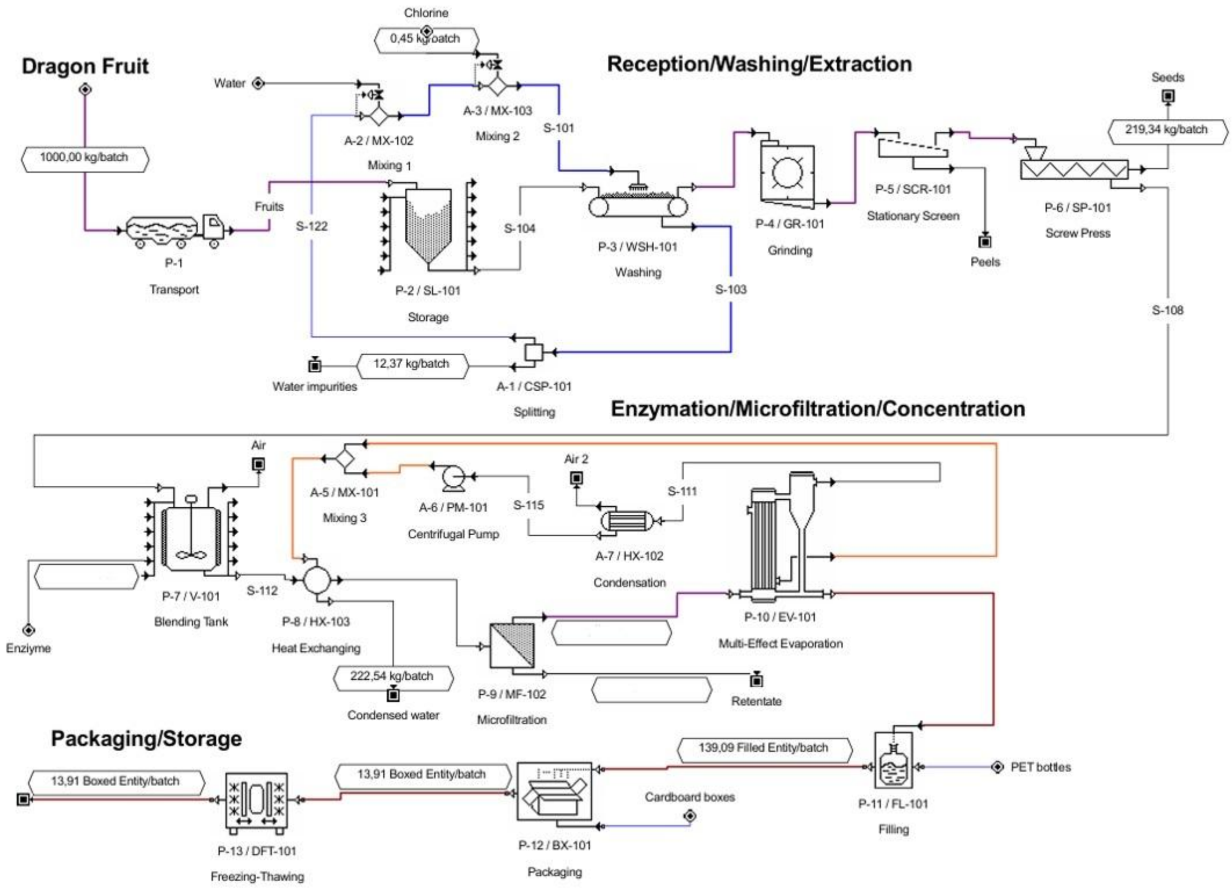


Figura S13. Diagrama do processo SC2.

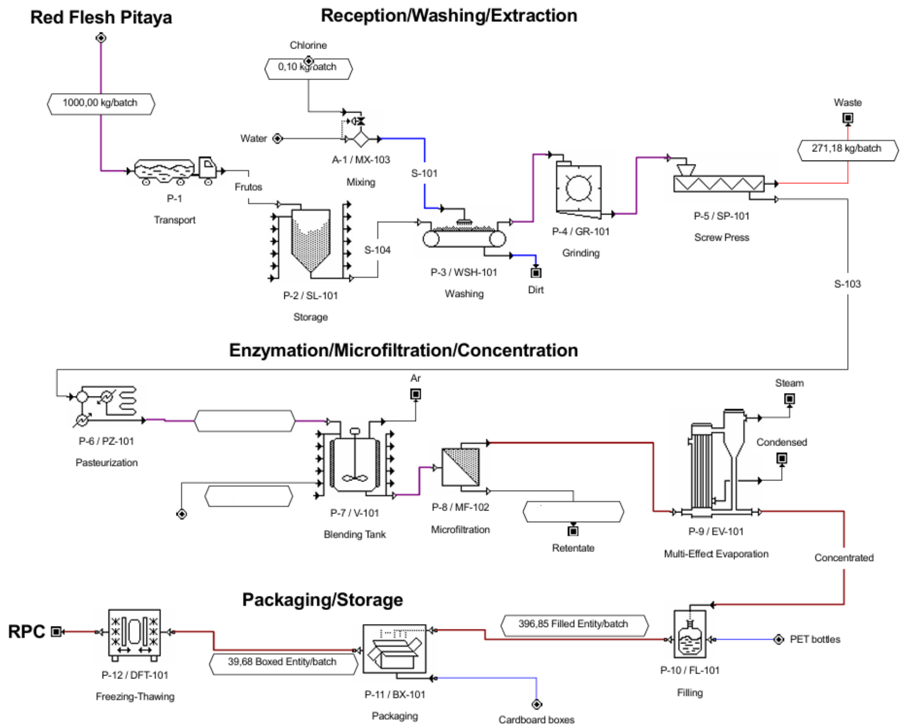


Figura S14. Diagrama do processo SC3.

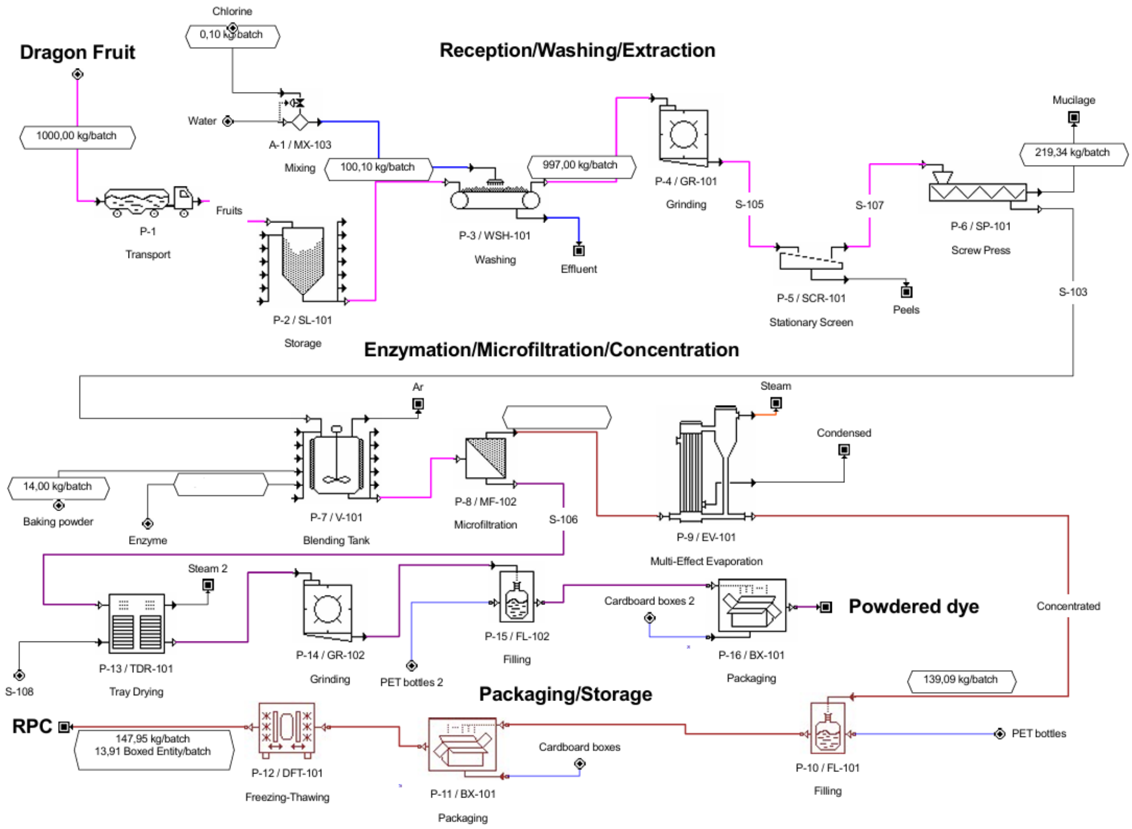


Figura S15. Diagrama do processo SC4.

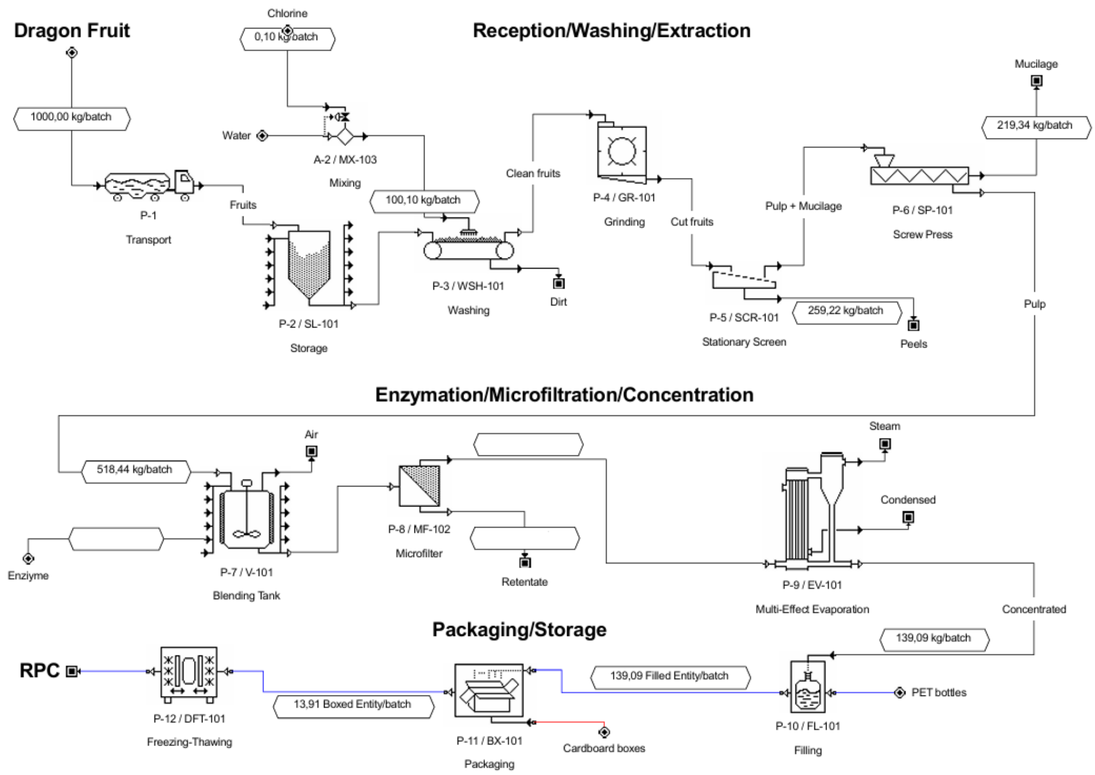
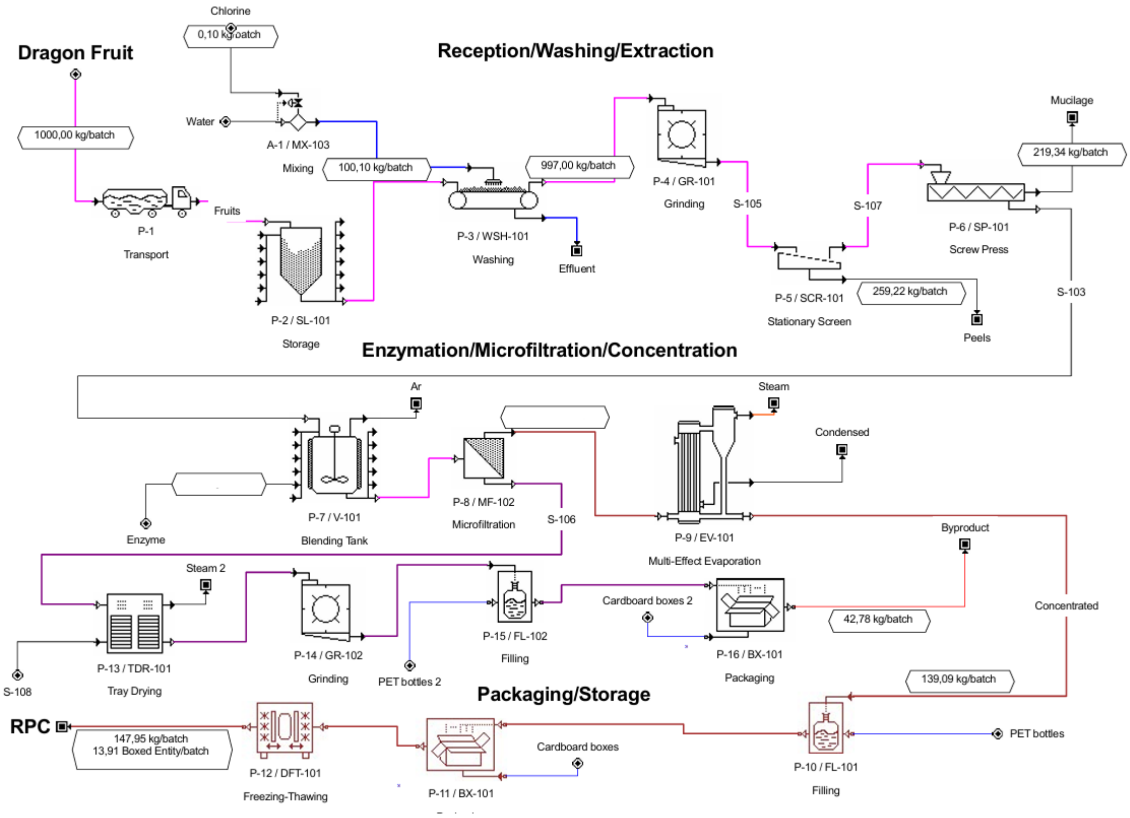


Figura S16. Diagrama do processo SC5.



9. Análise de risco de todos os cenários.

As figuras a seguir foram obtidas do *software* RStudio versão 2026.05.1.

Figura S17. Distribuição de probabilidade do Valor Presente Líquido (VPL) – SC1.

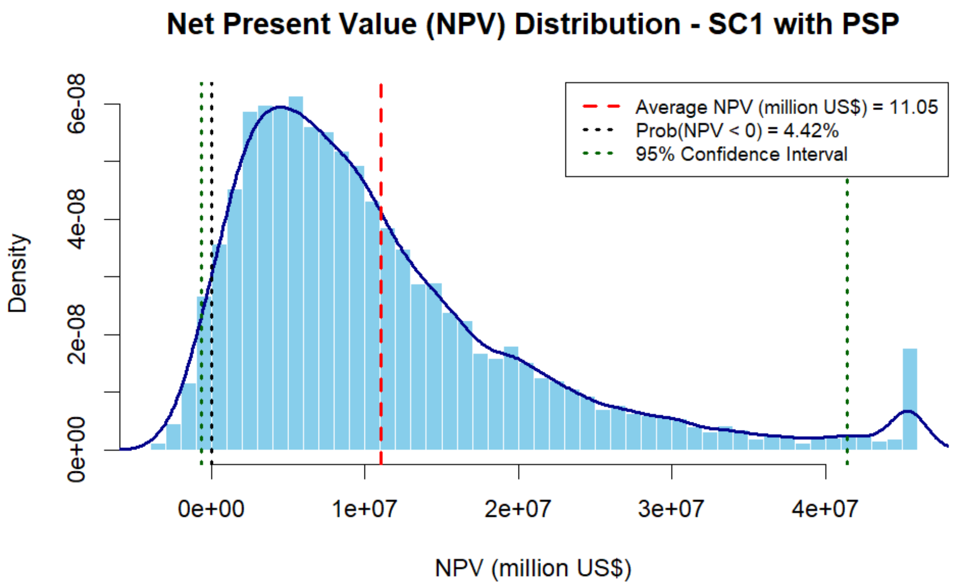


Figura S18. Distribuição de probabilidade do Valor Presente Líquido (VPL) – SC2.

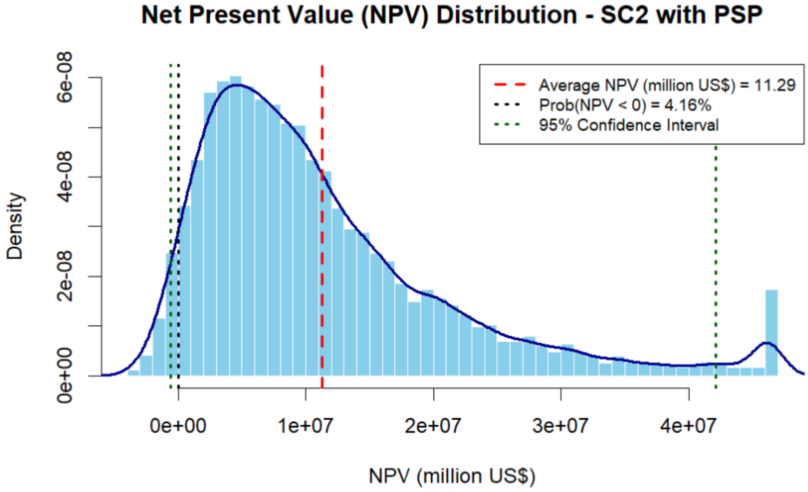


Figura S19. Distribuição de probabilidade do Valor Presente Líquido (VPL) – SC3.

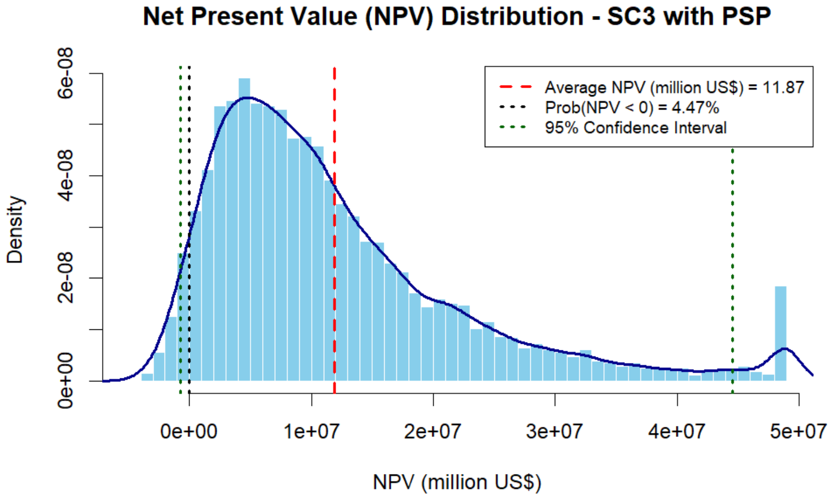


Figura S20. Distribuição de probabilidade do Valor Presente Líquido (VPL) – SC4.

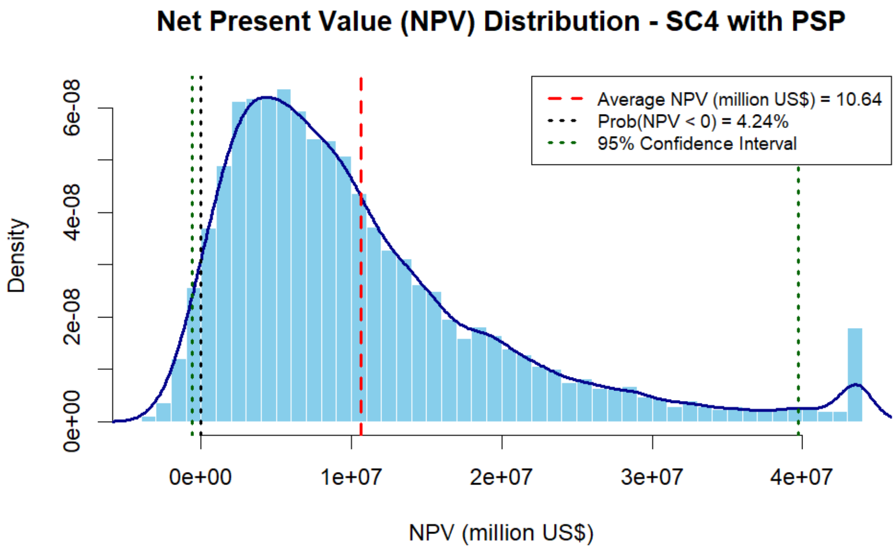
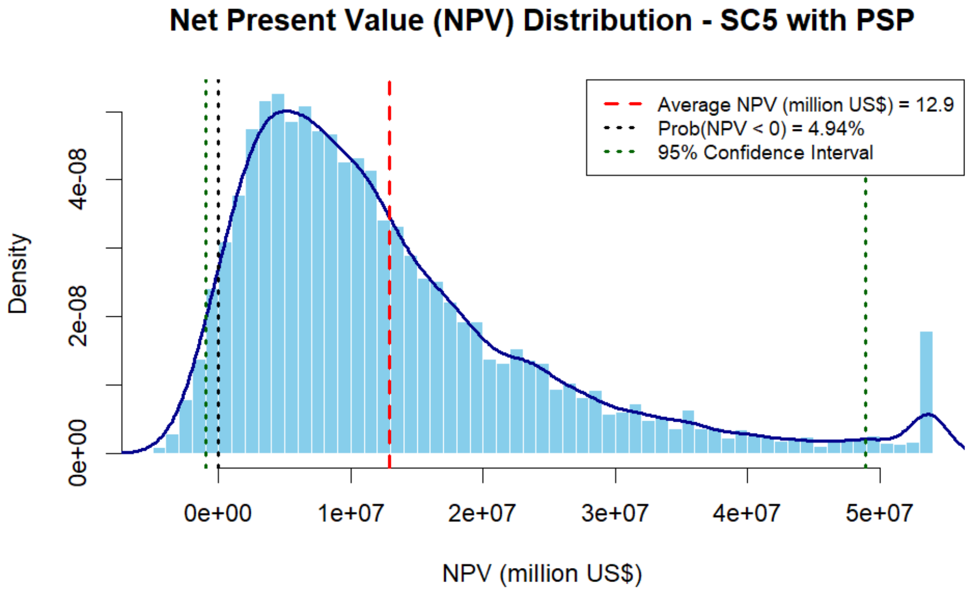


Figura S21. Distribuição de probabilidade do Valor Presente Líquido (VPL) – SC5.



10. Resultados econômicos da rota de referência e dos cenários.

Tabela S6: Resultados econômicos da RR1000 (rota de referência) e dos cenários.

	RR1000	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**
CAPEX	12,174,789.00	12,775,495.00	12,853,692.00	13,796,237.00	12,172,739.00	15,457,091.00
OPEX	5,084,841.00	5,157,195.00	5,440,568.00	5,463,250.00	5,062,303.00	5,558,365.00
Receitas (US$ /ano)*	6,544,219.00	6,685,231.00	6,984,855.00	7,111,921.00	6,521,314.00	7,403,690.00
Receitas (US$ /ano)*	7,198,680.00	7,353,723.00	7,683,371.00	7,823,082.00	7,173,461.00	8,135,753.00
Custo de produção (US$ kg^{-1} de corante RPC)	65.93	66.81	35.01	68.90	65.64	39.43

*Valores obtidos com a prática do Preço Mínimo de Venda.

References

1. De Lima, A. C. V., Dionisio, A. P., de Abreu, F. A. P., da Silva, G. S., Junior, R. D. L., Magalhães, H. C. R., ... & Zocolo, G. J. (2020). Microfiltered red–purple pitaya colorant: UPLC-ESI-QTOF-MSE-based metabolic profile and its potential application as a natural food ingredient. *Food chemistry*, *330*, 127222.
2. De Sousa Silva, F. T., da Rocha Viana, J. D., Gomes da Silva, M. D. F., Silvestre da Silva, G., Florindo Guedes, M. I., de Lima Rebouças, E., ... & Dionísio, A. P. (2024). Microfiltered red-purple pitaya concentrate: A promising multifunctional food-derived colorant. *Journal of Food Science*, *89*(10), 6759-6773.