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Research Article

Recovery of Carbon Fibres From Aged Epoxy Matrix Composites Using H_2O_2 as an Oxidant: A Thermodynamic and Technoeconomic Analysis

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There is an effort to use hydrogen peroxide for recycling carbon fibre from epoxy matrix composites because it is an ecofriendly material, and the related technology is feasible. However, there is little information on the technoeconomic impact of this method, thus whether it is economically better than current techniques. Therefore, in this paper, we discuss the technoeconomic analysis of recycling using hydrogen peroxide. The analysis also includes a thermodynamic model to calculate the amount of energy required to decompose the epoxy matrix. Various financial indicators, including the payback period, net present value (NPV), internal rate of return (IRR) and profitability index (PI), were used. The technoeconomic assessment revealed favourable outcomes across all key financial indicators, demonstrating the viability and potential benefits of the process. A capital investment of $17.34M over 10 years was required. The NPV of $15.56M with a 15% minimum discounted rate of return (WACC) was computed. The project is more likely to succeed with an annual production cost of $176.5 million for 50,000 tons in the first year, with this amount subject to annual inflation. A sensitivity analysis was also performed to assess the effect of input variables. In the sensitivity analysis, we calculated between 25,000 and 100,000 tons. The price of hydrogen peroxide and recovered carbon fibre are essential variables that have a high effect on the model.

Keywords: energy consumption; hydrogen peroxide; production costs; raw material costs; recycled carbon fibre; technoeconomic analysis

1. Introduction

Carbon fibre–reinforced polymers (CFRPs) are becoming more and more popular as a way to make new composite materials that can be used in many fields, such as transportation, construction of large parts of airplanes and wind turbine blades [1]. In these composites, the carbon fibres are embedded in a polymer matrix that is typically a thermoset material, such as epoxy, unsaturated polyester, vinyl ester and cyanate ester [2, 3]. However, thermoplastic matrices are also gaining popularity [4]. Carbon fibres provide high strength and modulus, while the matrix distributes the load towards the fibres, and provide the shape itself and protect the fibres from the environment [5]. The global market for CFRPs has experienced significant growth, valued at over $5 billion in 2019. By 2024, the market is projected to reach nearly $8 billion, reflecting an average annual growth rate of 10.6% [6]. The rapid growth is attributed to the exceptional mechanical properties of CFRPs, such as their high strength-to-weight ratio, high durability and extreme corrosion resistance, which surpass those of traditional materials' such as steel and aluminium [7, 8].

With all the benefits carbon fibre offers to composites industries, there are concerns and issues related to its environmental impact. The process of making carbon fibre uses a high amount of energy [9]. Carbon fibre production is 90% based on polyacrylonitrile precursor, while the rest is mainly pitch-based [10], both are fossil-based materials. The carbonization of these precursors is a multistep process that requires temperatures of 1500°C–3000°C in an inert atmosphere [9]. Additionally, the process releases substances such as carbon monoxide, carbon dioxide, volatile organic compounds and nitrogen oxides into the atmosphere, contributing to environmental pollution and greenhouse gas emissions. However, it is important to note that carbon fibre itself serves as a stable form of carbon storage, potentially offsetting some of the emissions associated with its production [11].

The matrix in CFRPs typically consists of a crosslinked thermosetting plastic, which is characterized by its irreversible chemical bonds formed during curing [12]. Unlike thermoplastics, these thermoset matrices cannot be melted or dissolved, making them challenging to recycle or repurpose [13]. As a result, the majority of CFRP parts, after reaching the end of their service life, are disposed of in landfills. This disposal approach not only wastes valuable carbon fibres but also raises environmental concerns due to the nonbiodegradable nature of thermoset polymers [10].

Even though recycling of carbon fibres is challenging, using recycled carbon fibre (rCF) would considerably reduce the environmental impact of CFRPs [11]. Additionally, recycling would reduce the waste in landfill sites that would break down only after hundreds or thousands of years [14]. According to the literature, the recycling rate of carbon fibre remains below 2000 tons per year, primarily due to the challenges associated with the organic decomposition of epoxy reinforced with carbon fibre [15].

Mechanical and chemical recycling methods have greatly improved in efficiency. Efficiency in recycling methods refers to the effectiveness of recovering materials with minimal waste, retaining high-quality properties for reuse, optimizing resource and energy use and achieving cost-effectiveness [16]. Mechanical processes like grinding and shredding, paired with advanced separation techniques, effectively recover high-quality fibres. However, a key drawback is that mechanical recycling tends to produce shorter carbon fibres [17]. Chemical methods have improved through research into new solvents and catalysts that work under gentler conditions, lowering energy use and making the process more sustainable [18, 19]. In those, hydrogen peroxide as a solvent and reagent is seen as an innovative and sustainable solution, since at low temperatures and low pressures, it can break down the resin or the matrix in which CF is embedded into. Compared to alternatives like nitric and sulfuric acids [20], hydrogen peroxide offers a safer and more effective option. Nitric and sulfuric acids only have up to 90% efficiency, whereas hydrogen peroxide proved to have an efficiency higher than 90%, where efficiency means the retention of the initial mechanical properties upon recovery [21, 22]. Recovery by hydrogen peroxide needs temperatures of around 100°C–150°C which renders it more ecofriendly than carbonization itself [23].

With the increasing interest in the use of hydrogen peroxide in the carbon fibre recycling process, a fundamental question arises: Does this innovative approach make economic sense? Sustainability should not be separated from a practical approach in terms of scaling up, especially in industries where profitability is essential [24–26].

Hydrogen peroxide decomposes to produce water and oxygen. Under specific conditions, the decomposition of hydrogen peroxide can also generate hydroxyl radicals (OH), which are highly reactive [27, 28]. These radicals are widely used in oxidation, degradation processes, environmental remediation, chemical synthesis and other industrial applications due to their significance in chemistry and engineering [27, 28].

To provide a comprehensive answer to this question, this study focuses on the technoeconomic analysis to assess the feasibility of recycling carbon fibre using hydrogen peroxide as a reactive solvent. This was achieved by using the concepts of the laws of thermodynamics. A thermodynamic equation was incorporated to the technoeconomic model to calculate the actual energy required by the recycling project. This model offers a comprehensive evaluation of the overall expenses linked to the carbon fibre recycling process using hydrogen peroxide. Furthermore, this model incorporates a comprehensive examination of several factors such as capital expenses, operating costs, maintenance and repairs, energy prices, labour costs, inflation and discount rate.

The assessment of the economic feasibility of the proposed technology incorporated various financial indicators: net present value (NPV), internal rate of return (IRR), profitability index (PI) and payback period (PBP). These measures provide a detailed overview of the financial projections by accounting for both the original investment, incoming cash flow and total expenses. Lastly, we determined the risk factors that might negatively affect the performance of the project. To assess how changes in input variables, such as raw material costs and other related expenses, would affect the financial performance of the recycling project, a sensitivity analysis was conducted [11].

This study contributes significantly to the body of knowledge by integrating thermodynamic principles into a comprehensive technoeconomic model. This approach enables precise calculation of both the energy demands and the overall costs associated with the proposed recycling method to determine its viability.

2. Methodology

All data represented in this paper are either from available literature or calculated using literature data and are based on general assumptions. Any financial data that do not fall within the realm of technical analysis are explicitly designated as a percentage relative to the total capital expenditure (CAPEX) of the project. Microsoft Excel was used for calculations and analysis. Enthalpy (H) of carbon fibre recycling reaction at a temperature greater than 298 K was also computed in the model to evaluate the analysis for energy balance of the rCF project.

The paper discusses the technoeconomic analysis of a theoretical rCF facility based on the elevated temperature and pressure hydrogen peroxide method with a 50,000-ton annual recycling capacity. Figure 1 illustrates the flow diagram of comprehensive technoeconomic assessment of this carbon fibre recycling plant. The flow chart begins with various input materials, comprising carbon fibre–reinforced epoxy composite waste (CF waste) sourced from industries like aerospace, automotive and wind energy. Due to the nature of the composite industry, these are typically large-size, shell-like parts or panels. The cost of sorting, collection and shredding is ignored because it is highly dependent on location. The recycling process involves oxidative decomposition of the epoxy matrix using hydrogen peroxide in a pressurised reactor (150°C and 6 bar) [23, 29]. Outputs include rCF and by-products. The economic evaluation analyses capital costs for project construction and operation, operating expenses for materials and energy, and revenue derived from rCF sales, ensuring a comprehensive overview of the recycling's financial viability.

2.1. Analysis of Technoeconomic Aspects. In this research, it is assumed that the recycling project would be constructed in South Africa. The manuscript uses USD values based on the exchange rate of 18.34 ZAR/USD observed during July 2023 exchange rate.

2.2. Terms and Equations. Data analysis was conducted through the creation of a Microsoft Excel model, which was used for the computation of the financial indicators. The definitions for calculating these financial indicators are as follows.

2.2.1. NPV. The NPV was determined as follows (1):

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t}, \tag{1}$$

where C_t denotes the net cash flow at time t, r is the discount rate used to determine the present value of future cash flows, and T is the total number of periods (years) during which cash flows occur.

The NPV is a representation of the current value of expected net cash inflows from an investment, minus the present value of the initial capital investment (equation (1)) [11, 30, 31]. When NPV is in the positive range, it indicates that proceedings with the investment are advisable, as the project promises a return higher than the discount rate used in the calculations. Conversely, if NPV falls below zero, it suggests that the investment should be avoided [19].

2.2.2. IRR. The IRR is defined as the rate of return at which the NPV of a project becomes zero, as explained by Yang et al. Therefore, equation (2) can be employed as follows to compute the IRR [32–34]:

$$0 = \mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_0, \tag{2}$$

where C_0 is the CAPEX.

2.2.3. PI. The PI (3) is an indicator that illustrates the relationship between the proposed benefits and expenses of the project. It is calculated as the ratio between the present value of expected future financial flows and the initial investment in the project; a higher PI indicates a more attracting project [35]:

$$\mathrm{PI} = \frac{P_v}{P_{\mathrm{init}}}, \tag{3}$$

where P_v is the present values of future cash flow, P_{init} is the initial investment, and $P_v = \mathrm{NPV} + P_{\mathrm{init}}$.

2.2.4. PBP. The PBP is a financial indicator utilized to determine the timeframe needed for a project to recover the entirety of its initial investment [20]. It signifies the period during which the total cash inflows generated by the project match or exceed the initial capital investment [11]:

$$\mathrm{PBP} = \frac{C_0}{C_t}. \tag{4}$$

2.3. Thermodynamic Equations. The model integrates thermodynamic equations to calculate the energy necessary for the decomposition of epoxy resin reinforced with carbon fibre. The decomposition is an endothermic reaction. The heat required to decompose the epoxy is the main energy requirement of the facility and is calculated in Mega joule (MJ).

2.3.1. Enthalpy and Its Change. Enthalpy (H) is a thermodynamic property of a system that represents the total heat content of that system [21]. This computation assumes that heat required is equal with the enthalpy change (ΔH). That is because the enthalpy change is the following (5):

$$\Delta H = \Delta U + \Delta pV, \tag{5}$$

where U is the internal energy, p is the pressure, and V is the volume. Since the reactor operates at moderate and constant pressure, ΔpV can be neglected. The specific equation we are

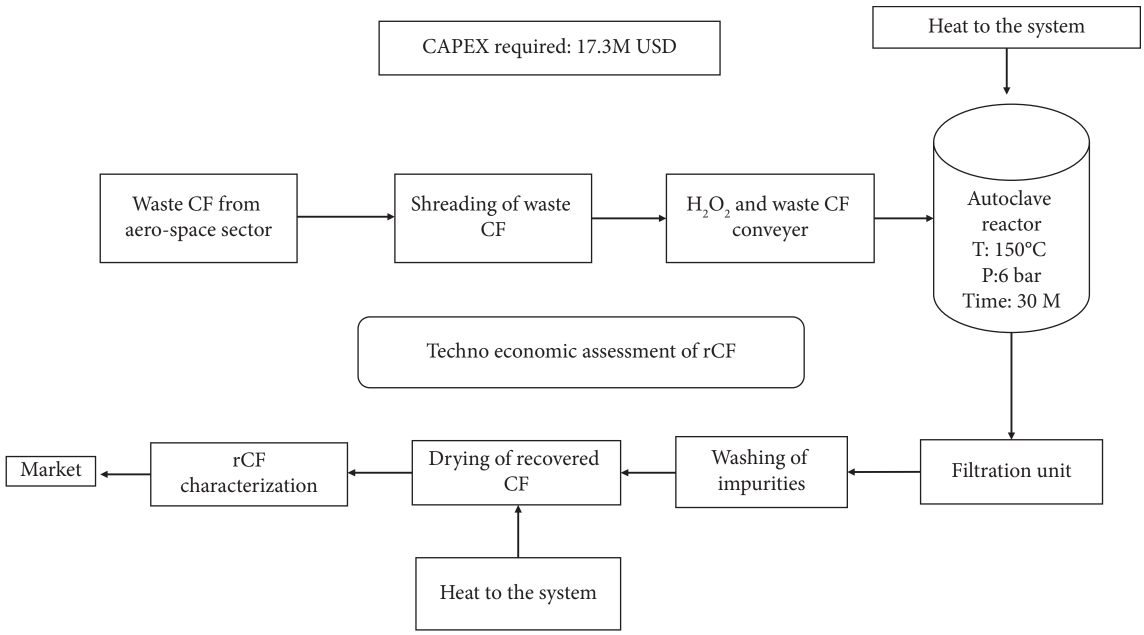

Figure 1: Schematic diagram of the hydrogen peroxide-based carbon fibre recycling process.

focusing on relates to the calculation of enthalpy is highlighted in equation.

Enthalpy H of a substance at a temperature greater than 298 K was calculated according to the following equation as follows:

$$\triangle H = Cp(T), \tag{6}$$

where C_p is the specific heat capacity (J.kg $^{-1}$ K^{-1}) and ΔT is the change in temperature of system (K).

Additionally, it is essential to acknowledge that the specific heat capacity (C_p) of a substance is influenced by temperature [36–38]. To determine the enthalpy at a temperature different from room temperature, a more intricate equation that accounts for the temperature-dependent nature of C_p is essential [39–41]. For this study, estimating the specific heat capacity involved the use of polynomial equations of C_p/R highlighted in equation (7) for temperatures higher than 298 K [41–43]:

$$\frac{C_p}{R} = a + bT + cT^2 + dT^{-3}. \tag{7}$$

The values a, b, c, d, and so on represent coefficients that depend on the solvents and epoxy used in this study and supplied in reference materials. To compute the enthalpy (H) at a given temperature (T), it is necessary to perform an integration of this equation for $C_p(T)$ across the desired temperature interval as stipulated in (7) [41, 42, 44]:

$$\triangle H = R\int_{T_1}^{T_2}\left(\frac{Cp}{R}\right)T, \tag{8}$$

where R is the specific gas constant (8.314 J/mol K) [41, 45] and T_1 and T_2 are the initial and final temperatures, respectively. Decomposition temperature in this study is assumed to be 403 K as most epoxies decompose in this temperature range, and it is substituted as T_2 in equation (8). T_1 is substituted as the initial temperature in equation (8), and in this instant, it is assumed to be 298 K [46].

Higher temperature corresponds to higher energy consumption due to equations (6) and (7) [47]. The assumed energy price was about \$0.022 or 2.2 cents per MJ, and the inflation rate was assumed to be 5% [11, 48].

In this study, bisphenol A diglycidyl ether ($C_{21}H_{24}O_4$), a common epoxy compound, was considered as the general material of the project. The reason is that epoxy compounds are characterized by a specific C-O-C functional group, often presented as R-O-R [49, 50]. In most cases, -R indicates C_3H_6. Therefore, for this reason, the interest lies in examining the behaviour of the C_3H_6 portion within the epoxy molecule, which contains three carbon atoms and six hydrogen atoms bonded together [51]. When this C-C chain is broken down, it entails the decomposition. This focus helps gain insights into its reactivity under specific conditions.

Epoxies are two-component systems consisting of a resin ($C_{21}H_{24}O_4$) that interacts with the 4,4-diaminodiphenylmethane dicyanamide and amine hardener (2,2-dimethyl-4,4-methylenebisto) form a cured network. During curing, the epoxy resin undergoes a reaction with the hardener involving the C-O-C functional group, resulting in the formation of covalent cross-links [50, 52]. These cross-links significantly impact the thermal stability, mechanical properties and overall decomposition behaviour of the cured epoxy. Therefore, it is important to note that the hardener plays a crucial role in the decomposition process as it forms cross-links with the epoxy.

The literature lacks reported coefficients for C_p unless experimental values are chosen. Instead, this study has opted to employ the functional group of bisphenols, represented as C_3H_6, and it is presented by equation (9). Similarly, the study has modelled the actual energy content for hydrogen peroxide (H_2O_2) 40 V% based on the constituents such as water

(H_2O) and oxygen (O_2) as highlighted in equation (10), and the equation was also used to calculate the enthalpy formation for H_2O_2. The total energy (enthalpy) for hydrogen peroxide was calculated using equation (11) [53]. Table 1 provides the coefficients used to calculate the energy output of the system using equation (6):

$$C_3H_6 + 2H_2O_2 \longrightarrow C_3H_6O_2 + 2H_2O \quad (9)$$

$$H_2O + \frac{1}{2}O_2 \longrightarrow H_2O_2 \quad (10)$$

$$\Delta H_{H_2O_2} = \Delta H_{H_2O} + \Delta H_{O_2} \quad (11)$$

Table 2 contains data derived from equations (5) and (6), presenting the enthalpy values associated with the individual constituents discussed in this paper. Equation (12) [42] corresponds to the enthalpy of formation for the chemical reaction outlined in equations (10) and (11). Table 2 entails the derivation of the enthalpy of constituents at 150°C

$$\Delta H_{\text{at } 25^\circ\text{C}} = \sum_{\text{at } 25^\circ\text{C}} \Delta H_{\text{product}} - \sum_{\text{at } 25^\circ\text{C}} \Delta H_{\text{reactant}}. \quad (12)$$

Table 3, on the other hand, encompasses the data utilized for computing the standard heat of formation during the epoxy's decomposition, yielding a value of approximately 19.700 kJ/mol. To determine the comprehensive system enthalpy, indicative of the system's energy output, the enthalpy calculated from chemical equation (11) [53] which is the total enthalpy at 150°C is added to equation (12), which is the sum of the enthalpy formation at 25°C manifested a value of −721.56 kJ/mol using Table 3 constituent values. Equations (9) and (10) were used to compute the enthalpy formation of hydrogen peroxide, end up in a value of 721.2 kJ/mol.

The energy required to break the epoxy hardener was also modelled. However, similarly to the bisphenol, the literature lacks C_p/R coefficients for hydrogen peroxide and dimethylamine $(CH3)_2NH$ (hardener), and the computation of methene (CH_4) and ammonia (NH_3) was considered to model the enthalpy required to decompose the hardener. Utilizing Hess's law application, our research computed coefficients *a* to *d* using the equations (7) and (13)–(15), enabling the calculation of the enthalpy required to break the C-N bond in dimethylamine:

$$(CH_3)2NH + H_2O_2 \longrightarrow (CH_3)2N(O) + H_2O \quad (13)$$

$$3CH_4 + NH_3 \longrightarrow (CH_3)_2NH + 6H_2 \quad (14)$$

$$\Delta H_{(CH_3)2NH} = \Delta H_{CH_4} + \Delta H_{NH_3} \quad (15)$$

To complete Hess law for enthalpy formation, $(CH_3)_2NH$ comprises two methyl (CH_3) groups and an amine (NH_2) group, whereas $(CH_3)_2NO$ comprises two methyl (CH_3) groups and a nitroxide (NO) group. ΔH values for these groups at 25°C cannot be obtained from reference tables in thermodynamic database. Hess's law was used to gather the estimate of enthalpy formation: For $(CH_3)_2NH$, ΔH can be estimated as −49.6 kJ/mol, calculated using the enthalpy formation of CH_3 and NH_2. Similarly, for $(CH_3)_2NO$, ΔH is estimated as −49 kJ/mol, using ΔH of CH_3 and NO. The values are indicated in Table 3. The sum of the total enthalpy using equation (12) constitutes about −95 kJ at 25°C. C_p/R, which is equation (7), was applied to equation (14) to compute for enthalpy formation, and values of both reactants constitute about 18,924 J/mol of energy required. Therefore, the total enthalpy required at 150°C and 25°C manifested a value of 18.82 kJ/mol.

The project's total capacity for recycling carbon fibre is 50,000 tons per year, which equates to a daily capacity of 192.30 tons. It assumes that the plant will operate regularly, with a daily operation of 260 days per year. The plant processes 24 tons per hour, and it would need to operate for about 8 h each day (192.30 tons/day ÷ 24 tons/hour = 8 h/day). The remaining 105 days are for maintenance and plant shutdowns. This schedule allows for routine upkeep and ensures the plant remains efficient and functional.

The enthalpy of the system was calculated by summating equation of 8 and 13. This total enthalpy represent the required amount of energy needed for decomposition of both hardener and epoxy. The energy consumption for the project is 778.63 kJ/mol per day.

In this study, the epoxy component of the CFRP system that we used reported above (propylene), having a molecular weight of 36.03 g/mol, and the hardener was which is $(CH_3)_2NH$ (dimethylamine), with a molecular weight of 45.09 g/mol. Based on the total CFRP mass of 192,307 kg/day, where 30% comprises these components (15% C_3H_6 and 15% $(CH_3)_2NH$), the calculated masses for both C_3H_6 and $(CH_3)_2NH$ were 28,846.05 kg/day each. Converting these values to moles, the system was found to contain 800,872 mol/day of C_3H_6 and 639,995 mol/day of $(CH_3)_2NH$, resulting in a total of 1441 Kmol/day, which requires an energy input of 1121.5 MJ/day. Using the standard conversion factor of 3600 kJ per kWh, the total energy required was calculated to be 311.53 kWh/day. This energy consumption reflects the input needed to facilitate the decomposition and recovery of carbon fibres, highlighting the energy demands for decomposition which manifest to about 80,997.4 KWh/year.

2.4. Determining Stoichiometric. The project assumes the treatment of 50,000 tons of waste CFRP annually, with a daily processing capacity of 192.3 tons. To determine the required amount of H_2O_2, stoichiometric modelling was utilized. According to the chemical reaction in equation (9), 2 mol of H_2O_2 is required for every mole of C_3H_6 decomposed [55]. Given the stoichiometric coefficient, 192.3 tons of CFRP corresponds to 4568 kmol of C_3H_6, which requires 9137.9 kmol of H_2O_2. This translates to a required H_2O_2 mass of 310.87 tons per day. With the density of H_2O_2 being approximately 1460.00 kg/m^3, this results in a daily consumption of 212.9 or 55,360 m^3 annually.

The autoclave reaction was conducted at 150°C and 6-bar pressure for 30 min, ensuring optimal decomposition and high-quality fibre recovery. In our previous study, we found that this short treatment time effectively yields high-purity and long-

Table 1: Coefficient of C_p (equation (7)) at 150°C, based on [42, 54].

Constituents	Coefficient (a)	Coefficient (b)	Coefficient (c)	Coefficient (d)
H_2O	3.470	$1.450 * 10^{-3}$	0	$0.121 * 10^{5}$
O_2	3.639	$0.506 * 10^{-3}$	0	$0.227 * 10^{5}$
C_3H_6	1.637	$22.706 * 10^{-3}$	$6.915 * 10^{-6}$	0
NH_3	3.578	$3.02 * 10^{-3}$	0	$0.816 * 10^{5}$
CH_4	1.702	$9.081 * 10^{-3}$	$-2.164 * 10^{-6}$	0

Table 2: Enthalpy at 150°C.

Constituents	Enthalpy (J/mol)
H_2O	4954
O_2	5481
C_3H_6	9264
CH_4	4875
NH_3	3612

Table 3: Enthalpy of formation at 25°C.

Constituents	kJ/mol	References
C_3H_6	20.6	[42]
H_2O_2	−190.7	[42]
$C_3H_6O_2$	−510.8	[42]
H_2O	−285.8	[42, 46]
NH_2	49	[42, 46]
CH_3	−74.8	[42, 46]
NO	90.3	[42, 46]

recovered carbon fibres [56]. While longer holding times could result in increased heat loss, the 30-min duration proved to be both efficient and effective for achieving the desired outcomes.

The hydrogen peroxide (H_2O_2) used in our study was priced at $76.06 per 5-L container, as quoted by Boshomane Chemicals and Sales, based in Krugersdorp, South Africa. This price leads to an annual H_2O_2 cost of $168.4 million for the projected consumption of 55,360 m^3 per year. It should be noted that purchasing raw materials in bulk would reduce costs and increase plant profitability. However, we opted not to obtain bulk quotations to prepare for economic downturns, ensuring that our model is resilient during challenging economic periods.

Equation (13) was used to calculate the amount that hydrogen peroxide required. The volume of hydrogen peroxide (H_2O_2) needed for a reaction involving 192.3 tons of dimethylamine $(CH_3)_2NH$ with a molar mass of 45.08 g/mol was determined using the balanced chemical equation (13), which shows a 1:1 stoichiometric ratio between $(CH_3)_2NH$ and H_2O_2. By converting the weight of $(CH_3)_2NH$ to moles, the amount of H_2O_2 required can be calculated. Finally, the volume of H_2O_2 is determined in cubic metres using its density. The resulting volume of hydrogen peroxide needed for the reaction is approximately 99.6 m^3. Annually, we need 25,900 m^3. The manifested cost is about 78.8 M$. Since the hydrogen peroxide of the hardener is minimal compared to epoxy, the amount for hydrogen peroxide required for the hardener was used to determine the required amount of hydrogen peroxide.

2.5. Financial Aspects of the Project. CAPEX estimation involved applying the "rule of six-tenths" in conjunction with data from the Chemical Engineering Project Cost Indices (CEPCI) found in the relevant literature (equation (16)) [15, 57]. This method entails approximating the cost of a new facility based on historical data from a similar one and adjusting it using the CEPCI corresponding to the estimation year, which was 2020, with reference to the 2022 CEPCI data. The calculated CAPEX was EUR 10.000M for a production capacity of 50,000 tons per year [15], considering an exchange rate of 1 Euro was about 1.09 USD for the mid-2023 through early 2024. The C_d amounts to $15.78 M with the capacity of 50,000 metric tons per year:

$$\mathrm{CAPEX} = C_r \left(\frac{d}{r}\right)^{0.6} \left(\frac{I_{2022}}{I_{2019}}\right), \tag{16}$$

where CAPEX represents the capital costs of a project designed for a specific annual capacity in tons, C_r corresponds to the reference capital costs of a project as documented in the literature, r is the capacity reported in the literature, d is our own desired capacity (50,000 tons/year), I_{2022} represents CEPCI index for year 2022, and I_{2019} represents the CEPCI index for the specific year corresponding to the reference data of the project.

As stated in Table 4, the CAPEX amounts of this project are about $15.078M representing 15% of the working capital [15], which totals $2.262M, and this amount accounts for Figure 1. The overall capital investment includes both the CAPEX and the fixed CAPEX, which is about $17.339M and the discounted rate assumed is 15% [11, 15]. The fixed CAPEX that is a long-term investment in essential assets such as buildings, machinery and technology accounts for 5% of this sum which is about $0.867M [58, 59].

The annual labour costs amount to $3.016M which is 20% of CAPEX, the labour cost with 260 working days per year and 10 employees shifts per day [11, 59].

The annual operational expenditure (variable OPEX) of this project is outlined in Table 5. The expenses of the project include insurance property damage, accidents, liability and intellectual property amount to $156,000, constituting 1% of the total investment, while project overhead costs are notably higher at $1.809M representing 60% of the total investment [59]. Research and development expenses amount to $150,777, equivalent to 5% of the total labour cost, while maintenance costs stand at $1.213M making up 7% of the total labour cost. Additionally, administrative costs are $542,798 accounting for 30% of the total labour cost. These operating expenses by a 10% annual inflation rate [59].

Table 4: Capital cost.

Capital costs	
Capital expenditure (CAPEX)	$15.078M
Per cent of working capital in CAPEX	15%; [15]
Working capital	$2.262M
Total capital investment (CTC)	$17.339M
Percentage of fixed cost	5%; [11]
Fixed cost	$0.867M

Table 5: Variable operational expenditure.

Variable OPEX	COST	%
Insurance	$0.156M	1% of total capital investment*
Project overhead	$1.809M	60% of labour cost*
Research and development	$0.151M	5% of project overhead*
Maintenance	$1.213M	7% total capital investment*
Administrative costs	$0.542M	30% of project overhead*
Chemical per 50,000 tons of rCF	$168,43M	4% inflation
Labour cost	$3.05M	6% annual inflation
Waste disposal cost per ton	$1.36M	5% annual inflation
Energy cost	$322,557	5% annual inflation**

*References [15, 60].
**Reference [11].

The quantification of waste from CFRP recycling is based on the epoxy content and the efficiency of the recycling process. In this scenario, with 30% epoxy in CFRP waste and an annual input of 50,000 tons, approximately 15,000 tons of waste (liquids and solids) is generated annually. Based on data from various EU countries, the cost of landfilling ranges between €0.076 and €0.09 per kg [61]. Using a conversion rate of approximately 1 EUR = 1.10 USD, the cost per kilogram of landfilling CFRP waste in USD ranges from about $0.0836 to $0.099. When applied to 15,000 tons (or 15,000,000 kg) of CFRP waste, the total landfilling cost varies. At the lower end of the cost range ($0.0836 per kg), the annual landfilling cost amounts to approximately $1,254,000. At the upper end of the cost range ($0.099 per kg), the annual cost reaches about $1,485,000. On average, considering a midpoint cost of $0.0913 per kilogram, the total annual cost is around $1,369,500.

AMT composite, South Africa, in Johannesburg, sells the carbon prepreg as 200 gsm (grams per square metre) with 30 vol % of the epoxy; therefore, this study uses 200 g of samples of rCF to determine the minimum selling price. The cost of rCF used in this study is about $0.74 per 200 g, it was calculated using sensitivity analysis, and the minimum value that makes the model viable was computed. Additionally, the selling price of rCF per year is $184.0M per 50,000 tons, with this price being increased annually due to 5% inflation for the period of 10 years [11].

2.6. Tax and Depreciation. Finally, the company tax rate selected for this study is set at 28%, which aligns with the current prevailing corporate tax bracket in South Africa [11, 48].

The depreciation method for this paper assumes a double-declining depreciation method, starting from operation with zero salvage value (equation (17)). The depreciation curve is highlighted in Figure 2(b):

$$D = 2\left(\frac{1}{n}\right)C_t. \quad (17)$$

In conclusion, the study assumed 14% fixed rate for repaying the loan associated with the total capital investment over a 10-year period. The study utilized a specific equation to determine the annual repayment amount, which in turn had an impact on the overall expenses. $33.242M was calculated using the following equation:

$$\text{Annual repayment} = \frac{P * r * (1+r)^n}{(1+r)^r - 1}, \quad (18)$$

where P is the principal amount (initial amount borrowed or invested), r is the interest rate per period (expressed as a decimal), and n is the number of periods.

2.7. Sensitivity Analysis. Sensitivity analysis serves as a valuable methodology for evaluating the uncertainties associated with a model's outcomes by methodically altering input parameters [62]. The sensitivity analysis with respect to the NPV, PI, IRR and PBP is outlined according to the following:

- High Sensitivity: When a model or output is highly sensitive, even minor input changes can cause significant output fluctuations, indicating increased financial vulnerability and potential higher risk [63].

- Low Sensitivity: Conversely, low sensitivity means the output remains stable, showing minimal responsiveness to input variations, enhancing predictability and lowering potential risks [64].

3. Results and Discussion

3.1. Model Results. The economic feasibility of a 50,000-ton rCF/year project using hydrogen peroxide as a solvent is being analysed [59]. The model was built upon a predefined set of general assumptions indicated under the methodology section. The operation uses 55,361 m^3 of hydrogen peroxide and incurs an energy consumption of 311 kWh/day for 192 tons. Financial data sets, including IRR, NPV, PI and PBP, were computed over the 10-year lifecycle of the RCF project, and these values are presented in Table 6.

The incorporation of waste disposal costs into the financial analysis of a CFRP recycling project results in a notable decline in key financial indicators such as NPV, IRR and PI. Specifically, the inclusion of these costs reduces the NPV approximately to $11 million, the IRR to 26%, and the PI to 1.64. Despite this the inclusion of waste disposal, the project remains financially viable, as all indicators remain positive.

The acceptable PBP typically adheres to the terms set forth in the financial investment contract agreement, where a shorter PBP indicates a profitable scenario meeting or exceeding the financial investor's minimum PBP [65]. It is crucial to clarify that, for the purposes of this study, we did not consider in the specifics of the financial investor contract agreement, how fix rate annual repayment was incorporated to the model as highlighted in equation (4). According to our analysis on this theoretical plant, as revealed in Table 6 and Figure 2(a), the rCF project boasts an impressively short PBP of just 4 years, aligning with findings in the relevant literature [66]. This remarkable 4-year PBP is based on a pricing assumption of approximately $0.71 per 200 g. Achieving such a swift PBP underscores the robust economic viability of the project and highlights its attractiveness of an opportunity when approaching potential investors.

As previously indicated under the methodology section, the NPV of the project is determined by aggregating its cash inflow and outflow, discounted at a rate commensurate with the project's risk profile. The NPV was derived using Figure 2(c), and it is evident that the net cash flow increases over time due to the inflation rate of 5% related to the selling cost of rCF.

The criteria for assessing the technoeconomic viability of the RCF project stipulate that if the NPV exceeds zero, the project or technology can be deemed economically viable. As indicated in Table 6, the NPV stands at $11 M over a 10-year period. This figure strongly suggests that the RCF project, utilizing hydrogen peroxide as a solvent, is indeed financially viable. Furthermore, projects exhibit higher NPV values for investment, primarily due to their greater handling capacity of approximately 50,000 tons and lower energy consumption [67].

Figure 2(d) indicates that in this scenario, the cost of the raw material, specifically hydrogen peroxide, is closely aligned with the revenue. This implies that economic challenges, like those experienced during the COVID-19 pandemic [68], can impact the project's performance if the price of the raw material rises. Additionally, the project's financial performance may be affected, particularly if it fails to meet its sales capacity. However, more revenue can be generated from by-products of this recovery process since the chemical degradation of the epoxy resin produces by-products such as acetic acid and formic acid [69]. These compounds have industrial applications as preservatives and in chemical synthesis. The process can also yield monomers and oligomers from the breakdown of the epoxy resin [70]. These products serve as precursors for the synthesis of new resins, enabling a closed-loop recycling system. However, we did not include the selling price of these constituents to our model which can also add positive contribution to the project. The reason is that the efficiency of extraction and purity of these by-products have yet to be investigated.

Table 6: Financial indicators over a 10-year period.

Life span (10 years)	With waste disposal cost included
NPV	$11,031,302.74
IRR	26%
PI	1.64
Payback period	4.00

It should be noted that Figure 2(d) represents the revenue generation based solely on recovered carbon fibres. The selling price per unit of rCF in this analysis was conservatively set at a minimal value sufficient to render the project profitable. This approach ensures the calculated profitability is achievable even under market conditions with lower rCF prices. A levelized cost analysis was conducted to determine the minimum value required for the project to be profitable and competitive compared to other composites, such as glass fibre.

An increase in the selling price of rCF, as frequently observed in markets requiring high-quality recycled materials, would significantly enhance the project's profitability. This underscores the adaptability and robustness of the process, particularly when catering to premium applications in industries like aerospace and automotive. Through our process, we achieved 93.8% decomposition efficiency, recovering fibres that retained 90% of their original mechanical properties [56]. The pricing of the recovered carbon fibres was determined based on their experimentally verified high purity and quality, making them ideal for high-demand sectors such as the automotive industry.

As previously stated, the project assumed a total capacity of recycling 50,000 tons of carbon fibre waste per year, with daily operational capacity, annual energy consumption and cost estimates provided for hydrogen peroxide. The yearly cost of hydrogen peroxide is $168.4M, subject to a 5% annual inflation rate. Similarly, stoichiometric computations are used to determine the volume of hydrogen peroxide required for the hardener's decomposition, amounting to approximately 99.6 m^3 annually, costing about $78.6M per year which constitute for about 32.8%.

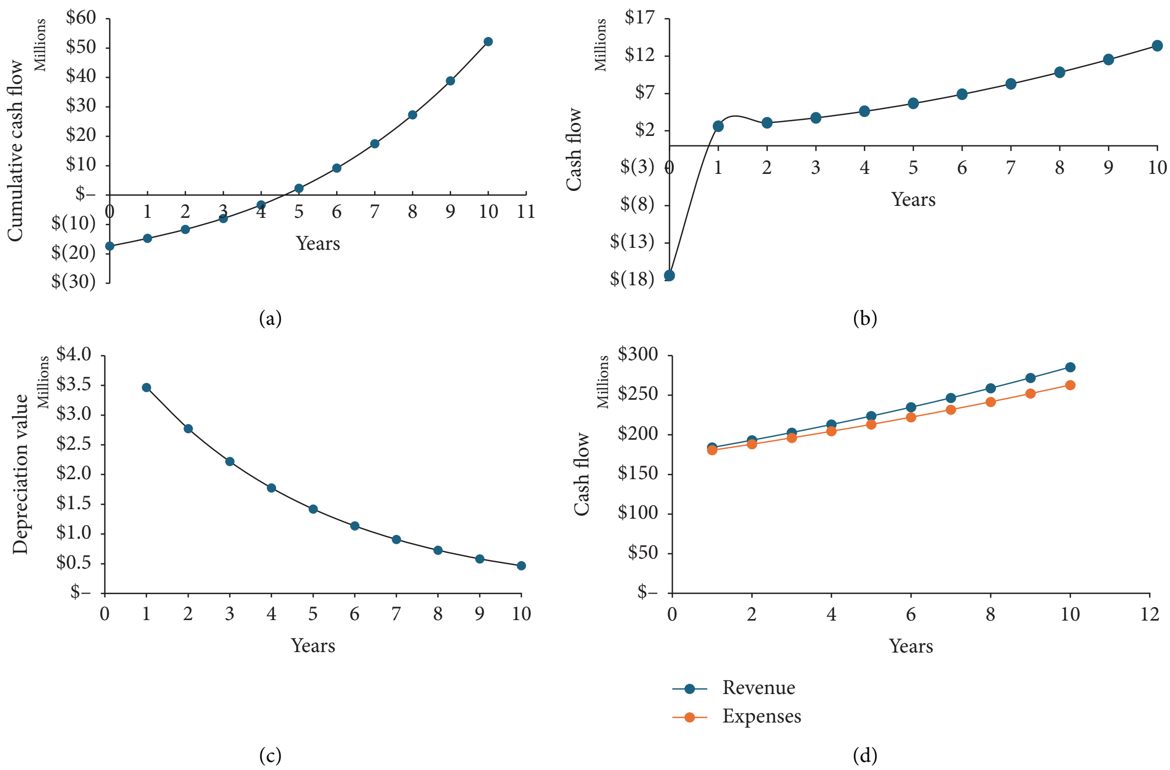

Figure 2: Main financial indicators of the project. (a) Payback period, (b) net cash flow, (c) depreciation curve, and (d) revenue versus expenses.

As previously defined, the profitability decision rule is to proceed with an investment when the PI exceeds 1.0, while refraining from investing when the PI falls below 1.0. In both 10-year scenarios examined, the PI proves to be profitable, as it exceeds 1. This signifies that the rCF project, operating under the assumptions delineated in this study, is poised to generate financial gains for its investors.

The study investigated financial indicators of the entire project over 10 years, particularly focusing on the IRR and minimum discounted rate of return (WACC) over a span of 10 years, and it is evident that the project gains valuable insights into its financial profitability of the rCF project. The IRR is 26%. This is the discount rate at which the project's cash flows break even, meaning the project is expected to generate a return greater than 15%.

This extended perspective emphasizes the enduring struggle of the project's cash flow to achieve significant profitability over the 10-year period. At the same time, the consistently high WACC at 15% signifies a substantial cost of capital that the project must continuously surpass to remain financially attractive over this extended period. As this financial indicator IRR is significantly low for over the course of a decade, it becomes crucial for the project team to implement effective way in expanding life span, cost management and strategies to enhance revenue. Furthermore, this underscores the importance of periodic reviews, adaptations and refinements to boost the project's financial performance and keep it aligned with its long-term goals. This 10-year analysis underscores the project's ongoing financial challenges and highlights the vital role of prudent financial management and proactive risk mitigation throughout its lifecycle.

PBP of 4 years signifies a rapid recovery of the initial investment, and the model manifested a quick return on capital within the project's first year [71]. This means the project break even after 4 years. This financial recovery minimizes extended exposure to ongoing financial doubts and market instabilities. Moreover, a short PBP underscores strong early-stage cash flow generation and indicates the financial stability of the rCF project.

These results collectively suggest that the recycling carbon fibre project is a financially viable for the investment to take place, as indicated by the positive NPV, high IRR than WACC, favourable PI and relatively short PBP. However, it is essential to consider other factors like market conditions such as economic inflations, operational risks and environmental impact before proceeding with the project.

According to Table 7, each recycling method has its own set of cost implications and performance advantages. Grinding is the most cost-effective but may require additional processing steps, simply because it suffers a drawback of impurities and torn fibres which limit the end product use [73]. Pyrolysis and microwave methods offer enhanced processing capabilities and better quality at higher costs. Supercritical water, while effective, is the most expensive.

Table 7: Comparison table with technologies from the literature [72].

Technique	Investment cost (USD)	CAPEX used in economic assessment (USD)	Investment cost per ton (USD)	CAPEX per ton (USD)
Grinding	$239,000	$316,075	$59.75	$79.02
Pyrolysis	$11,900	$1,732,750	$595.00	$866.38
Microwave	$11,596,400	$3,048,750	$231.93	$1524.38
Supercritical water	$5,770,000	$7,688,350	$5770.00	$7688.35
Our study (hydrogen peroxide)	$15,000,000	$17,339,408	$346.79	$346.79

The hydrogen peroxide method from our study offers a middle ground with moderate costs and effective chemical processing, making it a viable alternative depending on specific project needs and economic considerations.

3.2. Sensitivity Analysis

3.2.1. The Effect of NPV. Within the scope of this study, our primary focus is directed towards the NPV criterion for the recycling project. This emphasis on NPV is justified due to its paramount importance as the principal investment metric susceptible to changes in input variables. The sensitivity analysis model entails the deliberate manipulation of specific input parameters to discern their impact, whether positive or negative, on NPV. The selected parameters encompass NPV ($) itself, the discounted rate (WACC), energy consumption, cost of rCF, total CAPEX, cost of raw materials and the project's annual capacity. Each of these parameters will be systematically adjusted within a range spanning from −50% to +50%, and NPV will be recomputed accordingly, shedding light on how variations in these factors influence the project's financial viability.

The impact of changes in key input parameters on the NPV of the project is quite evident. For instance, when the discounted rate decreases by 50%, NPV experiences a substantial increase, reaching approximately $25M as highlighted in Figure 2. Conversely, when the rate increases by 50%, NPV decreases to about $2M. This highlights the profound effect the choice of the discount rate has on NPV, with higher rates diminishing the present value of future cash flows, potentially impacting the project's financial viability.

Interestingly, variations in energy usage by 50% have no direct impact on NPV, as it remains constant at approximately $11M. NPV is not sensitive to changes in energy usage, suggesting that fluctuations in energy consumption do not significantly affect the financial performance of the project.

In Figure 3, factors like CAPEX, energy consumption and discounted rate exhibit relatively low sensitivity variations. This is particularly intriguing in the case of CAPEX, which shows low sensitivity under both a 50% decrease and a 50% increase. A 50% decrease in total CAPEX leads to a substantial decrease in NPV, approximately $48M. Conversely, a 50% increase in CAPEX results in a negative NPV increase as highlighted in Table S1 in the supporting information. Total CAPEX plays a significant role in NPV. Lower CAPEX improves project viability, while higher CAPEX reduces it. It is evident that a negative change contributes positively to the project; however, the influence or effect is relatively low. This difference could be attributed to the positive influence of the selling price of rCF and the high project capacity, which seem to counterbalance CAPEX fluctuations.

On the other hand, the cost of raw materials, particularly hydrogen peroxide, displays high sensitivity to the project. A 50% decrease in the cost of rCF leads to a substantial decrease in NPV, roughly to $360M. Conversely, a 50% increase in this cost results in an NPV decrease. The cost of rCF has a significant influence on NPV. Higher cost of rCF enhances project profitability, while low costs diminish it. This sensitivity is primarily due to the significant quantity of hydrogen peroxide used and its price variations. The project's performance is considerably affected by changes in hydrogen peroxide sales and consumption. Despite this limitation, the analysis underscores the substantial influence of raw material usage on the project's financial dynamics. Revenue increases sharply with positive NPV variations, from −$384.71M at 50% decrease to $406.78M at 50% increase. Revenue is a dominant factor affecting NPV, underscoring the importance of market conditions or sales volumes.

Lastly, the project's capacity plays a pivotal role in sensitivity. A higher production capacity leads to greater profitability, while a lower capacity is associated with reduced profitability. This underscores the importance of carefully assessing and optimizing the project's capacity to ensure financial success.

3.2.2. Effect of IRR. In Figure 4 and Table S2 in the supporting information, the sensitivity analysis conducted for the recycling carbon fibre project, focusing on the IRR under various effects of change, provides critical insights into the project's financial viability. The study considered five key parameters: the discounted rate, energy usage, cost of rCF, CAPEX and the cost of raw materials. Notably, the discounted rate showed limited sensitivity, with the IRR remaining consistent across the range of adjustments. This was done to demonstrate the quality of the model. The financial indicator IRR is WACC, which makes the NPV zero. Therefore, the WACC itself does not directly affect the IRR, and we expect no change under sensitivity analysis.

Any significant changes in the WACC can indirectly impact the IRR by affecting the project's financing costs and, subsequently, its cash flows. Energy usage exhibited sensitivity, indicating that variations in consumption could impact the IRR. It is evident that in Figure 3, a manifestation of negative NPV was witnessed under this input variable. The IRR is essentially the discount rate at which the NPV equals zero, indicating a breakeven point or a point where the project becomes financially viable. In the case of a negative NPV, there may be no real IRR because the project is not expected to break even or become profitable. Furthermore, CAPEX and the project's capacity per year demonstrated substantial sensitivity.

Waste disposal costs show a decreasing trend with positive variations, from a 44% increase at −50% to a 5% reduction at +50%. This steady decline indicates a proportional response, showing moderate sensitivity compared to other factors. OPEX also decreases consistently as variations become positive, with reductions up to 16% at +50%. This suggests operational cost optimization becomes more effective with favourable variations.

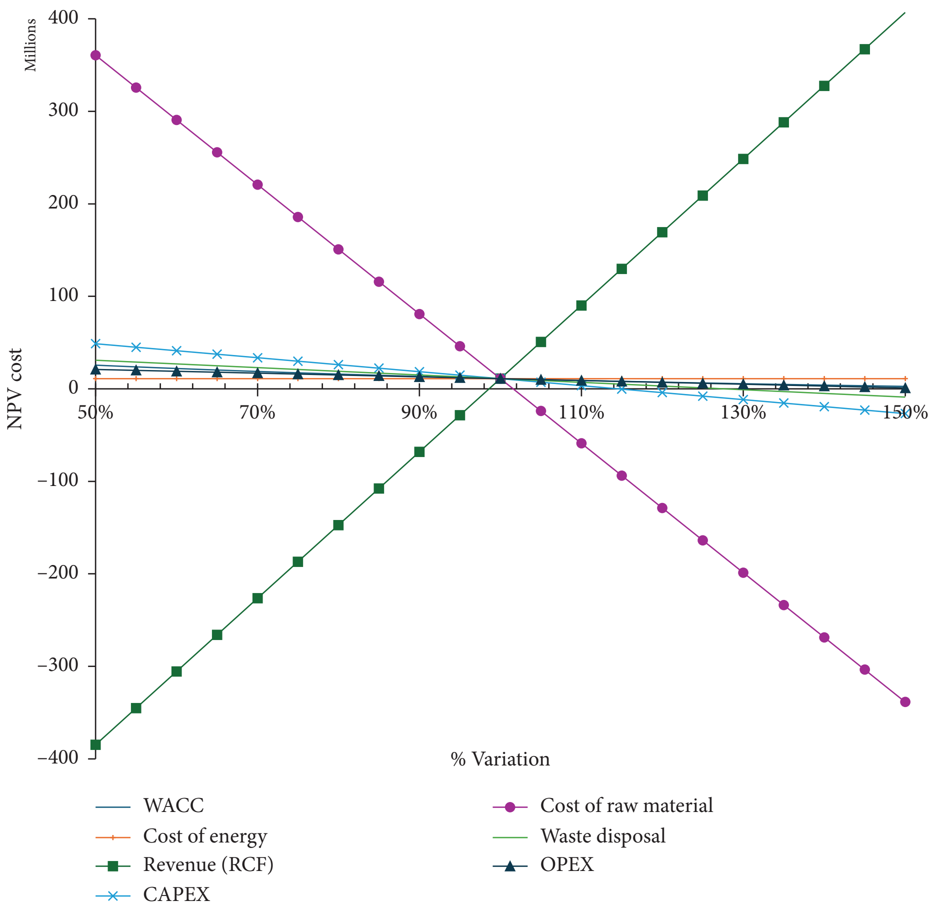

Figure 3: Sensitivity analysis of net present value (NPV).

3.2.3. The Variation of the PI. The sensitivity analysis conducted for the recycling carbon fibre project delves into the intricate dynamics that affect the project's PI under various scenarios of key parameters. One of the standout observations from this analysis is the remarkable impact of the discount rate on the project's profitability as highlighted in Figure 5 and Table S3 in the supporting information. A lower discount rate substantially bolsters the PI, making the project appear much more financially appealing. Conversely, as the discount rate increases, the project's attractiveness diminishes. This finding underscores the critical importance of selecting an appropriate discount rate in project evaluations, as it can significantly influence the financial viability of the project.

Energy usage, on the other hand, demonstrates a relatively stable influence on profitability. While it does affect the PI to some extent, the magnitude of this impact is moderate compared to other factors. This suggests that variations in energy usage have a milder effect on the project's overall financial performance, and as such, optimizing energy consumption becomes an important but not overwhelmingly critical aspect of project management.

The cost of rCF and raw materials emerges as a crucial sensitivity point in this analysis. A substantial decrease in these costs leads to a considerable boost in profitability, underlining the significance of effective cost management strategies for the project's success. Given the project's focus on recycling carbon fibre, efficient utilization of these materials is essential not only for environmental reasons but also for financial gain.

Furthermore, the sensitivity analysis highlights the importance of total CAPEX and production capacity in determining profitability. These findings emphasize that careful planning and cost control measures during the project's development and execution phases can have a substantial impact on its financial performance. Waste disposal and OPEX are less sensitive to the financial indicator PI.

Waste disposal has a moderate impact on PI. A −50% variation increases the PI to 2.78, while a 50% positive variation reduces it to 0.49. This suggests that while waste disposal costs are a factor, their influence is less significant than CAPEX or raw material costs. OPEX exhibits a steady trend, with PI improving as OPEX reduces. A −50% variation increases the PI to 2.21, while a 50% increase decreases it to 1.06. Operational efficiency is crucial for maintaining profitability, though the sensitivity is less pronounced compared to CAPEX or raw materials.

3.2.4. The Effect of the PBP. The sensitivity analysis conducted on the PBP sheds light on critical aspects that influence the project's financial return and investment

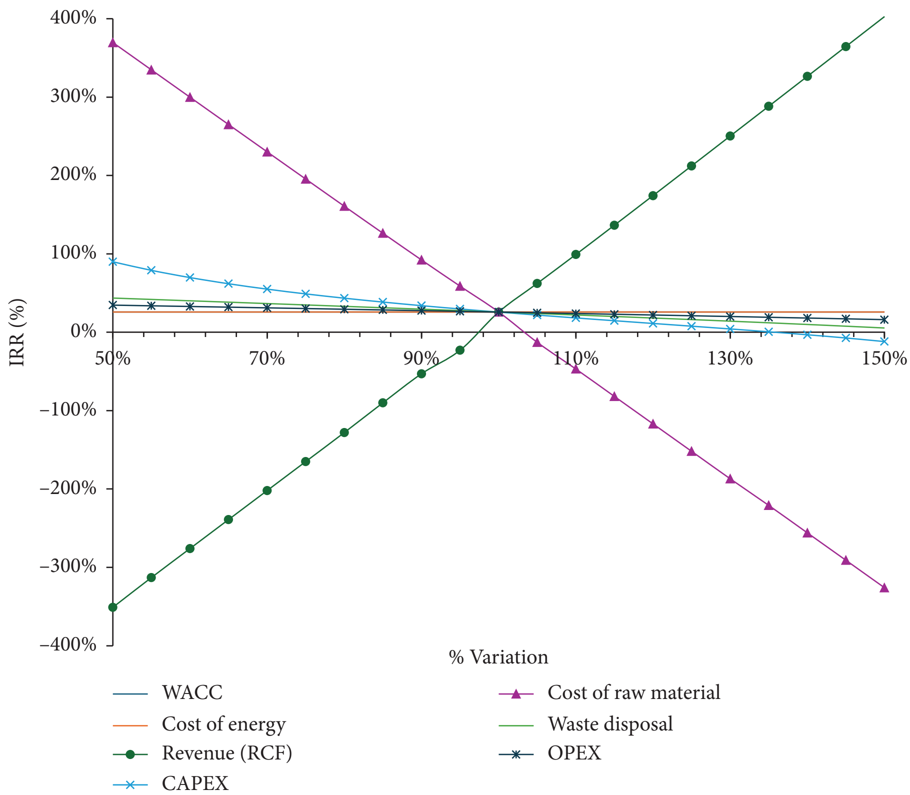

Figure 4: Sensitivity analysis of internal rate of return (IRR).

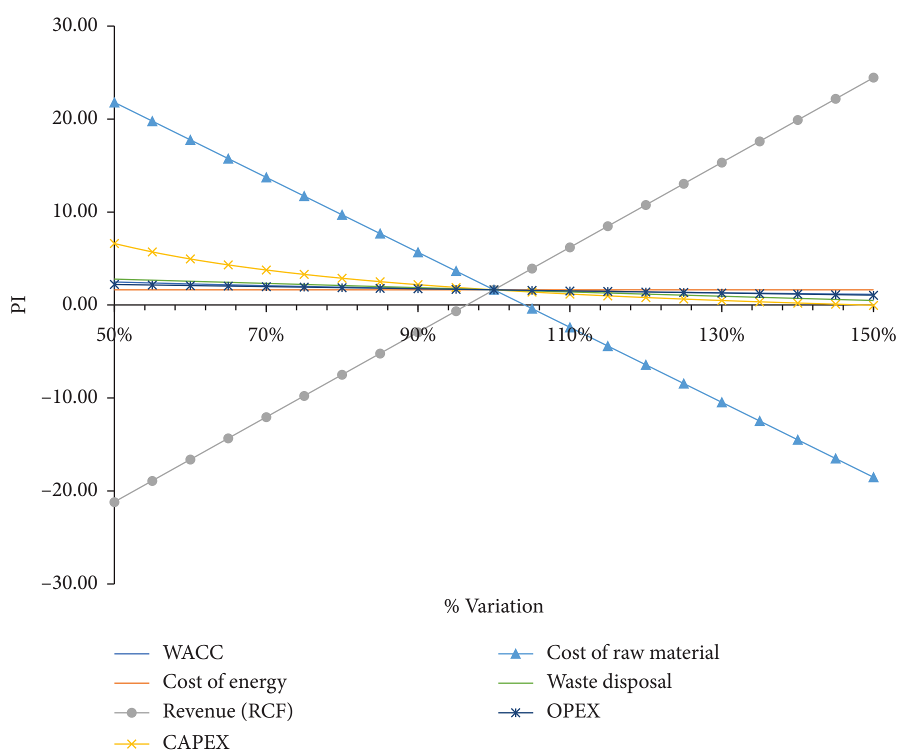

Figure 5: Sensitivity analysis of profitability index (PI).

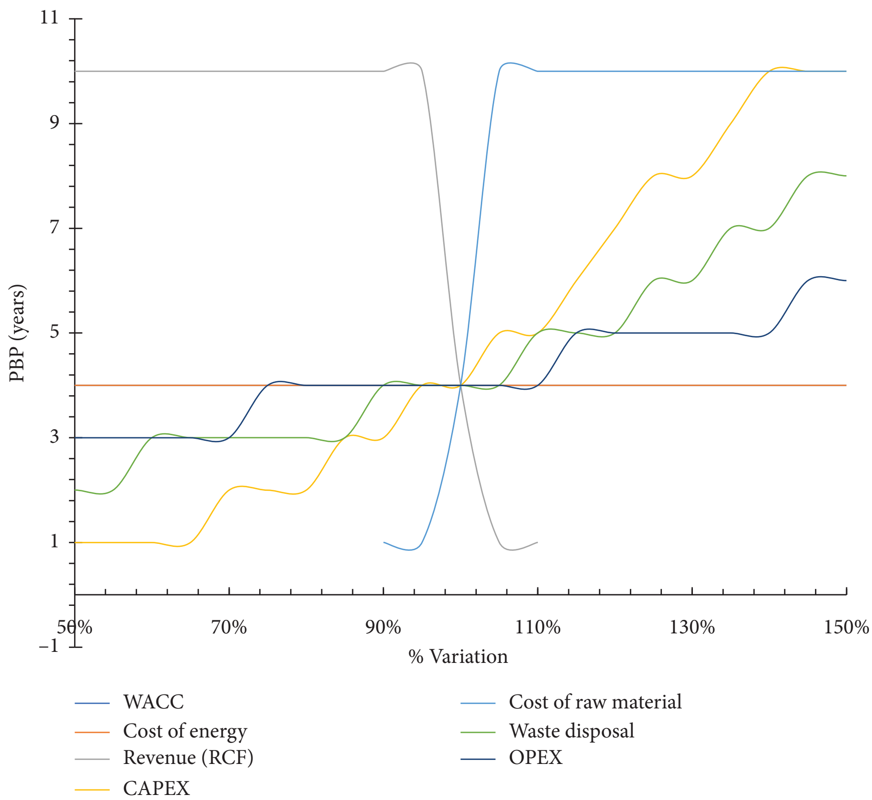

Figure 6: Sensitivity analysis of payback period (PBP).

recovery period. Figure 6 and Table S4 in the supporting information outline the sensitivity analysis with respect to the PBP.

First and foremost, the analysis shows that the discount rate and energy usage have a negligible impact on the PBP. Regardless of whether these parameters decrease or increase by 50%, the PBP remains consistent. This implies that variations in discount rates or energy efficiency do not significantly affect the time it takes to recover the initial investment in the RCF project. Therefore, the project appears to be relatively resilient to changes in these factors, providing a degree of stability in investment recovery.

In contrast, the cost of rCF and raw materials exerts a substantial influence on the PBP. When these costs decrease, the project achieves a much quicker payback, potentially indicating improved cost efficiency and profitability. Conversely, when these costs increase significantly, the PBP extends, suggesting that effective cost control measures and prudent procurement of materials are critical to ensuring a reasonable investment recovery timeline.

The total CAPEX and production capacity also play pivotal roles in determining the PBP. When CAPEX decreases, it contributes to a shorter PBP, reflecting the financial benefit of reducing initial project costs. Additionally, higher production capacity accelerates investment recovery, indicating that achieving optimal production levels is essential for timely returns on investment. Cost of energy does not change the PBP. This is expected as its costs are minimal values and do not affect the model over a period of time.

Reductions in OPEX shorten the PBP slightly (e.g., 3 years at −50%), reflecting moderate sensitivity. Positive variations have a more limited impact, with the PBP stabilizing at 5–6 years for increases of 25% or more. Waste disposal cost reductions improve the PBP, dropping to 2-3 years for reductions of 25% or more. Increases in waste disposal costs have a modest impact, with PBPs reaching 7-8 years for higher values.

3.3. Thermodynamics. Hydrogen peroxide process, requiring 1.62 kWh/ton, is significantly more energy-efficient than pyrolysis (694–972 kWh/ton) and solvolysis (1390–2780 kWh/ton). It operates under mild conditions, reducing energy demand as highlighted in Table 8.

The study computes the energy dynamics in CFRP decomposition by evaluating enthalpy changes (ΔH) for both the epoxy and hardener systems using thermodynamic principles. Enthalpy was modelled using specific heat capacities and polynomial equations, considering decomposition at 150°C. The required energy for the decomposition of CFRP components, C_3H_6 (epoxy) and $(CH_3)_2NH$ (hardener), totalled 311.53 kWh/day or 80,000 kWh/year. Stoichiometric modelling determined the H_2O_2 requirements at 55,360 m^3/year, costing $168.4M.

Table 8: Comparison table of CFRP recycling processes based on energy consumption.

Recycling process	Energy consumption	Operating conditions	Advantages	Disadvantages	References
Hydrogen peroxide (autoclave)	1.62 kWh/ton (311 kWh/day for 192 tons)	Mild conditions, typically below 200°C	Low thermal energy demand, chemical simplicity, reduced operational complexity	Requires chemical handling, cost of hydrogen peroxide	This study
Pyrolysis	2.5–3.5 MJ/kg (694–972 kWh/ton)	High temperature (500°C–1000°C), inert atmosphere	Effective for fibre recovery; no chemical waste	High energy demand; needs inert gas supply	[15, 74]
Microwave-assisted pyrolysis	1.6–2.2 MJ/kg (444–611 kWh/ton)	Rapid, localized heating; temperature ~700°C	Efficient heating with low energy loss	Equipment cost; limited industrial-scale adoption	[15, 74]
Solvolysis (supercritical fluids)	5–10 MJ/kg (1390–2780 kWh/ton)	250°C–400°C, high pressure (> 10 MPa)	High-quality fibre recovery; versatile solvent usage	Expensive equipment; high energy for pressure/heat	[15, 74]

4. Limitation of the Study

The investigation of this study solely explores hydrogen peroxide as a solvent, if other solvents used might impact the model, due to the stoichiometric behaviour. However, if another solvent is incorporated, relevant values of other coefficients of chemical solvents need to be incorporated in the model as well. Although sustainability is a central concern of this study, the environmental impact of the process itself, such as waste disposal, needs to be explored and validated in model.

5. Future Scope

The future scope of this research will include several promising opportunities for further investigation. First, optimizing the hydrogen peroxide recycling process through experimental validation and scale-up studies could enhance its practical application and efficiency. Additionally, exploring hybrid recycling methods that combine hydrogen peroxide with other sustainable technologies might offer improved results and broader applicability. Moreover, expanding the technoeconomic model to include lifecycle assessments and environmental impact evaluations could provide a more comprehensive view of the recycling process's sustainability.

6. Conclusion

The project focuses on rCF using hydrogen peroxide as a solvent to promote sustainability. Our main objective is to demonstrate the economic feasibility and viability of the rCF recovery process. We conducted a financial analysis using indicators such as NPV, PI and PBP to assess the project's financial viability. The NPV value of the project was approximately \$15M at a discounted rate (WACC) of 15%. The PI value of 1.9 indicates that the project's benefits outweigh its expenses. The discounted PBP was only 4 years. Additionally, the annual investor payback plan amounted to around \$2.97M per year over a 10-year period at a fixed annual interest rate of 14%. Considering the 5%–8% interest rate in USD would be beneficial from an economic standpoint. Even after deducting this amount from the cash flow, the project still demonstrated positive financial performance across all selected indicators. Lastly, the IRR is higher than the WACC, indicating a favourable financial outcome.

The sensitivity analyses have been valuable in identifying key factors that could affect the project's financial performance. The cost of rCF, the cost of raw materials (specifically hydrogen peroxide) and production capacity are crucial input variables that significantly impact the model. It is important to carefully validate cost constraints, optimize resource utilization and expand production capacity to improve the project's financial outcomes. The IRR is particularly sensitive to the cost of rCF, total CAPEX and cost of raw materials. Changes in energy usage have a relatively smaller impact on the IRR.

In conclusion, the rCF project has the potential to be a sustainable initiative, given its significant capacity and carbon fibre recycling capabilities. However, it faces financial challenges and uncertainties, especially regarding the impact of raw material costs, which closely correlate with revenue generation. Meeting the total capacity of 50,000 tons is crucial for maintaining positive financial performance. To ensure long-term success, effective financial management, continuous reassessment and adaptability are essential. As industries increasingly prioritize sustainable materials and practices, the rCF project is poised to play a significant role, provided it can effectively address its financial obstacles and capitalize on opportunities.

Recovering carbon fibre is crucial because, once its product lifespan ends, its widespread availability presents a valuable opportunity to address environmental issues through recycling. Prioritizing the recycling and reuse of carbon fibre can reduce environmental impact and open new avenues in polymer science, such as developing high-value rCF products that support a circular economy. These opportunities can be validated through technoeconomic analysis to assess process viability.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

The supporting information is structured according to the table arrangement outlined below:

Table S1: Summary of NPV subjected to negative and positive changes.

Table S2: Summary of IRR subjected to negative and positive changes.

Table S3: Summary of PI subjected to negative and positive changes.

Table S4: Summary of PBP sensitivity analysis.

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