

MACRÓFITAS AQUÁTICAS BIOINDICADORAS DE MUDANÇAS CLIMÁTICAS EM RESERVATÓRIO LÊNTICO DE UMA FAZENDA EXPERIMENTAL

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Introdução

As macrófitas aquáticas são vegetais que habitam desde brejos até ambientes verdadeiramente aquáticos, incluindo as macroalgas até as plantas vasculares. São classificadas de acordo com os biótopos, devido à heterogeneidade filogenética e taxonômica, refletindo o grau de adaptação ao meio aquático (THOMAZ; ESTEVES, 2011). Têm papel determinante na estruturação dos ecossistemas aquáticos, contribuindo para o aumento na heterogeneidade estrutural dos habitats, interferindo na

diversidade biológica, nas relações interespecíficas e na produtividade (AGOSTINHO *et al.* 2003). Uma das aplicabilidades é a sua utilização como bioindicadores ambientais (PEDRALLI, 2003).

A literatura aponta que as espécies mudam o período anual de seus ciclos de vida e suas distribuições espaciais (KEARNEY *et al.* 2008, THOMAS, 2010), sob efeito dos regimes anuais de temperatura e pluviosidade (WHITTAKER *et al.*, 2001). Assim sendo, as mudanças climáticas globais, sendo o intenso aquecimento da superfície terrestre, traz consequências físicas, como alterações nos padrões pluviosidade, além de efeitos biológicos, como alterações na fenologia e biogeografia da biodiversidade (PIEDEDE *et al.*, 2014).

Diante do exposto e tendo em vista a importância de tais organismos para a teia trófica aquática, esse trabalho objetivou avaliar a cobertura vegetal de macrófitas aquáticas ao longo dos períodos climáticos, em relação às características ambientais locais.

Material e métodos

Descrição da área

O estudo ocorreu na Fazenda Experimental Piroás (FEP), pertencente à Universidade da Integração Internacional da Lusofonia Afro-Brasileira – UNILAB, localizada no município de Redenção, estado do Ceará, distante cerca de 17 km do centro da cidade e se encontra nas coordenadas 4° 9'19,39 'S e 38° 47'41,48 'O, a uma altitude média de 240 m ao nível do mar. Apresenta precipitação média anual de 1.086 mm, temperatura média do ar de 26°C e a umidade relativa média do ar de 71,26 % (UNILAB, 2019).

Os meses de chuva na região ocorre entre janeiro e maio, já a estação de estiagem vai de junho a dezembro.

A FEP dispõe de 28,2 hectares de área total, destas, Área de Preservação Permanente (4,7 ha), Área de Uso Restrito (1,5 ha) e Reserva Legal (6,3 ha). É composta por dois açudes, denominados Auroras e Liberdade. Este último, sendo o local de estudo, tem profundidade média de 4,7 m, sua maior profundidade tem cerca de 5,5 m e o perímetro da margem é de 550 m, em que sua água é destinada para irrigação, além do consumo doméstico. É um reservatório perene, porém caracteriza-se por períodos de baixo nível durante a época de estiagem, e uma rápida ascensão na estação chuvosa.

Estratégia amostral

As amostras da água foram coletadas no açude Liberdade da FEP, para estudo das variáveis climatológicas (pluviosidade e evaporação), hidrológicas (temperatura da água) e biológicas (categoria de macrófitas, biomassa, peso seco e cobertura foliar). Para verificar a variabilidade sazonal, as coletas foram uma vez a cada mês, contemplando o período chuvoso (janeiro, março, maio/2019) e de estiagem (agosto, setembro e outubro/2019).

As informações meteorológicas, de evaporação, foram coletadas por um tanque USWB Classe A, enquanto que os valores de precipitação pluviométrica foram coletadas por pluviômetro, ambos os aparelhos instalados na FEP. Incorporado a isso, foram reunidas médias históricas de chuvas da cidade, segundo dados da FUNCEME (2019). Quanto à variável hidrológica, a temperatura da água foi obtida utilizando-se um termômetro de mercúrio com precisão de 0,5 °C. As medidas de temperatura foram rea-

lizadas em campo, durante os meses da amostragem, antecedendo o início de cada coleta de plantas.

Para as variáveis biológicas, para avaliar a cobertura e biomassa das espécies, foi escolhido um transecto na margem do açude, com perímetro de 550 m e a cada 5 m foi lançada uma parcela não fixa de 0,25 m² (50 x 50 cm), sendo contabilizados todos os indivíduos das unidades amostrais. Devido à oscilação da coluna d'água ao longo do ano, no período chuvoso, a área de amostragem média mensal resultou em 4,6 m², e o período seco resultou em tamanho médio mensal de 3,8 m². As plantas foram lavadas em água corrente, para eliminar resíduos e armazenadas em sacos plásticos, até análise em laboratório.

Análise dos dados

No Laboratório de Botânica da UNILAB, foi feita a estimativa de cobertura foliar para cada parcela, onde 20 folhas por espécie foram enumeradas e a partir do método do tamanho foliar, obteve-se a medição do comprimento (C), largura (L) individualmente, ambos expressos em centímetros (cm). Após estimada a área foliar, as folhas foram armazenadas em sacos de papel e mantidas em estufa de aeração forçada a 60°C por 24 horas. Em seguida, o material foi pesado em balança de precisão para determinação do peso seco (g). A partir de então, foram calculados os seguintes aspectos, considerado por parcela: 1) Área foliar (AF): expressa em cm²: $AF = C \times L \times \text{Coef.}$ Em que C é o comprimento do limbo; L é a largura máxima do limbo; Coef. é 0,79499, sendo este, o coeficiente de ajuste para macrófitas aquáticas, conforme Carvalho *et al.* (2011). Destaca-se que em parcelas que ocorreram mais de uma espécie foram somadas todas as AFs. 2) Área foliar específica

(AFE): expressa em cm^2/g : $\text{AFE} = \text{AF} / \text{MSF}$. Em que MSF é a massa seca das folhas, em gramas; 3) Índice de área foliar (IAF): em cm^2 : $\text{IAF} = \text{AF} / \text{AM}$. Em que AM é a área amostral, em m^2 ; 4) Razão da área foliar (RAF), em cm^2/g : $\text{RAF} = \text{AF} / \text{MST}$. Em que MST é a massa seca total da planta em g, resultando da soma de MSF + MSC, onde MSC é a massa seca do caule; 5) Razão de massa foliar (RMF): em g: $\text{RMF} = \text{MSF} / \text{MST}$; 6) Biomassa seca (Bio): expressa em g/m^2 : $\text{Bio} = \text{MST} / \text{AM}$. Adicionalmente, foi verificada a frequência de ocorrência (Fr) da comunidade das macrófitas aquáticas, por $\text{Fr} = \text{M} \times 100 / \text{m}$. Em que 'M' é o número de amostras em que o táxon ocorreu e 'm' é o número total de amostras estudadas. Assim, cada táxon foi classificado como Muito Frequente ($>70\%$), Frequente (entre 70% e 40%), Pouco Frequente (entre 40% e 10%) e Raro ($<10\%$). As espécies foram categorizadas por forma biológica, seguindo o recomendado por Pott e Pott (2000). Por fim, foi realizada a herborização de amostras vegetais, que auxiliou na identificação das espécies. A identificação dos táxons decorreu de comparações entre o material coletado e bibliografia especializada. Para verificar a variabilidade dos dados entre os períodos climáticos, foi aplicado o teste ANOVA One-way, Tukey *a posteriori*, no programa Statistica 7.0 (STATSOFT, 2004).

Resultados e discussão

Variáveis climatológicas

A pluviosidade foi marcante para ambos os períodos climáticos em estudo, em que o período chuvoso apresentou média de pluviosidade de 263,53 mm e o período seco (até o mês de outubro) uma média de 137,76 mm, o que pode representar bem o efeito para as macrófitas aquáticas, ten-

do em vista as preocupações com o efeito das mudanças climáticas para esses organismos. Em análise temporal, observa-se que houve tendência oscilatória da quantidade anual de precipitação na cidade de Redenção. O município tem uma média histórica anual de 1096,74 mm de precipitação, conforme aponta FUNCEME (2019), a média de 2019 foi de 1148,50 mm, já para a FEP a média do ano de 2019 (até o mês de outubro) foi de 133,32 mm. No presente estudo, para os meses mais chuvosos, a temperatura média do ar ($^{\circ}\text{C}$) na FEP foi de 27,43 $^{\circ}\text{C}$ e para o período seco a média foi de 27,86 $^{\circ}\text{C}$.

Entre janeiro e maio ocorreu uma rápida elevação do nível de água do açude, atingindo um pico máximo em março. Posteriormente, em função da baixa precipitação e alta evaporação ocorrida principalmente entre agosto e outubro, houve uma diminuição do nível da água. Além disso, é possível deduzir o crescimento também da incidência luminosa, desta forma, uma maior intensidade luminosa acarreta em altas taxas de fotossíntese e biodegradação, aumentando a biomassa por macrófitas aquáticas. Em regiões tropicais, a mudança sazonal de pluviosidade e a variação do nível de água têm se mostrado importantes fatores responsáveis pela variação sazonal da biomassa e produtividade das macrófitas aquáticas (BIUDES; CAMARGO, 2008).

Variáveis hidrológicas

A temperatura da água em açudes subtropicais e tropicais é de pequena oscilação. Porém, é possível observar padrões estacionais típicos com temperaturas mais elevadas na estiagem e mais amenas no período chuvoso. No presente estudo, a média da temperatura da água no açu-

de Liberdade foi 28,6 °C para os meses de maiores chuvas, sendo a média de 26 °C para os meses de estiagem. Dessa forma, a pequena variabilidade da temperatura da água possibilitou mudanças nas condicionantes limnológicas do reservatório.

Variáveis biológicas

Ao todo foram identificadas 9 famílias, 10 gêneros e 11 espécies, além de 4 morfotipos não identificados (Tabela 1). Três espécies foram muito frequentes em ambos os períodos, a saber: *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae), *Ipomoea pes-caprae* (L.) R.Br. (Convolvulaceae) e *Salvinia auriculata* Aubl. (Salviniaceae). No período chuvoso, um total de 14 espécies foram encontradas, dentre as quais quatro foram muito frequentes, ou seja, com 100% de ocorrência (Tabela 1), seguidas por duas espécies frequentes (66,67%), oito pouco frequentes (33,33%) e uma rara (<10%). Já no período seco, ocorreram sete espécies, em que três foram muito frequentes (100%), uma frequente (66,67%), quatro pouco frequente (33,33%) e sete raras (<10%). A vegetação aquática apresenta uma grande dinâmica, na variação e na quantidade de determinadas espécies de um ano para outro, influenciada pelas condições de cheia e seca (POTT; POTT, 2000), como demonstrado por Neves et al. (2006), em sua abordagem no semiárido baiano, em que registraram o maior número de espécies de macrófitas aquáticas no período chuvoso. Assim, a maior diversidade de espécies no açude liberdade durante o período chuvoso, pode estar relacionada a maior disponibilidade e renovação de água durante esses meses, possibilitando desenvolvimento de determinadas espécies.

Tabela 1 – Espécies identificadas de macrófitas aquáticas, de acordo com a família, forma biológica e frequência de ocorrência. Legenda: A = Anfíbia; FL = Flutuante Livre; MF = Muito frequente; F = Frequente; PF = Pouco frequente; R = Raro.

Família	Espécie	Forma Biológica	Chuvoso	Seco
Amaranthaceae	<i>Alternanthera philoxeroides</i> (M.) G.	A	MF	MF
Onagraceae	<i>Ludwigia helminthorrhiza</i> (M.) H. H.	FL	MF	F
Convolvulaceae	<i>Ipomoea pes-caprae</i> (L.) R. Br.	A	MF	MF
Commelinaceae	<i>Commelina</i> sp.	A	F	PF
Cyperaceae	<i>Cyperus difformes</i> L.	A	F	R
Salviniaceae	<i>Salvinia auriculata</i> A.	FL	MF	MF
Salviniaceae	<i>Salvinia mínima</i> B.	FL	R	PF
Loganiaceae	<i>Spigelia anthelmia</i> L.	A	PF	R
Fabaceae	<i>Centrosema brasilianum</i> (L.) B.	A	PF	R
Fabaceae	<i>Mimosa</i> sp.	A	PF	R
Poaceae	<i>Paspalum</i> sp.	A	PF	PF
Morfotipos 1, 2 e 3			PF	R
Morfotipo 4			PF	PF

Foram identificadas espécies de formas biológicas flutuante livre e anfíbia (Tabela 1), em que houve a predominância desta última, não tendo sido encontrada nenhuma submersa fixa, submersa livre, emergente ou epífita. Segundo Matias *et al.* (2003), a predominância de espécies anfíbias está relacionada com a baixa profundidade da coluna d'água e ao fato de a maioria dessas espécies resistirem à diminuição ou elevação do volume de água em açudes. Essas evidências corroboram os dados encontra-

dos no presente estudo, em que duas das espécies muito frequentes em ambos os períodos climáticos são anfíbias, *A. philoxeroides* e *I. pes-caprae*, podem estar associadas a ambientes úmidos, permanecendo em áreas mais rasas próximas às margens (BARROS, 2009). No presente estudo, a dominância dessa forma de vida no açude liberdade provavelmente está associada à resistência às alterações climáticas, ou seja, as modificações na disponibilidade hídrica, na intensidade de radiação solar, temperatura e nutrientes em margens mais rasas. Fia et al. (2008) demonstram que espécies anfíbias, como é o caso da *A. philoxeroides*, possuem alta capacidade de extrair nutrientes da água, em cerca de até 46% de nitrogênio, 28,8% de fosforo e 9,1% de potássio.

Os gráficos da Figura 1 demonstram a diferença entre os períodos de chuva e estiagem para os índices biológicos. Vale destacar que em parcelas com mais de uma espécie, foi realizado a soma das áreas foliares das mesmas. Não houve diferença significativa da área foliar (AF) entre os períodos, chuvoso e de seca ($p=0,77$) e, portanto, não sendo representativo para afirmar a influência climática sobre o desenvolvimento dessas plantas aquáticas (Figura 1A). A área foliar específica (AFE) é uma medida da alocação de biomassa, que reflete a área disponível para captura de luz. A AFE seria o índice que melhor justificaria as diferenças de biomassa entre os períodos avaliados, em que em períodos de maiores chuvas, as plantas tendem a estar submetidas a condições ótimas para a fotossíntese, com boa disponibilidade de água e de luz. No presente estudo, houve diferença sazonal significativa para AFE ($p<0,01$), sendo maior no período de chuvas ($218,39 \text{ cm}^2 \cdot \text{g}^{-1} \text{ cm}^2 \cdot \text{g}^{-1}$; Figura 1B). Em outras palavras, quanto maior o período de cheia para o reservatório, maior também serão os va-

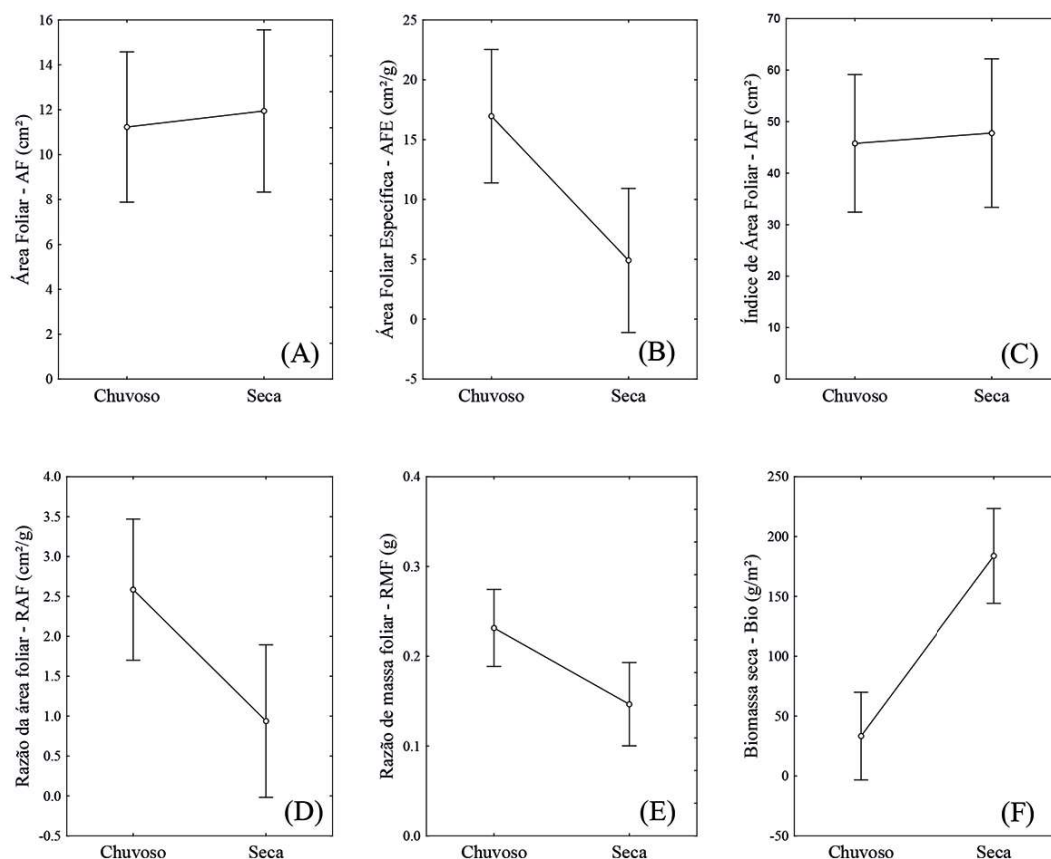
lores de área foliar específica. Essa resposta difere do que foi encontrado por Paiva (2005), ao estudar as respostas fisiológicas de plantas da Amazônia, onde a estação seca teve maior atuação sob variação da área foliar específica. Segundo o autor, em localidades que tenham uma estação seca mais pronunciada, as plantas tornam-se mais sensíveis e, por estarem mais expostas, desenvolvem diferentes mecanismos, como formas de adaptação ao ambiente.

O IAF é uma estimativa da biomassa, por meio da análise toda a parte vegetativa de planta. Para esse trabalho, a média para o período de chuvas desse índice foi de 698,72 cm², enquanto que para o período de seca a média foi de 477,77 cm², porém sem diferença significativa ($p=0,83$; Figura 1C) e, portanto, não havendo efeito das condições climáticas para esse índice. Dessa forma, não é viável a comparação da quantidade de cobertura presente na margem do açude liberdade e a distribuição sazonal entre os períodos.

A RAF demonstra a razão entre a área foliar sobre a massa seca total da planta. Não houve diferença significativa desse índice ($p=0,14$; figura 1D), mas observou-se uma tendência decrescente da RAF com a diminuição do nível de água, apresentando uma média de 45,25 cm²/g. Em contrapartida, houve diferença significativa para a RMF ($p<0,01$; figura 1E), a qual expressa a razão entre a massa seca retida nas folhas e a massa seca total acumulada na planta. No período chuvoso, essa razão apresentou uma média de 4,05 g, já no período seco a média foi de 1,47 g. O melhor desenvolvimento no período chuvoso sugere uma variação sazonal da massa seca das folhas em comparação com a biomassa total. À medida que a planta se desenvolve, surgem outras partes que crescem às custas de material importado das folhas, dessa maneira a maior ou

menor exportação de material da folha, pode ser uma característica genética a qual está sob a influência de variáveis ambientais (SANTOS, 2004). Esses resultados obtidos no presente estudo vão de encontro ao que foi relatado por Bortolini *et al.* (2007), em um ambiente lântico brasileiro, numa região do estado do Paraná, em que os autores registraram, no período chuvoso do local, os maiores valores de biomassa e os maiores valores de densidade de indivíduos por unidade de área, associado com os maiores valores de precipitação pluviométrica, favorecendo a alocação de nutrientes para a biomassa da macrófita aquática.

Figura 1 – Valores médios e intervalo de confiança para A) Área Foliar, em cm^2 ; B) Área foliar específica, em $\text{cm}^2.\text{g}^{-1}$; C) Índice de área foliar, em cm^2 ; D) Razão da área foliar, em $\text{cm}^2.\text{g}^{-1}$; E) Razão da massa foliar, em g.; F) Biomassa seca, em g.m^2 .



Por fim, a biomassa vegetal está entre os principais indicativos das influências ambientais sobre a comunidade de macrófitas aquáticas, visto que incremento na biomassa pode ser avaliado de acordo com os períodos de chuva e seca, bem como as flutuações do nível da água. Para o presente estudo, houve diferença significativa para a biomassa seca vegetal ($p < 0,01$; Figura 1F), com o seu maior valor nos meses do período seco (1838 g.m^2) e menor para o período chuvoso ($584,22 \text{ g.m}^2$). Condição oposta é indicada na literatura (SANTOS; ESTEVES, 2004, THOMAZ *et al.* 2006), em que os autores demonstram uma relação direta entre o aumento do nível da água e o aumento da biomassa da vegetação aquática. Outra variável que poderia ter influenciado a maior concentração de biomassa no período seco é a temperatura, a qual pode interferir diretamente sobre a produtividade das plantas aquáticas, causando adaptações na produção de sua biomassa (LUDLOW, 1987).

Os dados da biomassa no açude Liberdade podem ser suportados pelos maiores valores de cobertura no período de estiagem que foram da espécie *A. philoxeroides*, que elevou os valores de biomassa nesse período. É uma espécie considerada perene, de crescimento máximo no verão, além da sua morfologia particular, pois os caules crescem sobre a lâmina d'água até 60 cm de altura e possuem entrenós grandes e ocos, que podem se estender 15 metros sobre a superfície da água e se tornar tão robustos, ramificados e entrelaçados, que podem suportar o peso de um ser humano (GISD, 2019). Nesse contexto, o alto valor de biomassa seca para o período de estiagem, no presente estudo, se deve à grande fração de caules de *A. philoxeroides*, aumentando o valor de massa seca total (MST).

Foi possível verificar que a depleção da AFE e da RAF não afetaram a produção de biomassa, uma vez que essa

foi determinada principalmente pela massa dos caules, raízes e outras partes vegetais. Foi possível observar que o desenvolvimento de plantas aquáticas do açude liberdade pode ser influenciada pelos fatores abióticos, como temperatura, evaporação, disponibilidade de luz, que estimulam o ganho de biomassa das espécies, com proveito da energia solar quando a população se encontra adensada. Ferreira (2008), afirma que as condições para a produção primária vegetal e a decomposição da matéria orgânica está relacionada ao clima e à proximidade da linha do Equador, característica da região semiárida brasileira, com apresenta alta incidência luminosa, temperaturas altas, restrito período de chuvas e águas superficiais confinadas em açudes, o que promove.

Considerações finais

A relação da variabilidade climática com o estudo das macrófitas aquáticas para o açude Liberdade da Fazenda Experimental Piroás (FEP) sugere que a diminuição do nível de água, durante o período de menores chuvas, pode favorecer o aparecimento das espécies anfíbias, mesmo que temporariamente. Que foram, adicionalmente, determinados pela variabilidade climática os índices de Área foliar específica (AFE), Razão de massa foliar (RMF) e Biomassa. Durante o período seco, com menor frequência ou mesmo a ausência de eventos de cheias do reservatório, as plantas podem ter uma maior exigência por água, resultando em maiores taxas de crescimento e maior acúmulo de biomassa. Ou, ainda, em possíveis eventos climáticos extremos, espécies com maior disponibilidade de reservas poderão suportar maiores períodos de estiagem, como é o caso da espécie *A. philoxeroides*, de elevada biomassa

durante o período seco. Os dados biológicos para ambos os períodos climáticos podem subsidiar futuras abordagens sobre conservação e preservação do ambiente, a fim de melhorar o manejo da água, tendo em vista o efeito das mudanças climáticas globais.

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Review

Promising products based on hydrothermal liquefaction of agricultural biomass: an overview

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Received: 2 February 2025 / Accepted: 7 April 2025

Published online: 01 May 2025

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Abstract

The increasing global energy demand has driven the exploration of renewable alternatives to address the environmental challenges associated with conventional energy sources. In this context, agricultural, algae, and waste biomasses have emerged as highly promising and widely available renewable resources for the production of bioproducts through hydrothermal processes. Among these, hydrothermal liquefaction (HTL) is notable for its ability to convert wet lignocellulosic biomass in an aqueous medium, operating at lower temperatures and shorter retention times compared to pyrolysis. The primary product of HTL is biocrude. However, the process also generates high-value by-products with diverse applications. Therefore, this work provides a comprehensive literature review of the recent key aspects of HTL for biomass conversion. To achieve this, a systematic search was conducted, resulting in the selection of relevant articles published between 2015 and 2025. Recent studies report biocrude yields exceeding 50% for agricultural residues, with reaction times as short as 15 min. Furthermore, HTL facilitates the production of nitrogen and phosphate-based biofertilizers, supporting the recovery and reuse of these essential nutrients. It contributes to the synthesis of several valuable biochemical compounds, used in plastics, pesticides, and pharmaceutical industries. Consequently, biomass conversion via HTL represents a promising alternative to reduce environmental impacts while generating high-added-value products.

Keywords Hydrothermal process · Lignocellulosic biomass · Biocrude · Sustainable biofuel

1 Introduction

Fossil fuels continue to dominate the global energy matrix despite the well-documented issues associated with their use, including irreversible environmental impacts. Traditional fuel sources contribute to the release of 33.7 billion tons of CO₂ annually [1, 2]. The present scenario encourages the adoption of alternative methods that leverage abundant renewable resources, helping to reduce carbon emissions and support the development of sustainable energy solutions [3].

Agricultural biomass emerges as a promising renewable resource to reduce reliance on conventional energy sources, thanks to its high availability as a byproduct of agricultural production [4]. Furthermore, regardless of crop variation, agricultural waste primarily consists of organic materials and water, making it well-suited for hydrothermal transformation

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methods to produce bioproducts. These hydrothermal reactions include torrefaction, carbonization, liquefaction, and gasification, each one differing in processing techniques and resulting products [2, 4].

Hydrothermal liquefaction (HTL) stands out as an efficient method for converting wet agricultural biomass, as it operates effectively in water and requires minimal use of organic solvents [5]. In HTL, significant advantages include reduced processing time and energy savings, as there is no need to dry the raw material beforehand. Additionally, the HTL method enables the complete decomposition of biomass components, yielding biocrude as the primary product, along with biochar, aqueous and gaseous compounds, and high-value-added chemicals [6–8].

Despite the high versatility of the HTL method in converting various lignocellulosic and wet biomasses, the elemental composition of the raw material significantly impacts the yield and quality of the resulting bioproducts. Reaction temperature and retention time are key factors in determining the yields of biocrude and biochar, as these correspond to the liquid and solid phases obtained after processing [4, 9]. For this reason, ongoing studies focus on characterizing variations in raw materials with different compositions, as well as optimizing processing temperature and time. These efforts aim to enhance and expand the application of the HTL method as an efficient and sustainable energy solution [3, 6].

In this context, current literature explores yield parameters, advantages, variable influences, and applications of HTL as a transformative process for various biomass types. Biocrude yields above 30% for agricultural biomass converted through the HTL process are being reported [10–12]. The primary product of the HTL process can be utilized across various industries and sectors, including as fuel for powering aircraft [7, 13]. HTL has also been employed to recover residual phosphorus from biomass, which can be used as a biofertilizer for crops [14]. The biochemicals produced through the HTL process can also be utilized in industries such as plastics, pesticides, and pharmaceuticals [15]. Agricultural, forestry, and algae residual biomasses are used for this purpose [16–18]. Given its versatility and benefits, the manuscript presents and discusses consolidated concepts, applications, and raw materials used in the HTL process for biomass conversion, especially agricultural biomass, through a bibliometric review.

2 Methodology of review

A three-stage structured methodology was employed, as shown in Fig. 1, for searching, selection, and analysis of scientific articles. Web of Science and Scopus were chosen for their relevance and extensive coverage in the academic field.

In the first stage, keywords for the bibliographic search were defined and selected. The chosen keywords were “Hydrothermal liquefaction”, “Agricultural biomass”, “Industrial applications”, “Chemical”, “Bio-oil”, “Biofuel”, and “Biofertilizer”, as they were deemed representative of the proposed theme. The search was limited to articles published between 2015 and 2025 to include recent studies reflecting the most relevant scientific advancements. Additionally, specific filters were applied to focus on “articles” and “review articles” as document types.

The second stage involved searching the databases, which led to the identification of 617 studies on the Web of Science platform using the keywords “Hydrothermal liquefaction”, “Agricultural biomass”, “Industrial applications”, and “Chemical”, and 3,694 studies on the Scopus platform using the keywords “Hydrothermal liquefaction”, “Bio-oil”, “Biofuel”, and “Biofertilizer.” This search resulted in a total of 4,311 articles. These studies were exported to a reference manager to streamline the process of organizing and removing duplicates.

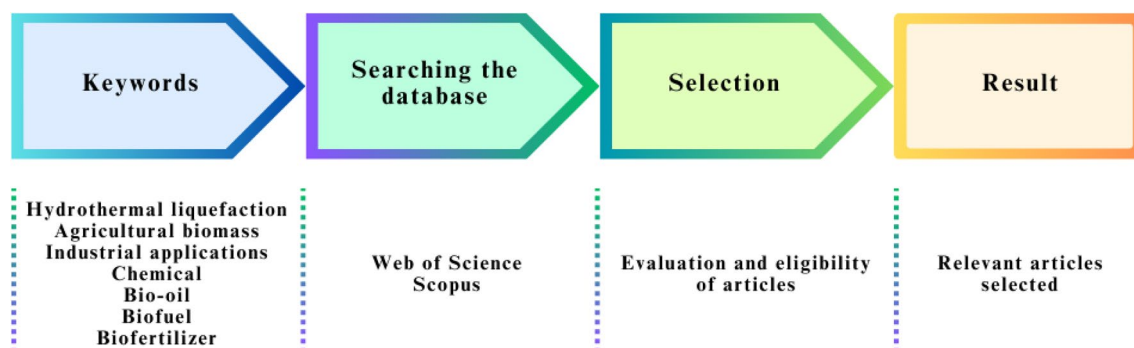


Fig. 1 Methodology used for article selection and eligibility

The third stage involved screening the articles by reviewing their titles, abstracts, and keywords. The goal was to assess whether the studies aligned with the objectives of the review. Inclusion criteria were established, which included: a) relevance of the study topic, b) alignment with the review's objective, and c) originality of the content.

After screening, 75 articles that met the established criteria were selected. These articles formed the basis for the analysis of the review and were considered highly relevant for addressing the research questions and contributing to the discussion on the potential of HTL applied to agricultural biomass and its applications. The selected studies underwent thorough analysis to extract key data, such as objectives, methodologies, results, and conclusions from each article. This process aimed to construct a critical synthesis, identifying patterns, research gaps, and advancements in the application of HTL, thereby providing a comprehensive overview of the current state of the art on the topic.

To prepare the section titled "Patents and Technologies," a targeted patent search was conducted using the PATENTSCOPE/WIPO platform. This platform was selected due to its broad international coverage and the ability to access detailed information on technological innovations registered across various fields. The search followed the same thematic criteria as for the scientific articles, incorporating keywords such as "Hydrothermal liquefaction," "Agricultural biomass," and "Industrial applications." The goal was to identify relevant patents that focused on technological advances and industrial applications related to the main theme of the review. The results were analyzed for their relevance and applicability to the study, enabling the integration of a comprehensive discussion on the latest and most innovative technologies in the HTL of agricultural biomass.

3 Current state of HTL research

3.1 What is HTL?

HTL is a thermochemical conversion technology designed to transform wet biomass into high-value energy products, helping to reduce the reliance on fossil fuels [11]. Compared to other conversion technologies, HTL offers several advantages and is regarded as a promising approach to renewable energy production [14, 19]. One of the key advantages of the HTL method is its ability to process biomass directly in its wet state, eliminating the need for prior drying. This advantage significantly reduces the energy costs of the process, making it a more efficient option for producing alternative energy sources [2]. HTL technology is particularly well-suited for materials with high moisture content, typically over 50% by weight, such as organic waste, food waste, algae biomass, and sewage sludge [9]. This makes HTL a viable solution for using waste that would otherwise be discarded, fostering sustainability and contributing to the circular economy.

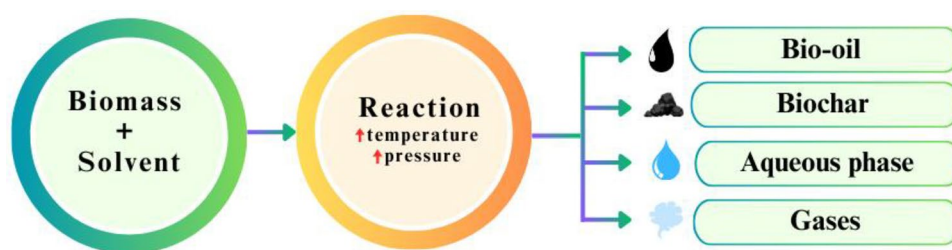
In the HTL process, wet biomass is subjected to temperatures that can vary from 220 to 350 °C and high pressures that can vary from 6 to 20 MPa [10–12, 14, 20]. Under these conditions, with water near its critical point, the thermal decomposition of biomass components takes place through reactions such as hydrogenation, decarboxylation, decarbonylation, condensation, and hydrolysis [10, 21]. During the HTL process, the biomass is exposed to a reaction at high levels of temperature and pressure (Fig. 2). HTL technology stands out for its remarkable flexibility regarding the moisture content of biomass, the quality of the biocrude produced, and the ability to control the oxygen content, especially when compared to the pyrolysis process [10].

3.2 Biomass for HTL

Biomass is an organic material that stores chemical energy in the form of carbon and hydrogen [2]. Among renewable energy sources, energy derived from biomass transformation stands out as a promising solution for the future reduction of fossil fuel dependence [14]. Through biomass transformation processes like HTL, it is possible to obtain materials that serve as sustainable energy sources. This is especially important as fossil fuels are finite and non-renewable, while the continuous growth of the global population and rapid industrialization drive an increasing energy demand [2, 10].

There are various types of biomasses, particularly organic materials like food crop residues and plant residues, which are classified as agricultural residues. These materials hold significant potential in the energy transition process, especially through the production of clean energy and bioproducts [11, 22]. With the growing volume of waste

Fig. 2 Graphical representation of the HTL process



from agricultural and industrial activities, there is a pressing need to find alternative sustainable solutions, such as converting these materials into energy. Organic waste, including agricultural residues, forestry waste, food processing byproducts, and municipal waste, holds great potential for bioenergy production through their transformation into liquid fuels via HTL [14, 23].

Thermochemical conversion methods for transforming biomass into biofuel include pyrolysis, hydrothermal reactions, and gasification. Pyrolysis occurs when biomass is heated in an inert atmosphere, leading to the degradation of the polymer chains present in it, resulting in the production of bio-oil, biochar, and non-condensable gases. This technique can be subdivided into slow pyrolysis, fast pyrolysis, and flash pyrolysis, depending on the residence time, heating rate, and temperature. Gasification consists of heating the biomass with a gasifying agent, generating synthesis gas, biochar, tar, and ash. Synthesis gas is composed mainly of CO, CO₂, H₂, and CH₄ [2].

When evaluating the environmental potential of agricultural waste for biofuel production in aviation in Brazil, sugarcane straw stands out as a significant resource. In 2015, the estimated amount of sugarcane straw waste was 70 Mt/year, with projections of 102 Mt/year by 2030, reflecting a 63% increase in sugarcane production in the country. This material has the potential to generate a technical–economic biofuel capacity of 0.67 EJ by 2030, with costs ranging between 19 and 65 US\$/GJ [24]. Sugarcane bagasse and straw are typically burned in boilers to generate heat and electricity. However, when considering energy densification, these materials have a high heating value (HHV) of around 17 MJ/kg. In contrast, the biocrude produced from these materials can achieve HHV values of approximately 33 – 36 MJ/kg, highlighting a significant improvement in energy content [11].

Canada's main agricultural biomasses include wheat, barley, canola, and linseed straw. When evaluating the most suitable raw material for biocrude production, it was found that barley straw exhibited the most promising characteristics. These characteristics included a low lignin content (8.0% by weight, compared to cellulose and hemicellulose), higher levels of hydrocarbons (C = 50.1% by weight and H = 6.1% by weight), and lower oxygen content (43.5% by weight) [10]. In the United Kingdom, ferns (*Pteridium aquilinum*) and reeds (*Juncus effusus*) are considered invasive species and are regularly cut as part of local agro-environmental management protocols. As a result, they are seen as potential sources of biomass [20].

There is a gap in the production of biocrude from natural crops and forage grasses. However, when evaluating the processing of these materials, it was found that HTL is an efficient and viable technology for biofuel production. It also serves as a valuable alternative for utilizing low-value biomass [25]. During the HTL process, several factors can influence the properties of the biocrude produced, with the temperature being one of the most significant. Generally, increasing the temperature leads to higher biocrude yields, although the optimal temperature depends on the specific properties of the biomass being processed [2]. In a study on the HTL of sugarcane bagasse and straw at temperatures between 300 and 350 °C, the optimal biocrude yields were achieved at 300 °C. This achievement was accomplished without the use of a catalyst and with constant minimum heating times [11]. Zhang et al. [14] found that cotton stalks are highly reactive at milder processing temperatures (220 °C). They also observed that the use of catalysts like CeO₂ and NaOH could enhance the results, with biocrude yields of 7.96% and 6.11% by weight, respectively, in the HTL process. The effects of various parameters on different biomasses are summarized in Table 1.

Agricultural and forestry residues represent two primary sources of lignocellulosic biomass. The term lignocellulosic specifically refers to the key structural components, including lignin, cellulose, and hemicellulose, which are inherent in both agricultural and forestry biomass. The elemental composition is predominantly comprised of carbon, hydrogen, and oxygen, along with trace amounts of nitrogen, sulfur, and mineral contaminants. The biocrude yield is highly influenced by the biochemical composition of the biomass, with the cellulose content weight percentage and the cellulose-to-hemicellulose ratio being critical factors that significantly affect the yield [27].

In Thailand, the hybrid giant grass (*Pennisetum purpureum* × *Pennisetum typhoideum*) serves as an energy source due to its high lignin content. It thrives in low-quality soils without water availability while still producing high biomass yields.

Biocrude yields can reach up to 50% by weight at 350 °C with a grass-to-deionized water mass ratio of 25% [1]. Another significant source of biomass in Thailand is tobacco, which generates annual revenues of approximately USD 1.65 billion and produces large amounts of waste with potential for biofuel conversion. A maximum biocrude yield of approximately 52% by weight was achieved at 310 °C with a reaction time of 15 min. Additionally, 90% of the energy was recovered in bio-oil and solid products under these processing conditions [9]. Tobacco industries typically dispose of processing waste in landfills or through incineration. However, this waste can be repurposed for chemical material extraction or bioenergy production via HTL [26]. Therefore, these investigations highlight the importance of using agricultural waste for clean energy production through HTL.

Furthermore, algae are regarded as promising biomass sources for biofuel production. They offer several advantages as a bioenergy feedstock, including the ability to grow on non-arable land and utilize residual combustion gases and wastewater for cultivation [28]. The use of agroindustrial wastewater for microalgae cultivation supports biomass generation while reducing costs and minimizing environmental impacts [29, 30].

Common lignocellulosic materials are predominantly composed of 40–60% cellulose, 15–30% hemicellulose, and 10–25% lignin, in addition to carbohydrates and lipids, which have high C, H, and O contents. Materials of biological origin, such as manure, animal waste, brewery waste, food waste, yogurt, egg white, human and animal waste, shellfish and shrimp shells, black beans, used coffee, soybean waste, and algae, also contain proteins and other N-containing compounds [31, 32]. Cow manure, wheat straw, and their combined liquefaction (co-HTL) were used to assess the catalytic hydrotreatment of biocrudes, revealing that co-HTL enhanced hydrocarbon content, leading to higher carbon efficiency in the biomasses [33]. Additionally, biocrude can be produced from agricultural digestates through the HTL process, with digested sewage sludge exhibiting a calorific value of up to 35.4 MJ/kg and an energy recovery potential of approximately 43.3% for straw and manure digestate [21].

In addition to converting biomass into biocrude and biofuels, there is a concern regarding the treatment of water produced during HTL. During the process, the raw biomass is heated and reacts in a condensed aqueous phase, causing a substantial portion of water-soluble substances to transfer into the liquid phase. The samples contained organic carbon levels ranging from 1 to 2% by weight in the aqueous phase, accounting for 34–45% of the total carbon fed to the reactor. Alcohols and ketones were the primary compounds identified and quantified [5]. In another study, the evaluation of using wastewater from the wheat straw and sewage sludge HTL process combined with anaerobic digestion revealed this approach demonstrated potential viability for energy recovery, generating methane that could be utilized as fuel [34].

Hydrothermal carbonization is also a method that has gained prominence due to its simplicity, low cost, and energy efficiency. In general, the method involves the reaction of the precursor with water in an autoclave, at temperatures ranging from 150 to 260 °C, under automatically generated pressures. During the process, the starting material undergoes a sequence of structural and decomposition reactions, starting with hydrolysis, followed by defunctionalizations, such as dehydration and decarboxylation, and recondensation and aromatization, resulting in a carbonaceous material known as hydrochar at the end of the process [35].

Table 1 HTL of some biomasses under different operational conditions

Biomass	Operating conditions	Biocrude yield (%)	HHV (MJ/kg)	References
Sugarcane straw	Temperature: 300 °C	30.9	–	[11]
Sugarcane bagasse	Temperature: 300 °C	36.2	–	[11]
Cotton stem	Temperature: 220 °C Reaction time: 4 h Catalyst: CeO ₂	8.0	23.1	[14]
Barley straw	Temperature: 270 °C Reaction time: 15 min Catalyst: K ₂ CO ₃	42.7	30.7	[10]
Tobacco processing waste	Temperature: 310 °C Reaction time: 15 min	52.0	31.9	[9]
Reed	Temperature: 350 °C Reaction time: 30 min	24.9	30.7	[1]
Tobacco processing waste	Temperature: 310 °C Reaction time: 15 min	50.0	–	[26]
Tomato plant residues	Temperature: 250 °C Reaction time: 30 min Catalyst: H ₂ SO ₄	45.1	18.5	[12]
Corn	Temperature: 350 °C Reaction time: 20 min	27.6	33.8	[25]
Triticale	Temperature: 350 °C Reaction time: 20 min	26.1	30.0	[25]
Oat	Temperature: 350 °C Reaction time: 20 min	25.1	32.7	[25]

3.3 Examples of products processed by HTL

Biomass can be converted into products through various methods, including traditional biological techniques like fermentation and digestion, or thermochemical processes such as combustion, gasification, pyrolysis, and liquefaction. Traditional methods often face challenges due to the long time required for transformation and the low yield of products. In contrast, thermochemical processes tend to offer higher efficiency in converting biomass into valuable products. HTL is widely used for the production of various products, such as bio-oil, biofuels, fertilizers, and platform chemicals (Table 2). According to Madsen et al. [36], during the liquefaction process, an aqueous phase rich in organic and mineral compounds, known as the aqueous co-product (ACP), is generated alongside bio-oil and solid waste. This ACP constitutes a significant portion of the waste produced and requires further treatment due to its high levels of dissolved organic compounds, including carboxylic acids, sugars, amines, and other soluble intermediates.

3.3.1 Biocrude

Biocrude is a renewable fuel, currently refined, and produced from biomass, which includes organic substances of both plant, algae, and animal origin. It is a thick and dark liquid formed by a mixture of organic compounds such as fatty acids, acids, ketones, phenols, and other chemicals. This sustainable liquid fuel results from thermochemical processes, including fast pyrolysis and HTL. It consists of a complex combination of organic compounds, formed by the thermal degradation of constituents such as cellulose, hemicellulose, and lignin [37, 38]. The primary raw materials used in biocrude production include organic waste, such as biomass (wood, straw, sugarcane bagasse), agricultural waste, vegetable oils, algae, and sewage sludge. These sources are valued for being renewable, abundant, and often derived from industrial or urban waste, which contributes to the sustainability of the process [39].

HTL was performed under different conditions of temperature, residence times, and with the use of recycling, using sugarcane bagasse as the raw material. The increase in temperature and the use of solutions resulted in a higher formation of phenolic compounds and a reduction in the concentration of ketones and furans. Additionally, the use of alkaline solutions promoted the dissolution of lignin, which contributed to the stability of its bonds. The main components of biocrude produced from sugarcane bagasse were identified as oxygen-rich compounds, including phenols and their derivatives, ketones, and furans. Operational interruptions affect the degrees of decarboxylation and dehydration in the reactions, leading to variations in the biocrude composition [40].

The effects of transition metals on the HTL process applied to coconut shell liquefaction were evaluated. To determine the optimal temperature for HTL oil yield, the direct liquefaction process was carried out between 240 and 330 °C for 30 min, under pure water conditions. The results showed that both the mass balance of HTL products and the properties of the produced oil were influenced by the temperature. The highest HTL mass oil yield (13.9%) was obtained at 300 °C, which decreased to 10.5% at 330 °C. This indicates that temperatures above 300 °C may not be optimal for maximizing yield [41].

The production of high-yield biocrude through the HTL of hydrocarbon-rich microalgae was evaluated [42]. The results indicated that by increasing the temperature from 250 to 310 °C, the oil yield increased by 27%. The oil yields were higher than those observed in the hydrothermal processing of other microalgae, owing to the high lipid content of *Botryococcus braunii*. Regarding biocrude yield at different temperatures, the authors found that there were no significant changes in the peak area of n-hexadecanoic acid as temperature increased. Higher liquefaction temperatures led to a reduction in 9-hexadecenoic acid, while the levels of other compounds increased. Hydrocarbon production was higher at elevated temperatures, and this temperature range favored the synthesis of starches. As for oleic acid, the main constituent of oxygenated compounds, its quantity increased with temperature, likely due to conversion into

Table 2 Examples of products obtained by HTL

Product	Main components	Applications	Challenges
Biocrude	Hydrocarbons and organic acids	Direct and precursor fuel	Stability and acidity
Biofuels	Green diesel, gasoline, and kerosene	Transport and energy	Need for refining and processing
Platform chemicals	Phenols and organic acids	Chemical industry	Separation and purification
Biofertilizers	Nitrogen, phosphorus, and minerals	Agriculture	Contaminant removal

other components, such as amides. The high content of oxygenates, particularly oleic acid, was attributed to the high lipid content in the feedstock [42].

Yang et al. [43] performed HTL with used coffee grounds, obtaining a biocrude yield of 47.3 wt% at 275 °C, a retention time of 10 min, and a water-to-coffee grounds ratio of 20 g water/g coffee. It was noted that oil production increased with increasing the water-to-coffee grounds ratio from 5 to 20 g water/g coffee. However, excessive use of water is not cost-effective for the process. Zhu et al. [44] performed HTL on barley straw with K_2CO_3 and noted that temperatures above 300 °C caused a reduction in oil yield due to predominant gasification reactions. The effect of some operational parameters, such as temperature, residence time, biomass-to-water ratio, and the presence of alkalis, was studied on the HTL of water hyacinth for the production of value-added hydrocarbons. According to the findings, the optimized conditions for high biocrude yield and conversion were a temperature of 280 °C, a residence time of 15 min, and a water-to-biomass ratio of 6 g water/g biomass. Additionally, the use of alkalis significantly increased biocrude yield. The maximum biocrude mass yield (23%), comprising biocrude 1 and biocrude 2, as well as a conversion rate of 89%, was reached with a 1 N KOH solution [45]. Biomass liquefaction with suitable solvents is a promising process, particularly when integrated with optimized conditions, enabling the simultaneous production of fuel additives and high-value chemicals. The HTL process, when using different solvents, has a lower environmental impact compared to other chemical treatments. This method is also notable for its ability to process biomass under high temperature and pressure conditions, leading to the production of high-quality biocrude.

Results of biocrude were obtained using the HTL process for both dry and wet feedstocks under optimized conditions. Aiming at maximizing biocrude yields, they varied across different feedstock categories. Dry feedstocks, which included lignocellulosic materials and agricultural residues, typically yielded biocrude between 20 and 35% by weight. Wet feedstocks, which were mainly derived from waste materials, often achieved a wider yield range, ranging from 25 to 60% by weight. This variation highlights the flexibility and potential of HTL for processing a variety of feedstock types [3].

3.3.2 Biofuels

Biofuels can be produced through hydrotreating and cracking of bio-oil derived from biomass pyrolysis or HTL. In research on the co-processing of diesel and bio-oil derived from algae and straw, a technical–economic analysis was conducted, comparing two scenarios: fast pyrolysis and HTL. The results showed that, based on the minimum selling price of gasoline obtained through co-processing, the HTL scenario had a cost of only USD 2.91 per gallon, while the fast pyrolysis scenario reached USD 3.50 per gallon. Therefore, the HTL scenario demonstrated a clear competitive advantage in the market. Additionally, a sensitivity analysis concluded that the price of gasoline is heavily influenced by process yield and the cost of vacuum gas oil [46].

Biodiesel is one of the best biofuels for internal combustion engines. No modifications are required when using a blend of biodiesel (up to 20%) with diesel in these types of engines. To use pure biodiesel, some modifications are required in the engines. The second generation of this type of fuel is produced from non-edible oils, while the third generation is produced from waste oils and algae, which are abundant in nature and commonly available locally. In the presence of oxygen and at high temperatures, biodiesel tends to oxidize. Because of these stability and decomposition challenges, biodiesel is often added to regular diesel [4]. Table 3 presents advanced biofuel production processes.

The HTL process holds significant potential for converting residual resources into high-value-added products. An innovative method that combines supercritical fluid extraction (SFE) and HTL for biofuel production was explored. Only the residual biomass remaining after the extraction of valuable compounds was used. The results showed that the HTL process generally increased the carbon and hydrogen contents of the biomass while decreasing its oxygen content [52].

The technical–economic analysis presented by Hu et al. [46] highlights the competitive advantage of the HTL scenario over fast pyrolysis. It was demonstrated by lower gasoline production costs, which underscores the process's potential in the biofuels market. The use of optimized solvents and innovative methods, such as combining SFE with HTL, significantly enhances biofuel quality and reduces environmental impact [52].

Elsewhere, a techno-economic analysis was done to predict the HTL economic performance with a machine-learned analytic equation. The most accurate machine-learned model consisted of three terms and required six adjustable parameters to predict independently published Minimum Fuel Selling Price values with an average deviation of approximately $\pm 20\%$. The reduced-order model demonstrated that its predictions fall within 40% of published values 95% of the time, with the worst-case discrepancy reaching approximately 46%, indicating that its accuracy is comparable to the techno-economic analyses used for its development. The model's terms were physically interpretable, enhancing

Table 3 Advanced biofuel production processes

Method	Description	References
Fermentation	Set of biochemical reactions to convert simple sugars into anaerobic ones through the action of microorganisms. The raw materials used in fermentation processes are categorized into three distinct categories: sugars, starch, and lignocellulosic substrates	[47]
Transesterification	Reversible reaction that produces esters and glycerol when fatty acids, alcohol, and an acid or base catalyst are mixed	[48]
Anaerobic Digestion	Process divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These reactions decompose organic macromolecules, giving rise to simpler molecules that lead to the generation of biogas and digestate	[47]
Pyrolysis	Thermochemical decomposition process that converts organic materials into solid biochar, bio-oil, and pyrolytic gas through the application of heat under anaerobic conditions	[49]
Gasification	The raw material that can be used is very heterogeneous. The gasifying agents can be air, pure oxygen, steam, carbon dioxide or mixtures	[50]
Hydrothermal liquefaction	HTL is a technology capable of efficiently processing wet and dry biomass without restriction of lipid content, from lignocellulosic to organic waste. The product generated in this process is called biocrude	[51]
Combustion	The process consists of an exothermic chemical reaction. Biomass is burned in the presence of air with the consequent release of chemical energy. Combustion occurs inside combustion chambers at temperatures between 800 and 1000 °C	[47]

the reliability of its predictions. Also, the model enabled the prediction of Minimum Fuel Selling Price dependence on biocrude yield, scale, and feedstock cost [53].

3.3.3 Platform chemicals

Platform chemicals, or biochemicals, are byproducts generated during the biomass conversion process to produce biocrude. While they are not the primary product of the conversion, platform chemicals play a crucial role in the formulation of herbicides, resins, plasticizers, and fuel additives [54–56]. In the case of agricultural biomass, lignin present in the plant cell wall is one of the primary sources of high-value biochemicals due to its rich content of aromatic rings in its structure [15, 57, 58].

Despite its structural complexity, lignin's versatility allows for the production of various chemical products and distributions. The composition of lignin is closely linked to the type of plant biomass used as raw material and the process applied to separate its compounds [15, 54, 59]. Lignin is composed of three monomeric units: coniferyl alcohol, sinapyl alcohol, and coumaryl alcohol, which are linked by ether bonds, biphenyl or alkyl bridges. During thermal degradation methods, such as depolymerization, these linkages are broken to yield various chemical products. The primary product resulting from the depolymerization of lignin is guaiacol, which serves as an intermediate for obtaining catechol. Catechol acts as a raw material for the production of polymers and adipic acid, which are important precursors for the synthesis of pesticides and pharmaceutical products with significant medicinal value [15]. The organic chemicals commonly resulting from the transformation of sugars in residual lignocellulosic material include 5-hydroxymethylfurfural, furfural, levulinic acid, 2,5-furandicarboxylic acid, 2,5-dimethylfuran, diols, ethanol, and liquid alkanes. These compounds are valuable intermediates in the production of biofuels and other chemical products [57, 60].

Liquefied compounds such as ethanol, ethyl propionate, 15-octane hydrocarbon, furfural, and isopentyl alcohol were obtained after processing the desert shrub *Salix psammophila* through HTL [16]. The aqueous phase from HTL of corn straw and pine residues was assessed, finding that glycolic acid, acetic acid, phenol, and 4-ethylphenol were dominant in the composition of the corn straw. In contrast, formic acid, methanol, and 2-methoxyphenol were prevalent in the aqueous phase derived from wood residue [5].

The aqueous phase from the HTL of eucalyptus wood lignin was analyzed, revealing a significant presence of methanol, along with compounds such as acetic acid, acetone, dimethyl ether, catechol, phenol, and formic acid [18]. Meanwhile, acetic acid, propanoic acid, butanoic acid, nitrogenous compounds, and traces of oxygenates were observed when analyzing the aqueous phase from the HTL transformation of freshwater and saltwater algae [61].

Recently, Deepika et al. [62] highlighted the great potential of microalgae for obtaining diverse bioproducts through HTL, particularly high-value-added chemical products. The authors also noted that the aqueous phase resulting from the degradation of wet biomass contains low molecular weight compounds, such as organic acids, aldehydes, and alcohols. Gu et al. [17] reviewed the available literature on algae transformation using HTL, emphasizing that the degradation of carbohydrates under hydrothermal conditions leads to the production of glucose, mannose, xylose, galactose, and carboxylic acids, with reduced amounts of furfural.

3.3.4 Biofertilizers

The techno-economic performance of the HTL process is directly influenced by the yields and recovery rates of the products, which depend on the feedstock used and the operating conditions. Although many studies on HTL have primarily focused on recovering crude bio-oil and biofuels, Munasinghe-Arachchige et al. [63] emphasized the importance of exploring the economic use of by-products generated during the HTL process, particularly for wet feedstock processing. In their research, the authors investigated the use of HTL by-products to recover biofertilizers. Their findings showed that HTL of wet organic solid waste produces biochar and an aqueous phase as by-products, from which high-quality biofertilizers can be easily recovered for beneficial reuse.

Another study focused on maximizing the recovery of phosphorus as a biofertilizer in a wastewater treatment system using algae. The algae have been used to treat settled sewage to recover energy and phosphorus from the resulting biomass through HTL. The results showed that the HTL of wet organic solid waste produces biochar and an aqueous phase as by-products, from which high-quality biofertilizers can be easily recovered for beneficial reuse. The recovery process was divided into three stages. The first stage focused on intensifying the critical point of phosphorus recovery, involving alkaline leaching of a phosphorus-rich byproduct, the biochar generated by HTL, to produce a phosphorus-rich eluate. In the second stage, a three-step procedure was developed to recover high-purity biofertilizers from the phosphorous-rich

eluate. The third step involved dissolving the precipitate generated in the first step and reprecipitating its phosphorus content as high-quality calcium phosphate. The optimal conditions for phosphorus leaching from biochar were identified as: a temperature of 60 °C, a solid-to-liquid ratio of 20 g/g, an NaOH concentration of 0.5 M, and a leaching time of 72 h. These conditions allowed for the extraction of over 86% of phosphorus at an estimated cost of USD 4.54/kg phosphorous. In the subsequent steps, phosphorus recovery was achieved with 72.7% as struvite and 22.7% as calcium phosphate through pH control. The overall process resulted in a 21% reduction in phosphorus recovery costs [64].

Abideen et al. [65] recognized the potential of algal biomass to produce biofertilizers, which can function as soil improvers and abiotic stress relievers. Fertilizers produced from biomass provide essential nutrients for plants, promoting their growth and helping to maintain soil fertility. Furthermore, algae-driven nanoparticles have been developed to promote plant growth, reduce nutrient loss, combat diseases, and increase productivity. The researchers also highlighted that algal biomass can be cultivated in reclaimed water, reducing the costs associated with fertilizer production.

A study conducted by Cheng et al. [66] quantified the mass and energy balances related to HTL of the low-lipid species *Galdieria sulphuraria* under variable reaction conditions using a 1.8 L batch reactor. It revealed that the biomass and HTL products contain several inorganic elements, most of which are microbial macro and micronutrients, in addition to traces of metals. In this case, a significant amount of aluminum was observed, which can be explained by the acidic growth medium and the use of aluminum in parts of the growth chamber, such as the paddle wheels, where corrosion was detected. Water-soluble salts, such as sodium and potassium, tend to accumulate in the aqueous phase, while less soluble elements, such as calcium, magnesium, phosphorus, and most metals, tend to accumulate in the coal. On the other hand, sulfur is present in all fractions, which justifies its presence in light biological crude oil. These results are crucial for the recovery of nutrients from the wet and carbonized fractions, as well as for elements in the oil that can cause sintering or fouling during further processing. After being processed by HTL, the solid biomass can undergo some other steps to further valorization. One example is the production of N–Mg doped biochars for phosphate adsorption. Nitrogen doping via solid-state co-carbonization was employed to enhance the phosphate adsorption capacity of engineered biochar. The biochar produced at a carbonization temperature of 700 °C, with an impregnation ratio of 12 wt% and a blending ratio of 50 wt%, exhibited an adsorption capacity of 112.4 mg/g. The analysis of metal concentration and nitrogen content indicates a strong interaction between nitrogen functional groups and magnesium in phosphate solutions. Detailed characterization using techniques in the area confirmed the involvement of Mg^{2+} ions in the adsorption process. Interface diffusion, electrostatic attraction, precipitation, and complexation reactions are identified as the primary mechanisms governing phosphate adsorption. Mg–N doped composites derived from renewable sources have broad applications, including phosphate removal from wastewater effluents, catalysis, and energy storage [32].

The incorporation of biofertilizers as a nutrient-rich nitrogen agent is an alternative approach to reforming agro-farming systems. While synthetic fertilizers have been widely used to enhance crop yield productivity, they often leach into the environment and contribute to greenhouse gas emissions. Compared to composting and synthetic fertilizers, densified chars (biofertilizers) originate from natural and agricultural biomass sources and are regarded as stable, sustainable, biodegradable, and environmentally friendly. Various nitrogen-rich waste materials, including those processed by HTL, can serve as cost-effective resources for producing densified chars. The application of nitrogen-doped densified chars has demonstrated positive effects on plant yield by providing a steady supply of nutrients through the gradual release of essential elements from the char [31].

HTL-derived solids were also obtained from biogas digestate using a continuous bench-scale HTL pilot plant to evaluate their potential as direct-use fertilizers. Optimal conditions for maintaining contaminant levels within permissible limits in mineral products were determined by assessing various reaction temperatures, both with and without a catalyst. The elemental composition of mineral products revealed high mass carbon content, ranging from 51.6 to 48.4%, phosphorus levels between 3.5 and 3.1%, and adequate nitrogen content varying from 1.2 to 1.1%. Additionally, the carbon stability was measured at 1.2 and 0.3, respectively, indicating the high quality of the HTL-derived mineral products. Overall, HTL-derived mineral products offer a sustainable alternative for improving soil fertility, minimizing dependence on environmentally harmful chemical fertilizers, and promoting both ecological and economic sustainability, thereby fostering a circular economy [67].

The studies demonstrate the significant potential of the HTL process, not only for the production of biocrude and biofuels but also for the sustainable use of its by-products, such as biochar (biofertilizer) and the wet phase. The recovery of phosphorus as high-quality biofertilizers underscores HTL as a promising and economically viable technology for treating wet organic waste and wastewater, contributing to a circular economy. The optimized conditions for phosphorus leaching and recovery, identified in the aforementioned studies, not only maximize process efficiency but also reduce operating costs. The combination of innovative strategies, such as alkaline leaching and pH-controlled treatment,

yielded impressive results, with over 86% of phosphorus extracted and recovered in reusable forms. Furthermore, the 21% reduction in recovery costs highlights the relevance of HTL for both industrial and environmental applications. A summarized scheme of the HTL process is presented in Fig. 3.

3.4 HTL applications

Researchers are highlighting bioenergy, or energy from biomass, as a sustainable alternative from a renewable and adaptable source. HTL is a thermochemical conversion process that mainly generates biocrude from different types of biomass, such as microalgae, wastewater, and crops [68]. HTL can be a viable and environmentally responsible solution for the recovery of iodine from sewage in the areas of waste management and renewable energy generation, for example. Research efforts continue to be intensified to increase conversion efficiency and transform this technology into a practical industrial application [69].

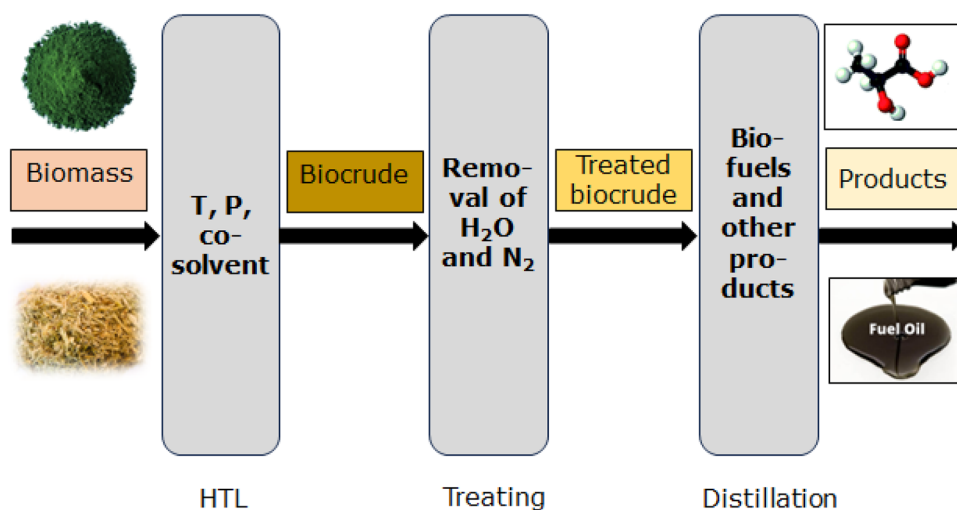
HTL is a commonly used technique in thermochemical conversion, aimed at transforming biomass raw materials with high moisture content into biofuels and various other industrial chemical products. The primary focus of the HTL process is the production of biocrude, biochar, gases, or industrial chemicals such as adhesives, benzene, toluene, and xylene. The secondary products generated serve as part of the auxiliary process flows. To optimize both the yield and the quality of primary products, it is essential to determine the ideal process parameters, which are key to ensuring its effectiveness. A thorough understanding of the chemistry involved in the reactions that occur during the process is crucial for its success [27].

In the HTL process, biocrude is the most commonly sought-after product, as it is considered a promising candidate for transportation fuel. The primary objective of HTL is to produce biocrude that not only achieves a high yield but also possesses a good quality, which is directly influenced by factors such as operating conditions, the type of catalysts, and the solvents used in the process [69], with yields typically ranging from 10 to 48% [70, 71].

HTL can also be utilized for the production of hydrochar as a byproduct, alongside crude oil and syngas. The goal of generating hydrochar through HTL is to use it as a sustainable adsorbent or as a catalyst support, helping to minimize waste generation while providing an additional energy source. The effective use of hydrochar, which can serve as a heat source in the process, can improve the economic viability of HTL. Therefore, characterizing hydrochar is crucial for understanding its potential applications [72].

The increase in temperature during the HTL process promotes the hydrolysis of organic compounds, leading to the formation of oligomers and monomers through reactions such as condensation, dehydration, and decarboxylation. At temperatures of 250 °C or higher, the dissociation of proteins, carbohydrates, cellulose, hemicellulose, and lignin occurs, gradually converting them into bio-crude. In contrast, lipids, which are mainly composed of non-polar, aliphatic compounds, are considered chemically insoluble in water under normal environmental conditions. Generally, cracking reactions require temperatures exceeding 300 °C [73]. Therefore, it is advisable to set the temperature for HTL above 300 °C, particularly when using pure water as the solvent.

Fig. 3 Illustration of HTL process



HTL of cosolvent-enhanced lignin fraction from five distinct biomass feedstocks, representing agricultural residues, softwood, and hardwood, was developed and provided key insights into the influence of lignin chemical structure on HTL reactivity. Strong correlations were seen between the syringol/guaiacol ratio and degree of condensation with biocrude yield and monomer composition, while char yield exhibited a negative correlation with the syringol/guaiacol ratio. It was reported that the findings contribute to the advancement of reactor and catalyst technologies aimed at maximizing the valorization potential of lignin through HTL [74].

Although various promising strategies have demonstrated the potential to enhance the efficiency of HTL, several challenges have hindered its progress beyond the laboratory stage, one of which is inadequate energy efficiency. HTL is unable to convert and transfer the entirety of the organic matter from the raw material into biocrude, leading to the generation of significant amounts of by-products in the aqueous phase. This aqueous phase, produced through iodine HTL, reveals the presence of substantial amounts (ranging from 20 to 50%) of carbon derived from biogenic feedstock. Among the compounds identified are organic acids, alcohols, aldehydes, ketones, and nitrogenous compounds. Additionally, 60 to 80% of the nutrients in the raw material are released into the aqueous phase [75]. In this context, Table 4 provides an overview of the products for potential applications of HTL. Furthermore, Table 5 presents a comparative analysis of the different HTL processes and applications.

Several studies have been conducted to address the commercialization aspects of the HTL process, and there are still many obstacles to be overcome to master this subject. Figure 4 presents some challenges to designing an efficient and well-operating continuous HTL system on an economic scale.

Although it faces several obstacles, HTL is a promising technology capable of producing high-quality fuels that can replace fossil fuels. However, the commercialization of this process still requires many aspects to be addressed to compete with other fuel sources [53]. The HTL process has advanced considerably and it has demonstrated the ability to convert biomass into high-energy biofuels. Given the current situation, further research is needed in experimental facilities, improvement of parameters for a continuous process, understanding of the physical characteristics of petroleum and, most importantly, improvement of more robust upgrading and distillation methods [27]. According to the study developed by Cervi et al. [13], HTL production routes stand out due to their reduced production costs, due to high conversion yields, and the expected decrease in capital intensity by 2030.

3.5 Patents and technologies

In recent years, there has been a substantial increase in dependence on technology and demand for energy across various sectors, including personal use, domestic activities, transportation, and agriculture. The majority of this energy demand is currently met by fossil fuels, such as coal, oil, and natural gas. The extensive use of these fuels results in high emissions of nitrogen oxides, sulfur, mercury, and other harmful chemical elements, which pose significant risks to human health and vegetation. Beyond these emissions, the combustion of fossil fuels plays a major role in the release of greenhouse gases, driving global warming and contributing to severe climate change. While the depletion of fossil fuels has long been a concern, environmental issues are now more urgent, prompting researchers to explore alternative sources of sustainable and renewable energy.

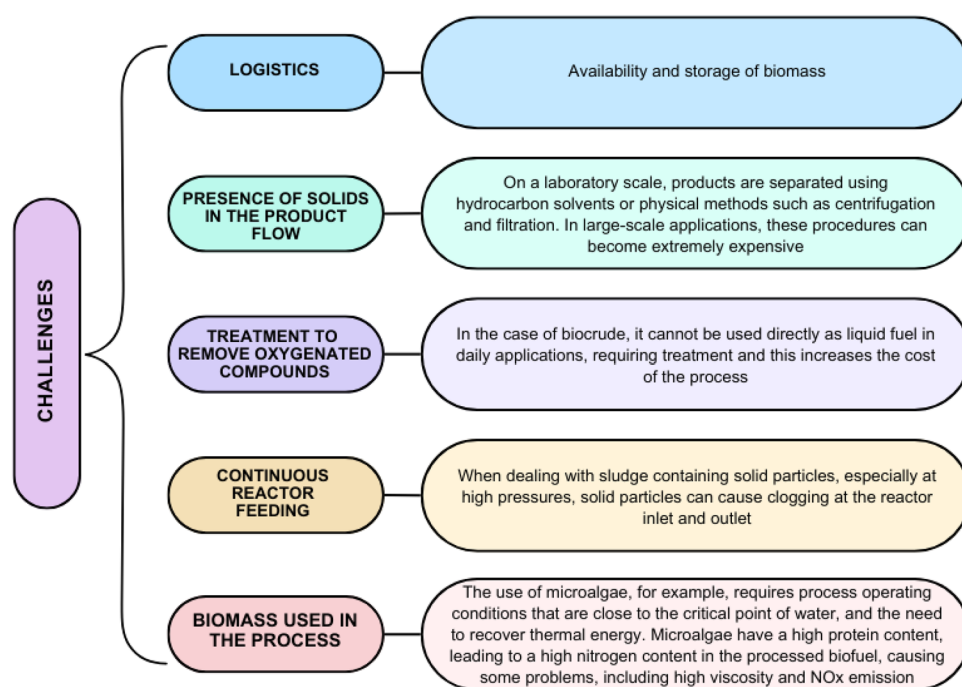
Among the registered technologies and patents, one focuses on a process for producing crude bio-oil from biomass with high moisture content, as well as a catalyst for the HTL of biomass streams with similar high moisture levels. This patent, registered in Brazil [76], addresses an efficient HTL process that generates a liquid stream rich in renewable molecules, with lower oxygen content, reduced water percentage, and lower acidity compared to other products derived from thermochemical biomass conversion processes. To implement this process, a catalyst was developed, derived from

Table 4 Description of characteristics of products for applications of HTL

Product	Description of characteristics
Biocrude	Brown and viscous liquid, with a high carbon content and low oxygen content
Water-soluble products	Secondary products in the batch process; they comprise low molecular weight organic acids and polyols, phenolic compounds, and ketones and sugar
Biochar	Contains varied mineral and organic contents based on biomass sources; it has a high calorific value and can be used in energy applications
Gaseous products	By-products obtained in the process; the gas fraction accounts for 5–15% by weight of the total product distribution of HTL

Table 5 Comparative analysis of different HTL processes and applications

Process	Methodology	Results	Reference
Bio-oil production by HTL	The conversion of hybrid giant grass to biofuels was investigated using batch reactors under variable reaction temperatures of 250–350 °C and biomass to deionized water concentrations of 15–25 wt% at a fixed residence time of 30 min	Bio-oil yields could be up to 50wt% at 350 °C and 25wt% of giant grass concentration for deionized water. Solid product yields of char and gas fluctuated within 10–25wt% and 30–45wt%, respectively. Higher heating values of the resulting bio-oil and char were remarkably better than those of the feedstock. An energy recovery of more than 50% from bio-oil as well as about 35% from char could be achieved	[1]
Evaluation of different residual biomass feedstocks under identical HTL conditions	T = 280 °C, P = 12 MPa, time = 30 min	Mustard flour exhibited the highest biocrude yield (38wt%), followed by canola flour (27wt%), attributed to its high lipid contents	[6]
HTL of high moisture tobacco processing waste in a multiple batch thermal reactor to produce biological crude oil	Temperatures of 280 to 340 °C and residence times of 15 to 45 min for a fixed biomass to deionized water ratio of 1:3	The reaction temperature significantly affected the yields and distribution of the products. The maximum yield of liquid biological crude oil obtained was over 52% w/w at 310 °C and 15 min. Under these conditions, almost 90% of the energy was recovered in crude oil and solid products	[9]
Production of biocrude from HTL of Canadian agricultural straws under identical conditions	A batch reactor was used and the initial temperature was 285 °C with a ramp rate of 5 °C/min at a stirring speed of 800 rpm. After 45 min of reaction time, heating was stopped and the reactor was cooled to room temperature	Barley straw is considered a promising raw material with lower lignin, higher biocrude yield, and lower oxygen content compared to other biomasses	[10]
HTL of sugarcane bagasse and straw, examining the distribution of products and the composition of bio-oil in relation to the reaction conditions	Temperature (300–350 °C), constant heating time (0–30 min), and the use of K ₂ CO ₃ concentration as catalyst (0–0.5 mol/L)	Milder conditions resulted in the highest bio-oil yields, 36% for BSC and 31% for SSC. The catalyst had no impact on biocrude production	[11]
HTL of high water content agricultural residues for crude bio-oil production	Tomato plant residues (TPR) were used as raw material for the production of biological crude oils by HTL at medium temperature (220–280 °C) in water or water–ethanol medium (17/3, v/v) in a 600 mL autoclave reactor	A high yield (45.1 wt%) of crude bio-oil was obtained from HTL of TPR in water–ethanol medium at 250 °C in the presence of acid catalyst H ₂ SO ₄	[12]

Fig. 4 Challenges in designing an HTL system

the calcination of castor bean shells, which is intended for use in the biofuels sector as an environmentally sustainable alternative for fuel production.

A Brazilian technology to produce biocrude from biomass by HTL consists of the liquefaction of biomass using a catalyst at temperatures ranging between 250 and 400 °C, and under pressures ranging from 7 to 22.5 MPa. The objective was to produce a mixture containing biocrude. Following this step, the mixture was cooled, and the biocrude was separated, yielding both the bio-oil and a residue containing the catalyst. The carbon mass content of the biocrude ranged from 60 to 85% [77].

China has registered patents in this field, including one published in 2019 for a device and method for producing biocrude through continuous HTL of biomass. The device consists of a feeding system with a double hydraulic cylinder, a material agitation tank, a preheating reactor, an HTL reactor, a product collection boiler, a back-pressure valve, a filter, a gas–liquid–oil separator, a water circulation pipeline, and a control unit. The feeding system employs a double hydraulic cylinder model combined with a high-pressure pump, enhancing raw material versatility, improving pumping efficiency, and reducing overall system costs. Regarding the method, it ensures effective product separation, enhances operational safety, and enables efficient and continuous separation of the resulting products [78].

The United States has also published patents in this field, including one issued in 2020 that focuses on the HTL of lignocellulosic biomass into bio-oils with controlled molecular weights. The innovation presented involves a method for liquefying waste derived from the hydrolysis of lignocellulosic biomass, as well as raw lignocellulosic biomass or municipal solid waste, using a mixture of alcohol and water in an alkaline medium. This process is designed to produce bio-oils with low molecular weight. The proposed approach is distinguished by its ability to enable the direct liquefaction of biomass while operating under relatively mild conditions [79].

Another patent, published in 2017 in The United States, describes a method for converting algal biomass into gas or biocrude through hydrothermal gasification or HTL. The invention pertains to techniques for processing algal biomass into gaseous or liquid biofuels, including the gasification and HTL of algal biomass in a primary reactor. The process involves the separation of the produced gas or biocrude from aqueous effluents and CO₂ generated at the reactor's outlet, the recovery of aqueous effluents, and the oxidation of these effluents in at least one secondary reactor. Additionally, the patent presents continuous processes for the cultivation of algal biomass and its subsequent conversion into gas or biocrude [80]. There are several technologies and patents registered around the world aimed at HTL using biomass to develop promising products. A summary of other relevant patents found on the WIPO platform is provided in Table 6.

Table 6 Some registered patents that deal with HTL

Number	Title	Nation	Year	Description
BR112022012219	Hydrothermal liquefaction system (HTL) and hydrothermal liquefaction method	Brazil	2022	HTL wastewater can be processed using thermochemical wet oxidation in a cost-effective manner that contributes more heat than is necessary for the energy-intensive HTL process; methods and devices for the integrated HTL of biomass and treatment of resulting wastewater are provided
BR112015000255	System for producing a saccharide solution using a biomass raw material and method for producing a saccharide solution using a biomass raw material	Brazil	2017	Biomass hydrothermal decomposition system that includes: a biomass supply unit, a hydrothermal decomposition unit, a biomass solid fraction discharge unit, a liquefaction tank, and a discharge unit that discharges the liquefied biomass solid fraction at a pressure ranging from an added pressure to normal pressure
CN118421350	Method for preparing bio-oil through synergic hydrothermal liquefaction of rice straw and municipal sludge waste	China	2024	Method for preparing bio-oil through synergistic HTL of rice straw waste and municipal sludge
CN113845966	Method and system for preparing bio-oil by colicefaction of lignocellulose biomass and waste cooking oil	China	2021	Method for preparing bio-oil by co-liquefaction of lignocellulose biomass and waste cooking oil
CN110377083	Monitoring system and monitoring method for continuous hydrothermal biomass liquefaction device	China	2019	Monitoring system and monitoring method for a continuous biomass HTL device; the monitoring system and monitoring method monitors the system running parameters and/or operating parameters such as system reaction temperature, pressure, feed flow, and motor power of the continuous HTL device, detects the electricity consumption and operating states of the system equipment, acquire and store the operating data of the reaction system regularly, display the operating data and curves in real-time, and perform audible and visual alarms on system temperature and pressure overload and operating failures in the reaction process
CN213853468	Product separation device by hydrothermal liquefaction	China	2021	The utility model provides a hydrothermal liquefied product separation device; an HTL product is cooled by the cooler and then enters the high-pressure filter to remove solid residue; without residue, the product is depressurized by the backpressure valve and then passes through the gas-liquid separator and the oil-water separator to respectively obtain a gas phase product, a water phase product, and an oil phase product, and the device is good in continuity, complete in product separation, simple operation process, easy to manufacture and install, and has high efficiency; no chemical reagent or centrifugal equipment is needed, the cost is low, the operation energy consumption is low, and the method can be widely applied to the separation of continuous HTL reaction products of biomass
CN114470953	Device and method for separation of hydrothermal liquefaction products	China	2022	The invention provides a high-pressure filter, and an inlet and an outlet of the backpressure valve are respectively communicated with a product outlet of the high-pressure filter; a gas-liquid inlet of the gas-liquid separator and a liquid phase outlet of the gas-liquid separator are communicated with a liquid phase inlet of the oil-water separator; no chemical reagent or centrifugal equipment is required, the cost is low, the operation energy consumption is low, and the method can be widely applied to the separation of products of continuous HTL reaction of biomass

Table 6 (continued)

Number	Title	Nation	Year	Description
CN110551767	Method for joint production of crude biopetroleum and methane from residual biomass	China	2019	The invention relates to the technical field of harmless treatment of residual biomass, in particular to a method for producing biocrude oil and methane together from residual biomass
IN3064/CHE/2014	Process and methods for converting algae, other carbonaceous raw materials and mixtures of algae with carbonaceous raw materials into crude petroleum and combustible products	India	2016	Integrated method for processing algal biomass comprising a strain of seaweed or a strain of freshwater (non-marine) algae or a plurality of strains of seaweed or a plurality of strains of freshwater (non-marine) algae or any combination thereof or other carbonaceous feedstocks such as biosolids or any combination of seaweed/algae mixtures and carbonaceous feedstocks to produce biofuel
AU2015278669	Method of processing algae, carbonaceous raw materials and their mixtures for biocrude and their conversion into biofuel products	Australia	2016	Integrated method for processing algal biomass comprising a strain of seaweed or a strain of freshwater (non-marine) algae or a plurality of strains of seaweed or a plurality of strains of freshwater (non-marine) algae or any combination thereof or other carbonaceous feedstocks such as biosolids or any combination of seaweed/algae mixtures and carbonaceous feedstocks to produce biofuel
WO2015198347	Method of processing algae, carbonaceous materials and their mixtures for biocrude and their conversion into biofuel products	France	2015	Integrated method for processing algal biomass including a strain of marine algae or a strain of freshwater (non-marine) algae or a plurality of strains of marine algae or a plurality of strains of freshwater (non-marine) algae or any combination thereof or other carbonaceous feedstocks such as biosolids or any combination of algae/algae blends and carbonaceous feedstocks to produce biofuel
US20170198223	Method of processing algae, carbonaceous raw materials and their mixtures for biocrudes and their conversion into biofuel products	USA	2017	Integrated method for processing algal biomass comprising a strain of seaweed or a strain of freshwater (non-marine) algae or a plurality of strains of seaweed or a plurality of strains of freshwater (non-marine) algae or any combination thereof or other carbonaceous feedstocks such as biosolids or any combination of seaweed/algae mixtures and carbonaceous feedstocks to produce biofuel

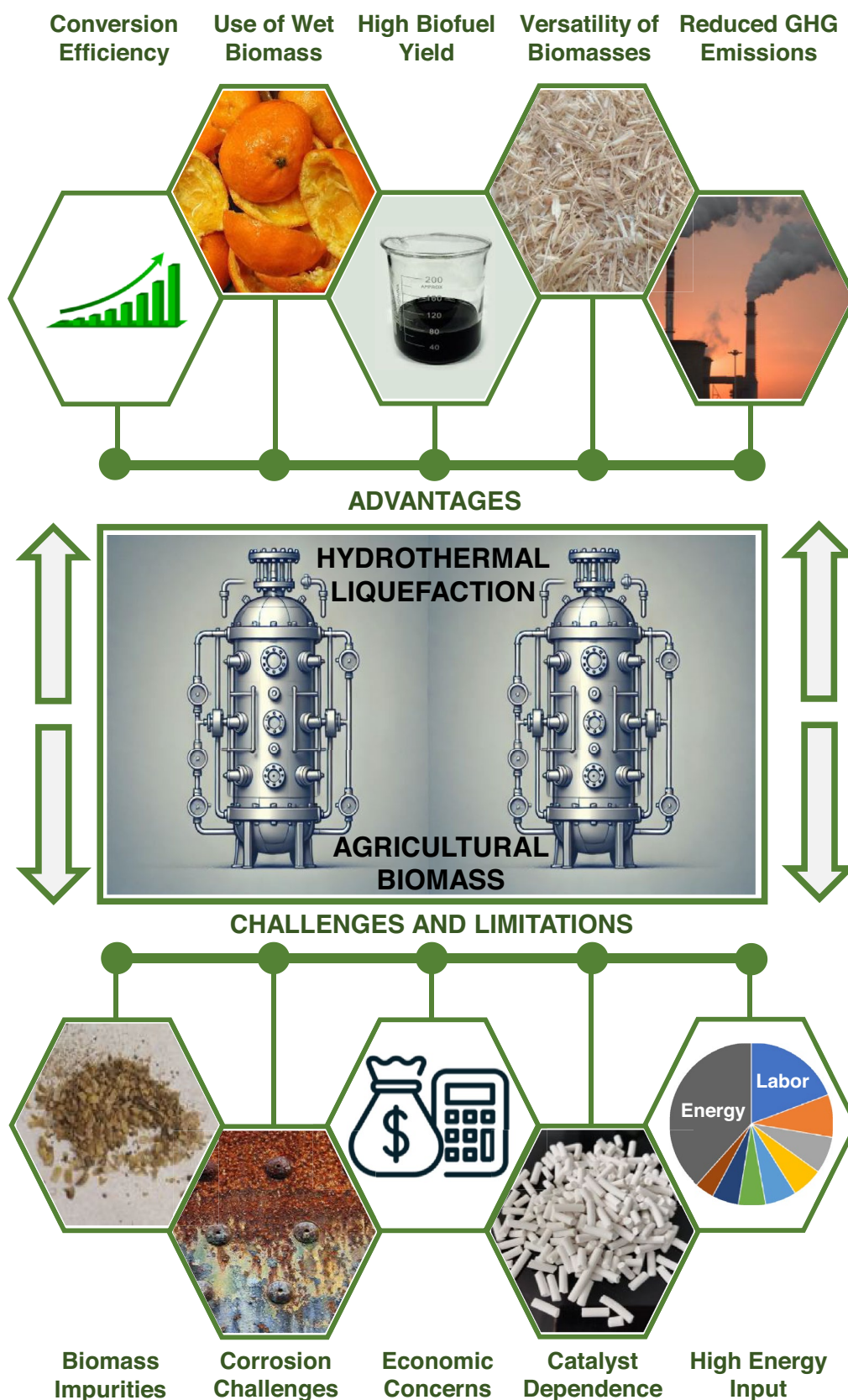


Fig. 5 Advantages, challenges, and limitations of HTL applied to wet agricultural biomass

4 Concluding remarks and prospects

This analysis highlights agricultural biomass as a highly promising renewable resource for reducing dependence on conventional energy sources. HTL is an efficient technology for converting agricultural biomass, enabling the complete decomposition of its components and producing liquid biocrude as the primary product, alongside biochar and both aqueous and gaseous by-products. This approach offers several advantages (Fig. 5) and is regarded as a promising pathway for renewable energy generation.

The HTL process plays a crucial role in enhancing biofuel quality, with operational parameters such as temperature, residence time, and applied technological innovations significantly influencing the composition and yield of bio-oil. Compared to pyrolysis, HTL is distinguished by its capability to convert lignocellulosic and high-moisture biomass in an aqueous medium, operating at shorter retention times. Therefore, biomass conversion via HTL represents a viable alternative for mitigating environmental impacts while generating high-value-added products.

The prospects are that the application of HTL to agricultural biomass will expand with the development of targeted studies concentrated on solving challenges and limitations that still exist, like the need for standardization due to biomass impurities, corrosion challenges, economic feasibility concerns, catalyst dependence, and high energy input (Fig. 5), among others. Based on the insights created by developing this work, some key remarks are listed:

- The unnecessary of energy-intensive drying of wet agricultural biomass can counterbalance the high energy used to heat the bulk reaction medium, overlapping the high input energy demand;
- The transition from lab-scale batch reactors to scaled-up continuous systems will benefit from tools of Artificial Intelligence (AI), like Big Data Analytics and Digital Twins plus AI, which will be powerful tools to create virtual replicas of physical systems, providing real-time insights to scale up;
- The use of AI to analyze inefficiencies and simulate continuous reactors can offer precise control over reaction parameters and energy recovery, therefore creating a favorable environment to obtain economic feasibility of processes and overcoming the economic concerns;
- The development of efficient and continuous separation techniques is crucial for maintaining uninterrupted operations, enabling the recovery of a greater number of products with higher purity;
- Collaborative robots in the HTL process will be essential to solving labor shortages by automating some tasks and integrating with human workers, thus improving safety and flexibility, especially in regions of high temperature and pressure;
- HTL produces four main products: biocrude, which is a brown and viscous liquid with high carbon content; water-soluble products, including organic acids and phenolic compounds; biochar, which is a high-calorific solid with varied mineral content; and gaseous products; these products will have better performance with expanding the aforementioned artificial tools;
- Creating Government-Industry Partnerships through public–private partnerships to fund technological research, workforce training, and infrastructure development can boost hydrothermal-related processes in this area.

Acknowledgements The authors are grateful for the funding received from the National Council for Scientific and Technological Development (CNPq; 404308/2023-6) and the Research Support Foundation of the State of Rio Grande do Sul (FAPERGS; 24/2551-0001977-4). G. L. Zabot (308067/2021-5) and M. V. Tres thank CNPq for the productivity grants.

Author contributions JS Baisch: Conceptualization, Investigation, Writing (Original Draft), Writing (Review and Editing); CL Dadjo: Investigation, Writing (Original Draft), Writing (Review and Editing); EJA Nunes: Investigation, Writing (Original Draft), Writing (Review and Editing); LO Carneiro: Investigation, Writing (Original Draft), Writing (Review and Editing); MV Tres: Writing (Review and Editing), Visualization; GL Zabot: Conceptualization, Writing (Review and Editing), Visualization, Supervision, Project Administration.

Funding National Council for Scientific and Technological Development, 404308/2023-6; 308067/2021-5, Research Support Foundation of the State of Rio Grande do Sul, 24/2551-0001977-4.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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Item (5)

**Desempenho produtivo de diferentes híbridos de milho na região da
Depressão Central - RS**

**Productive performance of diferent corn hybrids in the central Depres-
sion Region – RS**

**Rendimiento productivo de diferentes híbridos de maíz en la región de
la Depresión Central – RS**

DOI: 10.55905/oelv23n5-102

Receipt of originals: 4/18/2025

Acceptance for publication: 5/8/2025

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RESUMO

O milho (*Zea mays* L.) é uma cultura de grande importância econômica, especialmente no Rio Grande do Sul, onde a produtividade média ainda está abaixo do potencial observado em condições experimentais. Este estudo avaliou o desempenho agrônomo e morfofisiológico de três híbridos de milho (Pioneer 30F53, Morgan 300 e Morgan 616) na Depressão Central do Rio Grande do Sul, em delineamento em blocos casualizados com quatro repetições. Foram analisadas as variáveis: produtividade de grãos, número de grãos por espiga, massa de mil grãos, altura de planta, diâmetro do colmo, índice de área foliar e matéria seca da parte aérea. Os resultados mostraram diferença significativa entre os híbridos para produtividade, número de grãos por espiga e altura de planta. O híbrido Pioneer 30F53 apresentou a maior produtividade (21.187,66 kg/ha) e o maior número de grãos por espiga (644,63), superando os híbridos Morgan 300 e Morgan 616. A altura de planta foi maior no Pioneer 30F53 (144,68 cm), seguido por Morgan 616 (145,56 cm) e Morgan 300 (128,35 cm). Não houve diferença significativa entre os híbridos para massa de mil grãos, diâmetro do colmo, índice de área foliar e matéria seca. Conclui-se que a escolha do material genético é crucial para maximizar a produtividade, com o híbrido Pioneer 30F53 se destacando como uma alternativa promissora para a região estudada.

Palavras-chave: *Zea mays* L, Componentes de Rendimento, Desempenho Agrônomo, Produtividade.

ABSTRACT

Corn (*Zea mays* L.) is a crop of significant economic importance, especially in Rio Grande do Sul, where average productivity still falls short of the potential observed under experimental conditions. This study evaluated the agronomic and morphophysiological performance of three corn hybrids (Pioneer 30F53, Morgan 300, and Morgan 616) in the Central Depression of Rio Grande do Sul, using a randomized block design with four

replications. The variables analyzed were grain productivity, number of grains per ear, thousand-grain weight, plant height, stalk diameter, leaf area index, and dry matter of the aerial part. The results showed significant differences between hybrids for productivity, number of grains per ear, and plant height. The Pioneer 30F53 hybrid showed the highest productivity (21,187.66 kg/ha) and the highest number of grains per ear (644.63), surpassing Morgan 300 and Morgan 616. Plant height was higher in Pioneer 30F53 (144.68 cm), followed by Morgan 616 (145.56 cm) and Morgan 300 (128.35 cm). No significant differences were found between hybrids for thousand-grain weight, stalk diameter, leaf area index, or dry matter. It is concluded that the choice of genetic material is crucial to maximize productivity, with Pioneer 30F53 standing out as a promising alternative for the studied region.

Keywords: *Zea mays* L, Yield Components, Agronomic Performance, Productivity

RESUMEN

El maíz (*Zea mays* L.) es un cultivo de gran importancia económica, especialmente en Río Grande del Sur, donde la productividad promedio aún está por debajo del potencial observado en condiciones experimentales. Este estudio evaluó el rendimiento agronómico y morfofisiológico de tres híbridos de maíz (Pioneer 30F53, Morgan 300 y Morgan 616) en la Depresión Central de Río Grande del Sur, utilizando un diseño de bloques al azar con cuatro repeticiones. Se analizaron las variables: productividad de granos, número de granos por espiga, peso de mil granos, altura de planta, diámetro del tallo, índice de área foliar y materia seca de la parte aérea. Los resultados mostraron diferencias significativas entre los híbridos en cuanto a productividad, número de granos por espiga y altura de planta. El híbrido Pioneer 30F53 presentó la mayor productividad (21.187,66 kg/ha) y el mayor número de granos por espiga (644,63), superando a Morgan 300 y Morgan 616. La altura de planta fue mayor en Pioneer 30F53 (144,68 cm), seguido por Morgan 616 (145,56 cm) y Morgan 300 (128,35 cm). No hubo diferencias significativas entre los híbridos para peso de mil granos, diámetro del tallo, índice de área foliar o materia seca. Se concluye que la elección del material genético es crucial para maximizar la productividad, destacándose Pioneer 30F53 como una alternativa prometedora para la región estudiada.

Palabras clave: *Zea Mays* L, Componentes de Rendimiento, Rendimiento Agronómico, Productividad.

1 INTRODUÇÃO

O milho (*Zea mays* L.) é uma cultura mais importante do mundo, amplamente consumida *in natura* para alimentação animal e humana e tem diversificada utilização industrial (Silva *et al.*, 2021). É o cereal mais cultivado no mundo, sendo destacado pela

sua adaptabilidade a diferentes climas e solos, alto potencial produtivo e valor nutritivo (Antunes *et al.*, 2022). Além de seu consumo direto, o milho desempenha papel crucial na segurança alimentar e nutricional, sendo matéria-prima essencial para diversos produtos alimentícios processados e para a produção de biocombustíveis (Salla *et al.*, 2010). A cultura do milho também se destaca no manejo do solo, podendo ser utilizada como cobertura em sistemas de plantio direto ou triturada para compor silagem na alimentação animal.

Em termos globais, o Brasil ocupa o terceiro lugar no ranking de maior produtor de milho, com uma produção aproximada de 111,64 milhões de toneladas de grãos em 2024 (CONAB, 2024). Este volume coloca o milho como uma das principais culturas agrícolas do país, com importante contribuição na oferta nacional de alimentos e na produção de ração animal. A cadeia produtiva do milho no Brasil é extensa, abrangendo desde a produção agrícola até a agroindústria, com empresas que processam o grão para gerar uma variedade de produtos, como farinhas, fubá, óleos, amidos e xaropes de milho, que têm ampla aplicação nas indústrias alimentícia, de bebidas e de biocombustíveis (Almeida *et al.*, 2024).

O Brasil também é um grande exportador de milho, com destinos principais na Ásia, União Europeia e África, o que contribui significativamente para a balança comercial do país e gera receita para os produtores e exportadores (Budziak, 2024). No estado do Rio Grande do Sul, o cultivo de milho ocupa papel estratégico na agricultura, com destaque para a sucessão com soja e outras culturas, possibilitando a exploração em mais de uma safra por ano. A cultura do milho é particularmente relevante na cadeia agroindustrial de aves e suínos. Em 2024, o estado cultivou 783,3 mil hectares de milho, com produção total de 4,11 milhões de toneladas e valor bruto estimado em R\$ 3,17 bilhões (Azevedo dos Santos *et al.*, 2023).

No entanto, a produtividade média estadual ainda está abaixo de 6,00 t/ha, o que é considerado baixo quando comparado ao potencial produtivo observado em experimentos sob condições ideais, que podem ultrapassar 17,20 t/ha (Ben *et al.*, 2016). Essa diferença reflete uma lacuna de produtividade, que pode ser atribuída a fatores como limitações climáticas, práticas de manejo inadequadas e, em especial, à escolha do material

genético. Assim, a seleção de híbridos de milho adaptados às condições edafoclimáticas locais torna-se uma estratégia fundamental para mitigar perdas produtivas e aproximar a produtividade comercial do potencial máximo da cultura.

A escolha de híbridos é um dos principais fatores determinantes para o sucesso produtivo do milho. Silva et al. (2014) destacam que a variabilidade de híbridos cultivados no Brasil é considerável, o que evidencia a necessidade de uma avaliação agrônômica e econômica criteriosa para identificar os híbridos mais produtivos e rentáveis.

Sendo assim, o objetivo desse trabalho é avaliar o desempenho agrônômico e morfofisiológico de três híbridos de milho na região na depressão central do Rio Grande do Sul.

2 METODOLOGIA

O trabalho foi realizado de janeiro a abril de 2024, com o experimento de campo conduzido na unidade experimental pertencente ao Colégio Politécnico da Universidade Federal de Santa Maria (UFSM), localizada na região fisiográfica da Depressão Central do estado do Rio Grande do Sul (RS). As coordenadas da área são 29°42'55.7" S e 53°44'21.4" O, com altitude de 122 metros. De acordo com a classificação climática de Köppen-Geiger, a região apresenta clima do tipo Cfa (clima subtropical úmido), com estações do ano bem definidas e temperatura média entre 18 e 20 °C. O solo da área é classificado como Argissolo Vermelho Distrófico típico, segundo o sistema brasileiro de classificação de solos (EMBRAPA, 2018).

Foram realizadas coletas de solo para análise química, conforme Arruda e Moreira Pereira (2014), e as amostras foram posteriormente enviadas ao laboratório de análises de solo da Universidade Federal de Santa Maria (UFSM), onde foram determinadas as necessidades de macro e micronutrientes do solo. A adubação foi realizada conforme as quantidades recomendadas após as análises químicas, seguindo o Manual de Adubação e Calagem para o RS e SC (2024). A Tabela 1 apresenta os resultados das análises químicas do solo.

Tabela 1 - Resultado da análise com solo com características química dos nutrientes (P, K⁺, Ca²⁺, Mg²⁺, Al³⁺, H+Al); matéria orgânica (MO %); capacidade de troca de cátions efetiva (CTC ef); saturação base e argila em diferentes profundidades do solo.

Profundidade do solo (mm)	P mg/L	K+ -----	Ca2+ -----	Mg2+ (cmolc/L)	Al3+ -----	H+Al -----	MO (%)	CTC (ef)	S. base (V %)	Argila
0-20	3,7	0,174	7,809	3,466	0	3,5	2,1	11,4	76,8	27
20-40	8,8	0,624	6,942	3,099	0	4,4	3,5	10,7	70,6	21
40-60	3,8	0,123	5,877	2,948	1,02	13,7	1,6	10	39,6	36

Fonte: elaborado pelo autores

As análises físicas foram realizadas no laboratório de análises de solo da Universidade Federal de Santa Maria (UFSM). Os atributos físico-hídricos do solo foram avaliados antes da semeadura, com o objetivo de caracterizar a área em estudo, após a semeadura e ao final do ciclo da cultura. As determinações da textura e da densidade do solo foram realizadas conforme os procedimentos descritos para coleta e análise de solos (EMBRAPA, 2011). Para determinar a curva de retenção de água no solo, os limites superiores e inferiores, e a disponibilidade de água no solo, utilizou-se a câmara de Richards, submetendo amostras indeformadas do solo da área aos potenciais matriciais de -6, -10, -33, -100, -500, -1000 e -1500 KPa. A partir dos valores de umidade volumétrica e potencial matricial obtidos, foi ajustada a equação de Van Genuchten e construída a curva de retenção de água no solo. As características físicas do solo estão apresentadas na Tabela 2.

Tabela 2. Características físicas de densidade do solo (Ds), curva de retenção de água (CRA), ponto de murcha permanente (PMP), velocidade de infiltração (VIB), capacidade do campo (Cc) e textura do solo.

Profundidade do solo (cm)	Cc (m3m3)	PMP 1500kPa	Ds (g cm-3)	VIB (mm h-1)	Textura do solo
0-28	0,31	0,12	1,34		Franco
28-40	0,34	0,11	1,4	15	Franco argiloso
40-67	0,37	0,11	1,29		Argiloso

Fonte: elaborado pelos autores

O experimento foi conduzido em delineamento de blocos casualizados (DBC), com três tratamentos correspondentes a três híbridos de milho e quatro repetições. As

unidades experimentais foram compostas por parcelas de 4 m de largura por 4 m de comprimento, totalizando 16 m² por parcela. A área útil de cada parcela foi determinada desconsiderando as bordas laterais. Os híbridos foram semeados com espaçamento de 0,50 m entre linhas, com densidade populacional de aproximadamente 65.000 plantas por hectare.

Os tratos culturais e fitossanitários foram realizados de forma uniforme para todos os tratamentos, seguindo as recomendações técnicas para a cultura do milho. Os híbridos avaliados foram: Pioneer 30F53, Morgan 300 e Morgan 616, selecionados por seu potencial para sistemas produtivos sob sequeiro e pela ampla utilização regional.

A semeadura do experimento foi realizada em janeiro de 2024, dentro da segunda janela de plantio recomendada para a cultura do milho na região. A densidade de semeadura adotada seguiu as recomendações da área de produção de sementes para os híbridos selecionados, sendo de 65.000 plantas por hectare.

A adubação de cobertura foi feita em função do nível de matéria orgânica do solo, com base na análise química, aplicando-se 50 kg/ha de nitrogênio no momento da semeadura. A adubação de base foi realizada com a fórmula 05-20-20 (N-P₂O₅-K₂O) entre as fases de perfilhamento e alongamento do colmo da cultura, complementando a dose total de nutrientes.

Para a determinação do Índice de Área Foliar (IAF) na cultura do milho, foram selecionadas e marcadas quatro plantas por unidade experimental. A área foliar de cada planta foi estimada por meio da medição do comprimento (C) e da largura (L) de todas as folhas que apresentavam ao menos 50% da área verde preservada. As medições foram realizadas em cinco momentos distintos ao longo do ciclo da cultura, considerando apenas folhas totalmente expandidas. As medidas foram realizadas quinzenalmente durante o ciclo vital das culturas, totalizando cinco medições.

A área foliar individual foi calculada utilizando-se a seguinte equação:

$$AF = C \times L \times 0,75 \quad (1)$$

onde:

AF é área foliar, C é o Comprimento da folha, L é a Largura da folha e 0,75 é o coeficiente de correção específico para folhas de milho

A média das áreas foliares das plantas analisadas foi utilizada para estimar a área foliar total por unidade experimental. A partir desse valor, o Índice de Área Foliar (IAF) foi determinado pela razão entre a área foliar total (em m²) e a área de solo ocupada pela planta (em m²), conforme a equação:

$$\text{IAF} = \text{AFT} / \text{ASO} \quad (2)$$

onde:

IAF é índice de área foliar, AFT é a área foliar total e ASO é área do solo ocupado

Além disso, as mesmas plantas utilizadas nas medições da área foliar foram avaliadas quanto ao diâmetro do colmo, medido logo após o primeiro nó, e à altura da planta, registrada desde a base até o ápice da folha mais alta, com o objetivo de complementar a caracterização morfológica da cultura ao longo do ciclo.

A massa seca da parte aérea foi determinada por meio da coleta de cinco plantas em sequência na parcela, realizada cinco vezes ao longo do crescimento da cultura, utilizando-se toda a parte aérea da planta. Após a coleta, as amostras foram secas em estufa com circulação forçada de ar a 65 °C até atingirem massa constante, sendo posteriormente pesadas em balança de precisão.

O número de plantas por metro quadrado foi determinado pela contagem de plantas em 5 metros lineares e convertido conforme a largura da entrelinha (0,50 m). O número de grãos por planta foi obtido a partir do produto entre o número médio de fileiras por espiga e o número médio de grãos por fileira, considerando todas as espigas colhidas por planta. O peso de mil grãos foi medido em gramas, com correção para umidade padrão de 13%.

Para estimar a produtividade da cultura do milho, realizou-se a colheita de plantas em uma área de 5 metros lineares por unidade experimental (UEA), utilizando-se uma

linha central da parcela útil. Considerando o espaçamento entre linhas de 0,50 m, a área amostrada correspondeu a 2,5 m².

Os componentes de rendimento avaliados foram, (i) n° espiga/planta; (ii) n° grãos/fileira; (iii) n° espiga/metro; (iv) número de fileira por espiga; (v) massa de mil grãos; (vi) produtividade de grãos.

A produção por unidade experimental foi estimada utilizando a seguinte equação:

$$P = N \times NG \times PMG \quad (3)$$

onde:

P é a produção (g/cm²), N é número de planta por unidade da área (m²), e PMG é o peso de mil grão (g), corrigido para 13% de umidade

A produtividade foi obtida a partir da produção, utilizando a equação:

$$Y = PROD / 0,87 \times 10 \quad (4)$$

onde:

Y é a produtividade de grãos (Kg/ha), 0,87 refere-se à conversão da umidade dos grãos para a base padrão de 13%, e o fator **10** foi utilizado para ajustar a unidade de g/cm² para kg/ha,

3 RESULTADOS E DISCUSSÕES

Os resultados obtidos para as variáveis agronômicas, morfológicas e fisiológicas dos híbridos de milho evidenciaram diferenças significativas em alguns parâmetros, enquanto outros apresentaram comportamento estatisticamente semelhante entre os materiais avaliados.

As variáveis agronômicas avaliadas produtividades de grãos (PROD), número de

grãos por espiga (NGE) e massa de 1000 grãos (PMG) apresentaram variação significativa entre os híbridos apenas para PROD e NGE.

O maior valor de produtividade foi observado no híbrido Pioneer 30F53, com uma média de 21.187,66 kg/ha, destacando-se estatisticamente em relação aos demais. Os híbridos Morgan 300 e Morgan 616 apresentaram médias de 15.418,63 kg/ha e 14.576,75 kg/ha, respectivamente, sem diferença estatística significativa entre si.

Em relação ao número de grãos por espiga, o menor valor foi encontrado no híbrido Morgan 300, com uma média de 552,31 grãos por espiga, o que pode ter limitado sua produtividade final. Por outro lado, os híbridos Morgan 616 e Pioneer apresentaram médias maiores, de 618,88 e 644,63 grãos por espiga, respectivamente, sem diferença significativa entre eles.

Já a variável massa de 1000 grãos (PMG) não apresentou diferença significativa entre os híbridos, com médias variando entre 238,24 g e 260,41 g. Esses dados corroboram os resultados obtidos por Cunha et al. (2018), que relataram variação discreta na PMG entre híbridos comerciais cultivados em condições de chuva, sugerindo que essa característica tem menor influência nas diferenças de rendimento quando o enchimento de grãos ocorre sem limitações hídricas.

Tabela 3. Produtividade de grãos (PROD), número de grãos por espiga (NGE) e massa de 1000 grãos (PMG) dos híbridos de milho avaliados. Médias seguidas de letras diferentes na mesma coluna diferem entre si pelo teste de Tukey a 5% de probabilidade.

HÍBRIDOS	PROD (kg/ha)	NGE (grãos)	PMG (g)
Pioneer	21.187,66 a	644,63 a	260,41 a
Morgan 300	15.418,63 b	552,31 b	251,76 a
Morgan 616	14.576,75 b	618,88 a	238,24 a
Média geral	17.061,01	605,27	250,13
CV (%)	31,19	11,55	11,84

Fonte: elaborado pelos autores

Os resultados deste estudo estão em consonância com os de Schlösser et al. (2023), que também constatou diferenças significativas de produtividade entre os híbridos

sob condições climáticas adversas causadas pelo fenômeno La Niña. O estudo foi desenvolvido na safra de 2021/22 e dividiu os híbridos em quatro grupos distintos de produtividade, evidenciando a variabilidade genética dos híbridos avaliados. Neste estudo, o híbrido Pioneer 3016 apresentou o maior rendimento, com produtividade de 7.301 kg/ha. Da mesma forma, no presente trabalho, o híbrido Pioneer 30F53 também se destacou com a maior produtividade de grãos de 21.187,66 kg/ha entre os genótipos avaliados.

Em um experimento irrigado, Ferreira et al. (2021) constataram que a produtividade de grãos do milho aumentou com o aumento da reposição de lâmina, sendo máxima na reposição de 100% da evapotranspiração da cultura (ETc), e decrescendo em lâminas superiores, com resposta quadrática. Embora o presente estudo tenha sido conduzido sem aplicação de irrigação, o ciclo da cultura ocorreu sob boas condições hídricas naturais, com chuvas regulares ao longo do desenvolvimento. Isso possivelmente contribuiu para o bom desempenho produtivo observado, mesmo na ausência de irrigação, permitindo explorar o potencial genético dos híbridos avaliados de forma semelhante ao que se observa em estudos irrigados.

Esse desempenho do híbrido Pioneer 30F53 pode estar associado a características genéticas que favorecem o maior aproveitamento dos recursos disponíveis no ambiente, como maior número de grãos por espiga ou melhor desempenho da planta. Esse resultado ressalta que a escolha do material genético influencia diretamente o rendimento da cultura, e o híbrido Pioneer 30F53 se apresenta como uma opção promissora para as condições edafoclimáticas do local de cultivo.

A diferença encontrada entre os híbridos avaliados destaca a importância de estudos regionais de desempenho produtivo, considerando que o comportamento de cada material pode variar de acordo com o ambiente em que é cultivado. Isso reforça a seleção do híbrido como uma estratégia fundamental para a maximização da produtividade.

No presente estudo, o elevado desempenho do Pioneer também pode estar relacionado ao maior número de grãos por espiga (644,63), uma característica que influencia diretamente a produtividade da cultura. De forma semelhante, Soares (2019), ao avaliar diferentes doses de nitrogênio e lâminas de irrigação, observou NGE variando entre 639

e 573 grãos, valores comparáveis aos encontrados neste estudo, mesmo em condições de sequeiro e sem aplicação de irrigação suplementar.

Esses valores foram superiores aos verificados por Cao et al. (2022), que relataram um maior número de grãos por espiga no tratamento com irrigação, variando entre 432 e 425 grãos, conforme estudo realizado entre os anos de 2018 e 2019 com o híbrido de milho.

Da mesma forma, Schlösser et al. (2023), em sua pesquisa com diferentes híbridos de milho, constataram que o híbrido Pioneer 3016 apresentou o maior número de grãos por espiga (NGE), tanto com quanto sem a utilização de fungicida, diferindo estatisticamente dos demais híbridos. O híbrido Forseed 670 apresentou o menor NGE, tanto com quanto sem aplicação de fungicida. Não houve efeito significativo para a variável massa de mil grãos (MMG) entre os híbridos avaliados, como foi constatado no presente estudo.

As variáveis fisiológicas e morfológicas avaliadas – índice de área foliar (IAF), diâmetro do colmo (D. COLMO) e matéria seca da parte aérea (MS) – não apresentaram diferença estatística entre os híbridos avaliados ($p > 0,05$), indicando comportamento semelhante quanto à estrutura e acúmulo de biomassa nessas variáveis. Por outro lado, a altura de planta (ALT) apresentou diferença significativa ($p < 0,05$) entre os híbridos.

Tabela 4. Médias do índice de área foliar (IAF), altura de planta (ALT), diâmetro do colmo (D. Colmo) e matéria seca da parte aérea (MS) dos híbridos de milho avaliados. Médias seguidas de letras diferentes na mesma coluna diferem entre si pelo teste de Tukey a 5% de probabilidade.

Híbrido	IAF	ALT (cm)	D. Colmo (cm)	MS (g/planta)
Pioneer 30F53	3,90 a	144,68a	2,38 a	21,37 a
Morgan 300	3,79 a	128,35b	2,42 a	20,86 a
Morgan 616	3,54 a	145,55a	2,41 a	20,45 a
Média	3,74	139,53	2,4	20,89
CV (%)	6,9	7,22	7,45	8,7

Fonte: elaborado pelos autores

Os valores médios para a variável índice de área foliar (IAF) variaram de 3,54 (Morgan 616), 3,72 (Morgan 300) e 3,90 (Pioneer 30f53), o que indica que todos os híbridos mantiveram uma área foliar ativa e equilibrada, favorecendo um bom desempenho

fotossintético durante o ciclo da cultura.

Os híbridos avaliados atingiram seu pico máximo de IAF após o estágio de florescimento, aos 68 dias após semeadura (DAS). Os valores máximos observados foram de 7,44; 7,24 e 7,15 m^2/m^2 para as cultivares Morgan 616, Morgan 300 e Pioneer 30f53, respectivamente.

Resultado semelhante foi encontrado no trabalho de Manfron et al. (2003), que, ao trabalhar com diferentes híbridos de milho, encontrou resultados superiores aos do presente estudo, com um IAF máximo de 7,50 m^2/m^2 . Por outro lado, Ortiz et al. (2025), ao analisarem diferentes genótipos de milho para a produção de silagem de grãos, encontraram resultados inferiores aos do presente estudo, com um IAF máximo de 4,45 e 4,56 m^2/m^2 . Esse fato pode ser atribuído às diferentes condições experimentais nas quais os estudos foram conduzidos, além de o IAF ser influenciado pelas características dos genótipos, pelo manejo e pelos fatores climáticos.

Para a variável altura de planta, o híbrido Morgan 300 obteve a menor altura média (128,35 cm), diferindo dos híbridos Pioneer 30F53 (144,68 cm) e Morgan 616 (145,56 cm), os quais não diferiram estatisticamente entre si. O híbrido Pioneer 30F53 destacou-se por alcançar maior porte, o que pode favorecer a interceptação de luz e contribuir para o maior acúmulo de biomassa observado neste material.

Em relação ao diâmetro do colmo, as médias oscilaram entre 2,38 cm (Pioneer), 2,38 cm (Morgan 616) e 2,42 cm (Morgan 300). Essa uniformidade indica uma estrutura similar entre os híbridos, o que pode garantir uma boa sustentação das plantas e menor risco de acamamento. Dados semelhantes foram encontrados no trabalho de Almeida et al. (2023), que não constataram diferença significativa no desempenho agrônômico entre os híbridos estudados. Isso pode sugerir que a variabilidade genética não seja expressa de forma marcante em determinadas condições ambientais. Por outro lado, o presente estudo diverge dos resultados obtidos por Simões et al. (2018), que constataram diferença significativa entre os híbridos quanto ao diâmetro do colmo.

Quanto à matéria seca, os valores variaram de 20,45 g/planta (Morgan 616), 20,73 g/planta (Morgan 300) e 21,37 g/planta (Pioneer). Essa semelhança indica um acúmulo

equilibrado de biomassa entre os híbridos, possivelmente favorecido pelas boas condições hídricas durante o ciclo.

Conforme França et al. (2011), o rendimento da matéria seca está relacionado à transferência de carboidratos para outros órgãos em crescimento, especificamente às espigas.

4 CONCLUSÃO

De acordo com a metodologia empregada e o objetivo do estudo, que é avaliar o desempenho produtivo e as características agrônômicas, fisiológicas e morfológicas de três híbridos de milho, os resultados demonstraram que houve diferença significativa entre os híbridos apenas para a produtividade de grãos, número de grãos por espiga e altura de planta, sendo o híbrido Pioneer 30F53 o mais produtivo. As demais variáveis morfofisiológicas apresentaram comportamento semelhante entre os materiais, indicando adaptabilidade ao cultivo em condições de sequeiro. Assim, o Pioneer 30F53 se destaca como uma opção viável para sistemas de produção sem irrigação.