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Unlocking the circular economy potential: Techno-economic analysis of rapeseed meal valorisation through pyrolysis

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Abstract: Despite the European Green Deal's pursuit for a resource-efficient economy, industry remains largely dependent on linear material use. This paper presents an analysis of rapeseed meal valorisation through pyrolysis to unlock its circular economy potential, set against the backdrop of the European Green Deal's ambition for a resource-effective economy. The study investigates the transformative role of converting agro-industrial waste into valuable products. Through strengths, weaknesses, opportunities, threats and techno-economic analysis, the feasibility and opportunities of rapeseed meal pyrolysis are examined. An overview of the economic performance of a pyrolysis plant with a capacity of 32,000 Mg per year is presented. Based on the results, the plant is economically viable, as it presents a positive net present value and an appropriate internal rate of return for the condition considered. The annual cash flow amounts to EUR5.05 mln and the initial investment is EUR25.24 mln, which demonstrates the plant's ability to not only cover operational costs but also generate considerable profits. Additionally, despite the existing challenges in scaling up from laboratory-scale to industrial application, strategic approaches are proposed to overcome obstacles. Overall, this study underscores the significance of rapeseed meal valorisation as a pathway toward a more resilient, resource-efficient and sustainable future.

Keywords: circular economy, pyrolysis, rapeseed meal, techno-economic analysis, valorisation

INTRODUCTION

Half of the total greenhouse gas emissions and over 90% of biodiversity loss and water stress are caused by raw material extraction and processing of materials, fuels and food by industries (UN, no date). Although the European Green Deal has initiated a comprehensive strategy for a climate-neutral and resource-effective economy, the industry still has a linear approach relying on the extraction, trade, and processing of new materials, which finally leads to their disposal as waste or emissions. Only 12% of the materials used in the industry are derived from recycling (Communication, 2019). The wider implementation of the circular economy (CE) strategy can play a pivotal role in reaching climate neutrality by 2050 and breaking the link between economic growth and resource consumption (EC, 2020). To fulfil this ambition, in the European Union (EU), significant endeavours are underway to transition towards CE characterised by resource efficiency and waste elimination (EESC, 2019). The CE functions as a comprehensive solution with the potential to enhance the existing economic system, initiating a sustainable approach to economic growth by overcoming constraints related to non-renewable sources and greenhouse gas (GHG) emissions (Giampietro, 2019). Along with rising energy demands, growing GHGs and the depletion of fossil fuels, biomass emerges as a crucial renewable energy source poised to address both current and future human needs (Ubando, Felix and Chen, 2020), which can represent a favourable form of circular economy. Food processing industries produce large amounts of organic residues and effluents every year. In the oil sector, a major by-product is oil cakes, created during the extraction of oil from seeds (Sadh, Duhan and Duhan, 2018). These oil cakes come from various sources, such as canola, sunflower, coconut, sesame, mustard, palm kernel, soybean, groundnut, cottonseed, olive, and rapeseed (Ramachandran *et al.*, 2007). Agro-industrial residues are valuable feedstocks rich in fibre, protein, and fat (Sadh, Duhan and Duhan, 2018), making them highly suitable not only as animal feed but also as promising raw materials for biorefineries (Mirpoor, Giosafatto and Porta, 2021). Rapeseed meal (RSM) is a solid by-product obtained from oil pressing generated during rapeseed processing, consisting of crude protein, fibre, and carbohydrates. These components serve as rich precursors of carbon, oxygen, and nitrogen (Saka and Kusdiana, 2001; Lena Di *et al.*, 2021; Sun *et al.*, 2023). Being the dominant oilseed crop in Europe, rapeseed constitutes roughly 25% of global production, with Germany, Poland, and France emerging as the top producers in Europe (Soleymani Angili, Grzesik and Jerzak, 2023; Statista, 2024). The increase in rapeseed oil production corresponds with the growth of rapeseed meal, which achieves an annual global production of 71 mln Mg. By efficiently managing rapeseed meal as a by-product of oil extraction, industries can transform waste into valuable materials (Gallorini *et al.*, 2023). Hence, the utilisation of rapeseed meal in biorefineries further enhances its value proposition by maximising its potential as a feedstock for producing bio-based materials, biofuels, and other high-value compounds. This aligns with CE principles, aiming to optimise the utilisation of biomass while minimising waste and emissions through the conversion process (Cherubini, 2010) and producing value-added products. Within biorefineries linked to agricultural by-products, there is a strong emphasis on the strategy of waste valorisation including the conversion process of residues into premium products (Böckin *et al.*, 2022). Consequently, pyrolysis has emerged as an appealing approach for waste management due to its ease of operation and capability to handle complex feedstocks like tires, plastics and lignocellulosic residues. Pyrolysis is a process that converts biomass materials into bio-oil, charcoal, and a gaseous phase resembling syngas. The yields fluctuate depending on process conditions and the treatment varies accordingly for biorefinery applications (Cherubini, 2010). Several studies in the literature examine the techno-economic aspects of pyrolysis applied to various feedstocks and installations. For example, techno-economic studies on the pyrolysis of lignocellulosic residues, such as wheat straw, forestry by-products and sugarcane bagasse, have demonstrated variations in process efficiency, product yields and economic feasibility depending on feedstock characteristics and operational parameters (Czernik and Bridgwater, 2004; Bridgwater, 2012; Mirkouei *et al.*, 2017). Similarly, research focusing on the pyrolysis of plastic waste and mixed municipal waste highlights unique challenges related to feedstock heterogeneity, product upgrading and cost management (Butler *et al.*, 2011; Miandad *et al.*, 2017; Sharuddin *et al.*, 2018). A study in 2017 revealed that catalytic pyrolysis processes have shown promise in enhancing product quality, though with increased complexity and costs (Lopez *et al.*, 2017). Furthermore, the integration of pyrolysis within biorefineries has been evaluated for its potential to optimise energy recovery and align with circular economy principles (Zabaniotou, 2018). A comparative analysis of these studies underscores the critical role of aligning feedstock selection, process conditions and product valorisation pathways to maximise the environmental and economic benefits of pyrolysis systems. Currently, there are no commercial enterprises utilising intermediate pyrolysis to produce bioenergy or biomaterial from rapeseed meal. This study is the first to discuss this subject. The presented research focuses on the potential of rapeseed meal as a valuable asset within the circular economy. The paper indicates how rapeseed meal can be utilised in a way that contributes to developing a sustainable economy. Furthermore, the research demonstrates how the valorisation of rapeseed meal biomass is evaluated through a preliminary techno-economic analysis (TEA). This analysis highlights the economic feasibility of converting rapeseed meal into various high-value products. The findings underscore the importance of integrating rapeseed meal valorisation into biorefinery processes, ultimately supporting the transition towards more sustainable and competitive bio-based industries. Additionally, this study aligns with the goals of the EU bioeconomy strategy by contributing to food and nutrition security, reducing dependence on non-renewable resources, limiting and adapting to climate change, and strengthening European competitiveness by creating jobs (EC, 2018).

MATERIALS AND METHODS

BACKGROUND INFORMATION

Pyrolysis process

Pyrolysis is a thermal process in which organic feedstock decomposes at high temperatures, typically between 450°C and 550°C, without the presence of oxygen. This process simultaneously produces three products: pyrolysis liquid (comprising bio-oil and water), pyro-gases, and biochar (Yang *et al.*, 2017; Kazawadi, Ntalikwa and Kombe, 2021).

Intermediate pyrolysis, characterised by a residence time of 4 to 10 minutes, is especially well-suited for processing low-value residues such as sewage sludge, digestate from biogas plants, manure, and agro-industrial waste (Zimmer *et al.*, 2022). In this study, the boundary conditions of the intermediate pyrolysis process of RSM were determined from laboratory-scale experiments by Jerzak *et al.* (2022) and then verified commercially. The scalability of the pyrolysis plant was determined based on details presented in section "Preliminary techno-economic assessment." The experimental setup involved initially placing the catalyst in a cylindrical fixed bed reactor, which was externally heated to 500°C and maintained at this temperature for 1 hour. Throughout the experiment, temperature control was achieved through a control unit connected to a K-type thermocouple and the pyrolysis chamber. Subsequently, dried RSM was placed on a boat near a water cooler and the reactor was purged with nitrogen at a flow rate of 100 $cm^3 \cdot min^{-1}$ for 5 min. Once the reactor reached its optimal operational conditions, the RSM boat was introduced into the central heating zone of the pyrolyser. Upon completion of the pyrolysis process, the sample boat was returned to the cooling water zone. The resulting hot volatiles were directed to an ice tank, where the aqueous and oil phases condensed, while non-condensed gases were collected in a Tedlar bag for subsequent gas chromatography analysis. The rapeseed meal employed in the experiments was obtained from a rapeseed pressing facility located in Poland. To prepare the rapeseed meal samples for the pyrolysis process, they were air-dried under ambient conditions. The composition of the rapeseed meal employed in this study can be observed on Figure 1.

Products

As noted earlier, the intermediate pyrolysis process generates three main products: bio-oil, pyro-gas, and biochar. The various products are obtained through the valorisation of RSM (Fig. 2). Although gas products are not considered in this study, bio-oil and biochar are discussed because of their significant yield and economic impact on the present work. Kazawadi, Ntalikwa and Kombe (2021) outlined reasons and advantages suggesting that intermediate pyrolysis is suitable for the simultaneous production of bio-oil and adsorption biochar. Furthermore, Laghezza *et al.* (2023) presented that char significantly impacts the economic feasibility based on its intended use. Char is a key output of the process with high carbon content (Xu *et al.*, 2020; Jerzak *et al.*, 2022), which makes it beneficial by enhancing its energy efficiency, soil amendment properties, industrial applications, environmental benefits and economic value. Biochar produced from intermediate pyrolysis is well-suited as a long-term fertiliser and soil amendment (Hornung, Stenzel and Grunwald, 2024). It can serve as a plant nutrient, potentially decreasing reliance on fertilisers. However, it is crucial to consider the presence of heavy metals and organic pollutants, to ensure adherence to specific thresholds (Schmitt *et al.*, 2019). Additionally, biochar is a valuable form of char that serves as a viable option for charcoal production. Biochar, when formed into briquettes can serve as a storable fuel alternative to fossil coal. It has a high heating value (*HHV*) of 30.8 $MJ \cdot kg^{1}$, which is comparable to that of bituminous coke (30.2 $MJ \cdot kg^{-1}$) (Hornung, 2014; Laghezza *et al.*, 2023). Moreover, hot recycled char has been shown to function effectively as both a heat carrier and a catalytic cracking medium due to the ash content in the char (Yildiz *et al.*, 2015). Regarding industrial applications, when processing feedstocks containing high moisture levels, the resulting char may develop characteristics similar to activated carbon due to significant steam interaction (Warhurst, McConnachie and Pollard, 1997). From an environmental standpoint, char can be utilised for CO_2 storage in the soil, which not only enhances soil fertility but also reduces greenhouse gas emissions (Pröll *et al.*, 2017; Li and Tasnady, 2023). Garcia-Garcia *et al.* (2024) published a study in 2024 demonstrating that pyrolysis provides significant environmental benefits through its oil and char outputs. Their life cycle assessment (LCA) results highlight the importance of oil production, which serves as a substitute for commercial diesel and emphasise that char combustion exhibits very low environmental impact (Garcia-Garcia *et al.*, 2024). The liquid output of intermediate pyrolysis includes organic (pyrolysis oil) and aqueous phases that can be easily separated. Bio-oil is characterised as a dark brown, viscous organic liquid resulting from pyrolysis consisting of numerous complex oxygenated compounds (Bridgwater and Peacocke, 2000). This product stands out for its efficacy as an energy carrier and its compatibility with engine applications (Brammer, Lauer and Bridgwater, 2006), allowing it to be blended with up to 50% biodiesel and used in unmodified diesel engines for heat and power generation (Hossain *et al.*, 2013; Yang *et al.*, 2014; Neumann *et al.*, 2016). It demonstrated that pyrolysis oil possesses a high calorific value with minimal water content and a low acid number, effectively preventing corrosion of engine components. Their findings also highlight that the oil's non-polar nature enables seamless blending with vegetable and mineral oils for direct use in engines.

SWOT APPROACH

The strengths, weaknesses, opportunities, threats (SWOT) analysis is widely employed as a strategic planning instrument to evaluate an organisation comprehensively. It examines what the enterprise does well and where it needs to improve, along with considering outside factors and helps decision-makers under-

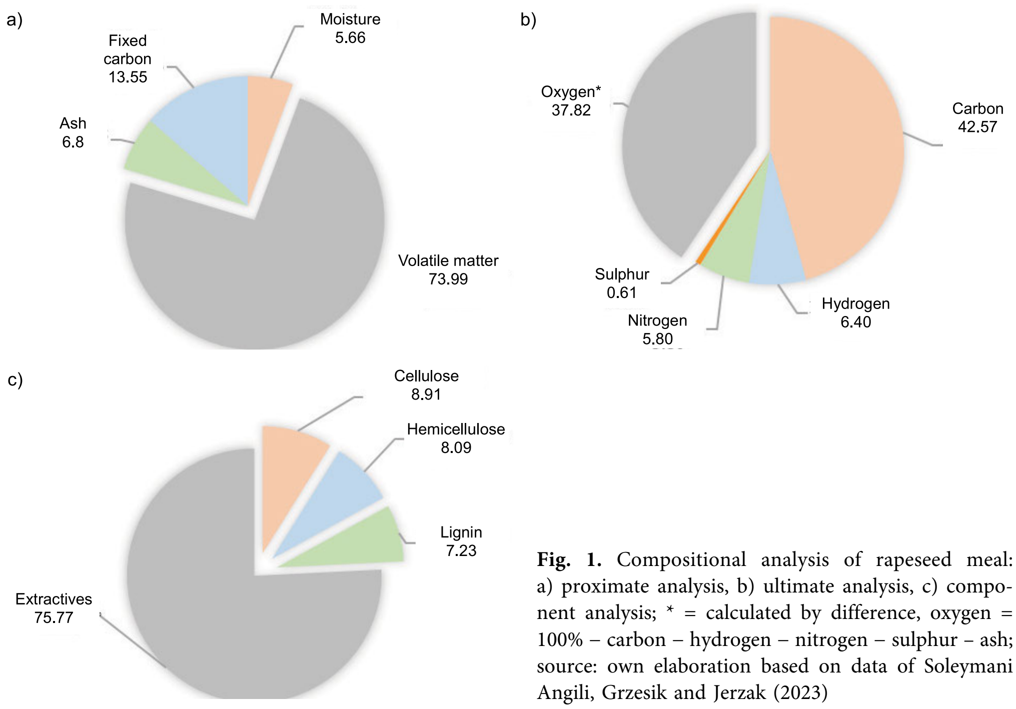

Fig. 1. Compositional analysis of rapeseed meal: a) proximate analysis, b) ultimate analysis, c) component analysis; * = calculated by difference, oxygen = 100% – carbon – hydrogen – nitrogen – sulphur – ash; source: own elaboration based on data of Soleymani Angili, Grzesik and Jerzak (2023)

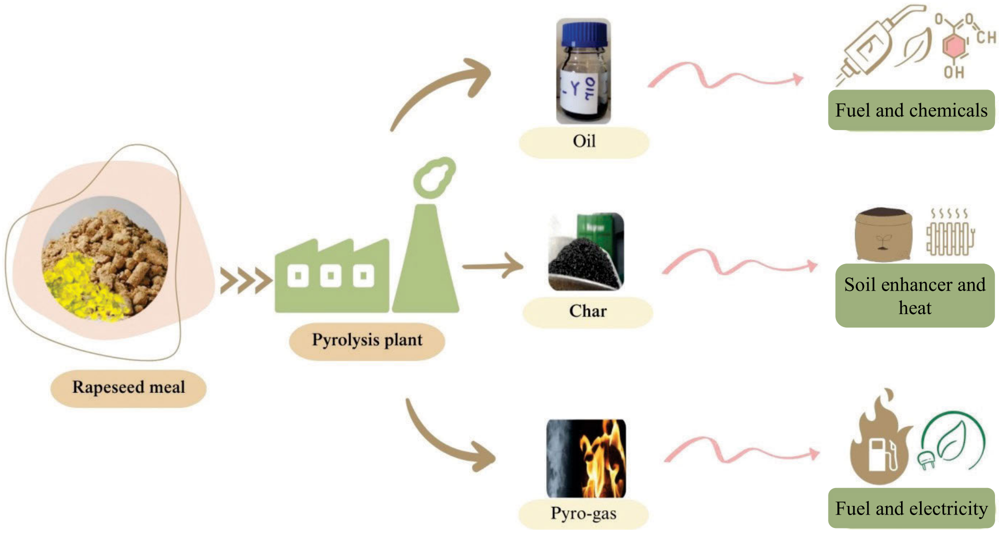

Fig. 2. Schematic illustration of products derived from rapeseed meal valorisation; source: own elaboration

stand the best actions to take (Imran Khan, 2018). Accordingly, to understand the current status of the planned facility, a SWOT matrix analysis was conducted. This analysis helps examine the project's internal aspects, like strengths and weaknesses, as well as external factors such as threats and opportunities. The most popular classifications of SWOT analysis factors were proposed by Kotler and Armstrong (2018) (Tab. 1). The SWOT analysis for matching the biorefinery`s strengths to promising opportunities while overcoming the weaknesses and reducing the threats is presented in the next section.

PRELIMINARY TECHNO-ECONOMIC ASSESSMENT

Assumptions for techno-economic analysis

Evaluating the economic viability of new waste treatment technologies is crucial, going beyond their mere technological aspects. Therefore, in this section of the study, the techno-economic feasibility of the proposed venture is evaluated through the analysis of various parameters. In this context, a techno-economic analysis can offer valuable guidance for assessing the value of implementing pyrolysis for rapeseed meal valorisation.

In the current study, techno-economic analysis has been carried out based on parameters including net present value (*NPV*) and internal rate of return (*IRR*). The *NPV* assesses a project's viability by considering the current value of all cash flows, including the initial investment. A higher *NPV* indicates greater project benefits, while a low or negative *NPV* suggests that the project should be avoided. The *IRR* is a percentage indicating the project's feasibility. In this study, the *NPV* and *IRR* were calculated using Equations (1) and (2), respectively. The *IRR* is an annual rate of growth expected to be generated by an investment. It can be calculated as the discount rate at which the net present value of all cash flows equals zero. The corporate income tax (CIT) rate for the planned facility's profits was set at 19% for 2023 in Poland (Ministry of Economic Development and Technology, 2023).

$$NVP = \sum_{t=0}^{T} \frac{CF_t}{(1 + r)^t} \tag{1}$$

where: *NVP* = net present value (in EUR), T = the operation years, r = the discount rate, t = the specific time period, CF = cash flow.

$$0 = NPV = \sum_{t=1}^{T} \frac{CF_t}{(1 + IRR)^t} - C_0 \tag{2}$$

where: *IRR* = internal rate of return, C_0 = initial investment.

To calculate the mentioned metrics, capital (fixed and working) and operating expenditures were considered. Capital expenditures (CapEx) are one-time expenditures related to the acquisition or improvement of physical assets like machinery, buildings and equipment. Capital costs are typically incurred at the outset of a project and are considered long-term investments. Operating expenditures (OpEx) are ongoing expenses directly associated with the day-to-day operation of the production process. The OpEx includes items such as raw materials, labour, energy consumption, maintenance, and other regular expenses (Towle and Sinnott, 2008).

Table 1. Classifications of SWOT factors

Kind of factors	Positive factors	Negative factors
Internal	**strengths** capabilities that may help company reach its objectives	**weaknesses** limitations that may interfere with a company's ability to achieve its objectives
External	**opportunities** factors that the company may be able to exploit to its advantage	**threats** current and emerging external factors that may challenge the company's performance

Source: adapted from Kotler and Armstrong (2018).

Selected parameters

The reference year for the economic analysis is 2023 and all the prices used in this study refer to 2023 prices in the EUR currency. The intermediate pyrolysis process of rapeseed meal is evaluated as a first-of-its-kind technology, since there is no commercial experience in Europe, except for laboratory-scale research. It is assumed that the pyrolysis plant is located in Poland and is fed with 4 Mg of dehydrated rapeseed meal per hour, with a continuous operating time of 8000 $h \cdot y^{-1}$. The economic analysis of the pyrolysis plant is conducted over a 20-year period. This study employs methodologies from Peters and Timmerhaus (1990) and Towle and Sinnott (2008), alongside research on commercial prices, vendors, and relevant literature, to calculate project investment expenditures and equipment costs. Equipment cost values collected before 2023 have been adjusted to 2023 values by using the chemical engineering plant cost index (*CEPCI*), which are 603.1 for 2018 (Jenkins, 2019), 816.0 for 2022 and 798 for 2023 (Towering skills, 2020) through Equation (3).

$$C_{\mathrm{upd}} = C_{\mathrm{orig}} \left(\frac{CEPCI_t}{CEPCI_0} \right) \tag{3}$$

where: C_{upd} = updated cost, C_{orig} = original cost, t = current year, 0 = original cost year.

For estimating capital costs as formulated below, order of magnitude estimates is selected, with an accuracy typically ranging from about 30 to 50%. These estimates are often based on the costs of comparable processes and do not require detailed design information, making them suitable for initial feasibility studies and screening purposes (Peters and Timmerhaus, 1990; Towle and Sinnott, 2008).

$$\mathrm{CapEx} = FCI + WC \tag{4}$$

where: CapEx = capital expenditures, *FCI* = fixed capital investment, *WC* = working capital.

The fixed capital includes direct costs (installation, piping, buildings, land, service facilities, electrical, etc.) and indirect costs (engineering and supervision, construction, contingency, legal fees, etc.) were calculated by Equation (5) where purchased equipment cost, multiplying the corresponding Lang factor which is 4.1 in the study by Peters and Timmerhaus (1990). The working capital was estimated at 15% of the fixed costs.

$$FCI = F_{\mathrm{lang}} \sum\nolimits_{i=1}^{n} C_{p,i} \tag{5}$$

where: *FCI* = fixed capital investment, F_{lang} = Lang factor, $C_{p,i}$ = cost of all delivered equipment.

Operating expenses (OpEx) as per the following formula are calculated by accounting for direct manufacturing costs, encompassing expenses related to raw materials, utilities, labour, etc. and general expenses, such as distribution and marketing costs, as well as research and development expenditures.

$$\mathrm{OpEx} = C_{\mathrm{mfg}} + GE \tag{6}$$

where: OpEx = operating expenses, C_{mfg} = manufacturing cost, *GE* = general expenses.

Parameters influencing manufacturing costs are detailed in the Table 2.

In this study, since the biorefinery is situated at the site of oil extraction, the cost of raw materials, which comprises waste generated during oil extraction and transportation costs were both designated as zero within the calculation of direct production costs. For labour cost assessment, the following assumptions were considered: an eight-hour shift, with three shifts per day and an average monthly gross salary in Poland of PLN7,290.06 (about EUR1,645.36). This amount was calculated based on average gross wages and salaries for employees in the relevant enterprise sector in 2023 (Statistics Poland, 2023). It is assumed that a shift team consists of one supervisor and three operators working in three shifts, along with a day team comprising one plant manager, one administrator, and one technical manager.

The utility costs considered for the pyrolysis plant include electricity, natural gas for heating the pyrolyser and water for the process cooling. While the literature on intermediate pyrolysis plants is scarce, Yang *et al.* (2017) suggested an electricity consumption estimate of 36.8 kWh per Mg of feedstock. Utilising this data in the current study is justified due to the shared nature of intermediate pyrolysis in both studies in terms of similar feedstock moisture levels and pyrolysis temperatures. The average electricity price for non-household consumers in Poland is EUR0.21 per kWh in 2023 (QERY, 2023a). It is estimated that the pyrolysis plant requires 17 m^3 of water per Mg of feedstock (Yang *et al.*, 2017). The average price for water and sewage in Poland's largest cities is EUR2.59 per m^3 (Statista, 2023) and this price is used in this study. This presents an average value that combines the costs of water usage and wastewater processing. According to Zabaniotou and Vaskalis (2023), the required natural gas usage is estimated to be 6 mln $m^3 \cdot y^{-1}$, with a price of EUR0.09 per m^3 for non-household consumers in Poland (QERY, 2023b). The catalyst amount is estimated at 0.5 kg per kg of feedstock based on Patel *et al.* (2020) for a catalyst from the zeolite family, and the basis for cost calculation for Poland is the zeolites price trend and forecast as published by Procurement Resource (2023). Linear depreciation is considered throughout the plant's lifespan (20 years) with the assumption that no equipment will be replaced during this time. Plant overhead covers general plant upkeep, payroll overhead, packaging, medical services, safety and protection, restaurants, recreation, salvage, laboratories, and storage facilities (Peters and Timmerhaus, 1990).

General expenses include administrative costs, distribution and marketing expenses, research and development, which are presented in the Table 2. The revenue of the pyrolysis plant comes from the sale of biochar and oil products, the gas product is not considered in the profitability of the plant. The products are estimated based on output presented by Yang *et al.* (2017), where reaction mechanisms, feedstock and the ultimate analysis of feedstock and products, are similar to this study.

RESULTS AND DISCUSSION

SWOT ANALYSIS

The results of the strengths, weaknesses, opportunities, and threats (SWOT) analysis can provide an overview of the positive and negative factors affecting the planned biorefinery from both the internal and external environments. This study employed a SWOT analysis framework to evaluate the feasibility of using rapeseed meal as raw material in the pyrolysis process. Strengths

Table 2. Operating costs for catalytic pyrolysis plant

Parameter	Definition	Cost (EUR)	Reference
Manufacturing cost			
Operating labour	number of workers × salary	177,699	Statistics Poland (2023)
Natural gas	annual consumption × price	540,000	QERY (2023b), Zabaniotou and Vaskalis (2023)
Electricity	annual consumption × price	304,638	Yang *et al.* (2017), QERY (2023a)
Water	annual consumption × price	1,736,663	Yang *et al.* (2017), Statista (2023)
Catalyst	utilisation × operating days × price	480,432	Patel *et al.* (2020), Procurement Resource (2023)
Maintenance and repair	annual maintenance materials 10% of the total installed equipment cost	334,553	Peters and Timmerhaus (1990)
Operating supplies	20% of maintenance and repair	66,911	Peters and Timmerhaus (1990)
Laboratory charges	20% of operating labour	35,540	Peters and Timmerhaus (1990)
Depreciation	straight line method and service life of one year	133,821	Peters and Timmerhaus (1990)
Property taxes and insurance	4% of fixed capital	4,389,338	Towle and Sinnott (2008)
Plant overhead	70% of cost for operating labour, supervision, and maintenance	412,363	Peters and Timmerhaus (1990)
Total 8,611,956			
General expenses			
Administration cost	15% of operating labour and maintenance	76,838	Peters and Timmerhaus (1990)
Distribution and selling	20% of total product cost	2,317,012	Peters and Timmerhaus (1990)
Research and development	5% of total product cost	579,253	Peters and Timmerhaus (1990)
Total 2,973,103			
OpEx 11,585,059			

Source: own elaboration based on literature.

are internal qualities and resources that help achieve success, while weaknesses are internal qualities and resources that hinder success. Opportunities are external factors that can be leveraged for benefit, while threats are external factors that can jeopardise success (Hay and Castilla, 2006).

According to the SWOT matrix, there are more strengths and opportunities than weaknesses and threats in the valorisation of rapeseed meal through the pyrolysis process. The main strengths and opportunities of this facility relate to aspects connected to the circular economy concept (Fig. 3).

Through the pyrolysis plant, a large portion of the waste generated in the oil extraction industry can be eliminated. As a result, valuable products, such as char, oil and pyro-gas are obtained.

These products not only add economic value but also contribute to reducing environmental impact by minimising waste and promoting resource efficiency. Furthermore, the facility benefits from low transportation costs, decarbonisation through biochar production, and the prevention of fossil resource depletion. By reusing these products as energy resources within the plant, it further enhances sustainability. Additionally, the facility aligns with and fulfils the requirements within the European Green Deal, reinforcing its commitment to the principles of the circular economy. The pyrolysis plant stands out as a flexible technology offering a streamlined approach to converting rapeseed meal into valuable products. Unlike many other feedstock valorisation methods, rapeseed pyrolysis eliminates the need for the pre-treatment, shredding and drying stages. This efficiency not only saves time but also reduces operational complexity and associated costs. The valorisation of rapeseed meal feedstock also serves as a local economic driver by creating employment opportunities and fostering strategic collaborations with local entities. To maximise efficiency and reduce logistical challenges, industrial installations for rapeseed meal valorisation are best located close to rapeseed processing plants (oil production). This ensures a steady supply of rapeseed meal as feedstock, minimises transportation costs and streamlines the integration of the biorefinery with existing operations. Farmers play a vital role in the upstream supply chain by providing rapeseed to processing plants. While they are not directly involved in the extraction of rapeseed meal, strategic collaborations with farmers could enhance feedstock management and ensure a consistent supply of raw materials. Such synergies between farmers, processing plants and biorefineries can strengthen local economies, create employment opportunities, and promote the development of rural areas. Exploring partnerships with research institutions to advance pyrolysis technology could lead to further efficiencies and innovation.

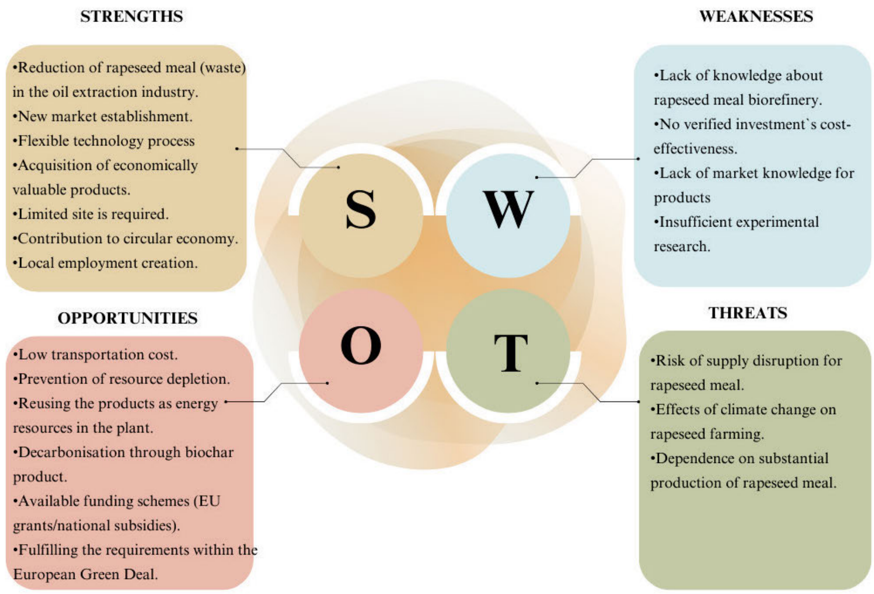

Fig. 3. SWOT matrix concerning planned pyrolysis facility; source: own study

The creation of jobs in the local community, the development of new skills in renewable energy technology and the potential for rural development are all aspects that warrant attention and analysis. Furthermore, this facility promotes market expansion, introducing bioproducts while requiring minimal space for deployment. Moreover, access to funding schemes such as EU grants and national subsidies supports its establishment and operation, further solidifying its role in sustainable development. On the other hand, weaknesses and threats refer to several negative factors. These include a lack of comprehensive understanding of rapeseed meal biorefinery operations and insufficient experimental research, which may hinder effective implementation and optimisation. Additionally, the absence of verified investment cost-effectiveness poses a risk, potentially affecting the project's financial viability. Furthermore, limited market knowledge of products may impede successful market distribution and revenue generation. The dependence on substantial production of rapeseed meal is a threatening factor that exacerbates vulnerability to supply chain disruptions, especially given the seasonal fluctuations in rapeseed availability. The risk of supply disruptions due to the effects of climate change on rapeseed farming adds to these challenges, underscoring the need for comprehensive risk management strategies and proactive measures to mitigate these threats. Based on the SWOT analysis, the pyrolysis plant for valorising rapeseed meal reveals numerous strengths and opportunities, aligning well with circular economy principles and offering economic and environmental benefits. Given that the significant positive factors outweigh the weaknesses and threats, conducting a techno-economic analysis is worthwhile to assess its financial viability and optimise its implementation strategy.

TECHNO-ECONOMIC ANALYSIS

A preliminary economic evaluation is conducted for a pyrolysis plant with a capacity of 32,000 $Mg \cdot y^{-1}$, utilising rapeseed meal. The positive *NPV* and high *IRR* indicate strong financial viability, suggesting that the plant is well-positioned to recover its initial investment and generate substantial returns over time. An overview of the plant`s economic performance is provided in Table 3. The analysis results suggest that the planned facility is economically viable, with a positive *NPV*. The annual cash flow of EUR5.05 mln makes the case study favourable, and with an *IRR* of 19.5%, the plant can recover the initial investment.

Significant cost contributors to the economic analysis of a plant are capital-related costs (including equipment, installation, piping, electrical, etc.). Among the cost contributors to the CapEx, the biomass pyrolysis reactor was identified as the most expensive piece of equipment. In the context of a circular economy approach, equipment costs emerge as a significant aspect of any biorefinery operation. Leveraging idle or second-hand equipment, such as standard storage tanks or reactors, presents an opportunity for substantial cost reduction. The focus shifts from merely identifying expensive equipment to exploring strategies for cost reduction, aligning with the broader theme of optimising resource use and efficiency. Expanding on this theme, Zabaniotou and Vaskalis (2023) demonstrated the influence of the reactor type on pyrolysis performance, process duration and final product properties. They recommended choosing the reactor type based on production scale and conditions. In terms of product sales revenue, biochar, as a primary product of the process generates around 41.3% of the plant's annual revenue.

Table 3. Overview of the feasibility of the pyrolysis plant

Parameter	Amount
Capacity ($Mg \cdot y^{-1}$)	32,000
Investment (EUR mln)	25.24
Operating cost (EUR $mln \cdot y^{-1}$)	12
Net cash flow (EUR $mln \cdot y^{-1}$)	5.05
NPV (EUR mln)	62.9
IRR (%)	19.5

Explanations: *NPV* = net present value, *IRR* = internal rate of return.
Source: own study.

While the oil product represents a larger share at around 58.7%, it plays a complementary role in enhancing the plant's overall profitability. Additionally, the analysis of operating costs reveals the significant impact of property taxes and insurance, and water costs, accounting for 50.95% and 20.16%, respectively, of the overall OpEx. General costs such as research and development, administration and distribution costs make up approximately 25.66% of the unit's total annual operating costs. It is worth noting that integrating feedstock supply at the plant's location eliminates transportation costs entirely, thereby impacting both operating and total investment costs.

CHALLENGES AND STRATEGIES IN SCALING UP

The present study marks a significant milestone in the field by reporting on the valorisation of rapeseed meal through intermediate pyrolysis for the first time. This study offers techno-economic and sustainability aspects for transforming agro-industrial waste into valuable products. However, as with many laboratory-scale investigations, transitioning to industrial application presents challenges. One of the foremost obstacles is ensuring the economic viability and feasibility of scaling up the process. This entails assessing factors such as production costs, resource requirements, and market demand. Addressing these challenges is crucial for realising the full potential of rapeseed meal valorisation on a larger scale, thereby maximising its benefits for both the environment and the economy. In line with the principles of the circular economy, when purchasing new equipment for rapeseed meal valorisation, it's crucial to prioritise both cost-effectiveness and sustainability. Obtaining multiple quotations and avoiding overly strict design limitations not only increases the likelihood of achieving a low-cost estimate but also promotes equipment durability and potential for reuse (Peters and Timmerhaus, 1990; Thilakaratne *et al*., 2014; Yang *et al*., 2018). Additionally, if second-hand equipment is viable for the plant and process, provided it doesn't compromise efficiency or significantly increase maintenance costs, it presents an opportunity to further enhance resource utilisation. This approach fosters a circular mindset, optimising resource utilisation and minimising waste while ensuring long-term environmental and economic benefits. Selecting less expensive and more robust materials can also have a profound impact on cost and economic parameters. Meyer *et al.* (2020) suggest that using cost-effective catalysts in the pyrolysis oil upgrading process can substantially reduce production costs. One particular challenge identified in this study is the high operating cost of water consumption, as shown in Table 2. Given the increasing scarcity of water resources and the rising costs associated with water use, implementing a closed-loop process water cycle emerges as a compelling strategy. Although this approach may lead to higher initial investment costs due to the requirement for infrastructure such as water filtration and recycling systems, it would significantly reduce ongoing operational expenses and align with sustainability principles. Furthermore, such an approach enhances the environmental profile of the biorefinery by reducing freshwater demand and minimising wastewater discharge, making the process more resilient to future water availability constraints. Incorporating this strategy into the design phase of the plant is critical for ensuring scalability and long-term viability.

In the present research, the price of rapeseed meal as feedstock is zero and transportation costs are negligible as the plant is integrated with the oil extraction facility. It is important to note that if feedstock needs to be sourced from other locations, transportation costs could significantly impact economic viability and raise environmental concerns. Since successful biorefineries must capitalise on both low-cost and sustainable conditions, the energy required for the process or other activities in the plant could be sourced from the outputs (Parascanu *et al*., 2019; Laghezza *et al*., 2023). Accordingly, in the current study, it is possible to utilise oil, pyro-gas, and char to generate heat and electricity within the system aiming for a self-sufficient energy process. An overview of the challenges and strategies discussed in this section are provided in the Figure 4.

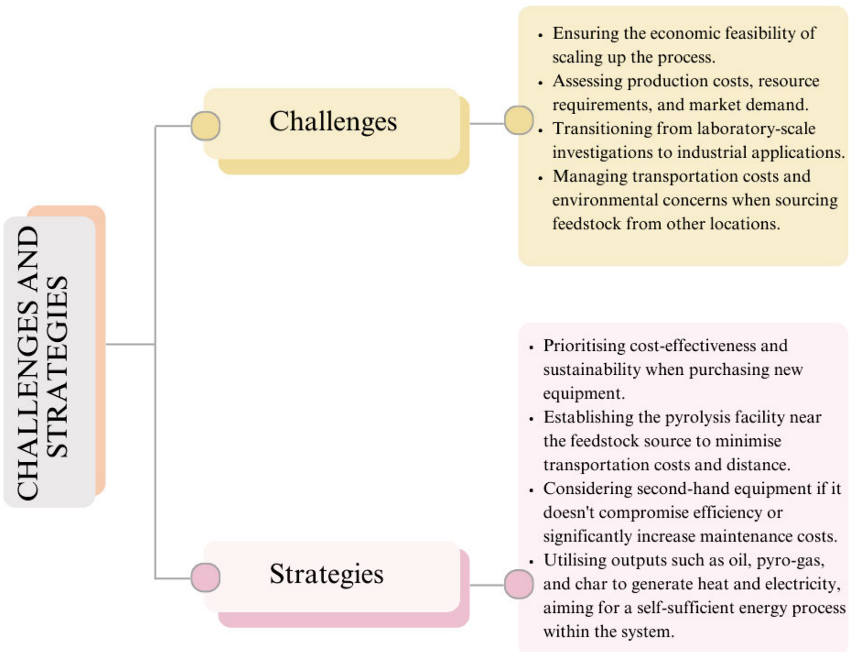

Fig. 4. Summary of challenges and strategies; source: own study.

CONCLUSIONS

The comprehensive assessment provided in this research highlights how rapeseed meal valorisation through pyrolysis can be transformative within the circular economy framework. By converting agro-industrial waste into valuable products, this approach not only addresses environmental challenges but also offers economic opportunities for sustainable growth.

Through techno-economic analysis, it becomes evident that the proposed pyrolysis plant demonstrates strong financial viability, with a positive net present value and a high internal rate of return. This economic feasibility underscores the attractiveness of rapeseed meal valorisation as a potentially commercially viable feedstock. Furthermore, the SWOT analysis reveals numerous strengths and opportunities associated with rapeseed meal pyrolysis, aligning well with the principles of the circular economy. From minimising waste and promoting resource efficiency to creating local economic opportunities and contributing to climate goals, these benefits are multifaceted. However, transitioning from laboratory-scale investigations to industrial applications involves challenges. Addressing these challenges requires a holistic approach, considering factors such as production costs, resource requirements and market demand. Strategies such as prioritising cost-effectiveness and sustainability in equipment selection, leveraging second-hand equipment, and optimising resource utilisation will be crucial for overcoming these obstacles.

In conclusion, the valorisation of rapeseed meal through pyrolysis represents a significant step towards unlocking the circular economy potential of agro-industrial waste. By integrating technological innovation with economic feasibility and sustainability principles, this approach offers a pathway toward a more resilient, resource-efficient, and sustainable future.

ABBREVIATIONS

CE = circular economy
EU = European Union
GHG = greenhouse gas
NPV = net present value
SWOT = strengths, weaknesses, opportunities, threats
IRR = internal rate of return
TEA = techno-economic analysis
CEPCI = chemical engineering plant cost index
PLN = Polish złoty
CIT = corporate income tax
mln = million
RSM = rapeseed meal
LCA = life cycle assessment
HHV = higher heating value
CapEx = capital expenditures
OpEx = operating expenditures

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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