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Techno-economic and life cycle assessment of lignin-based blended resin for 3D printing

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ABSTRACT

As CO_2 emissions reach record highs, finding renewable, low-cost, and low-carbon alternatives to fossil fuel-based products is critical. This study examines the techno-economic and life cycle assessment (TEA-LCA) of lignin-based blended resin for 3D printing, investigating lignin, a renewable and affordable resource, as an alternative to petroleum-derived resins. Kraft lignin was fractionated into a low molecular weight fraction and combined with commercial resin in a 9:1 ratio or 10 % by weight. TEA estimated the production cost of the resin at $38.43/kg with a minimum selling price of $38.85/kg for a 10 MT/batch plant. LCA results revealed a global warming impact of 6.64 kg CO_2 eq/kg of resin, with highest emissions coming from the commercial epoxy resin. Utilizing higher percentages of lignin instead of the commercial resin could substantially lower both production costs and environmental impacts, providing a more sustainable option for 3D printing.

1. Introduction

The global reliance on petroleum-derived products has contributed to record-high CO_2 emissions, which reached 35.9 billion metric tons in 2023, elevating atmospheric CO_2 concentrations to critical levels (IPCC, 2023; Liu et al., 2024). As the environmental impact of fossil-based industries becomes more evident, there is an urgent need to explore renewable, biobased alternatives that can reduce the carbon footprint of manufacturing processes and promote sustainability (Hurmekoski et al., 2022; Jakes et al., 2016; Steel et al., 2021). Among the most promising solutions is the utilization of biomass, particularly lignocellulosic materials such as lignin, to produce renewable polymers, resins, and fuels. (Mujtaba et al., 2023; P. Ahire et al., 2024; Ramirez Brenes et al., 2023; Schubert, 2020).

Additive manufacturing (AM), commonly known as 3D printing, has revolutionized modern manufacturing by enabling the layer-by-layer construction of complex geometries that are difficult to achieve with traditional methods (Vafadar et al., 2021; Zhou et al., 2024). 3D printing gives economic advantage of reduction in initial costs, as seen with the example of a $2000 desktop 3D printer, versus hundreds of thousands for injection molding setups and cuts per-unit expenses for small runs (<1000 units), such as custom phone cases, by eliminating costly molds (Faludi et al., 2015; "Formlabs," 2025; Huang et al., 2013). Environmentally, it reduces material waste by up to 90 % compared to CNC machining, halves energy use across the production cycle for instance, in producing lightweight aerospace parts and curbs CO_2 emissions by through localized on-demand printing (Hogan, 2023). Moreover, its flexibility enables rapid prototyping and customization, as demonstrated by Adidas' 3D-printed shoe soles, accelerating innovation cycles ("Materialise," 2025). Collectively, these benefits enhance resource efficiency and adaptability, positioning 3D printing as a sustainable, efficient alternative manufacturing landscape.

The development of AM has been a long process, its conceptualization dating back to the 1940s (Schittecatte et al., 2023). In 1986, Chuck Hull successfully commercialized his similar ultra-violet (UV) light-based process, introducing "stereolithography" (SLA), while Digital Light Processing (DLP) and Liquid Crystal Display (LCD) printing followed in the early 2000s (Su and Al'Aref, 2018). Currently, SLA, DLP, and LCD printing dominate the field of photopolymerization-based 3D printing (Quan et al., 2020). SLA is predominantly used in scientific research and high-resolution applications, while DLP and LCD are more common in consumer-grade systems (Weng et al., 2016). However, these technologies are largely dependent on petroleum-based resins, raising concerns about their environmental sustainability. The reliance

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on fossil-derived resins in AM not only contributes to global CO_2 emissions but also undermines the environmental benefits of this otherwise innovative manufacturing approach (Dobrzyńska et al., 2021). All three technologies rely on the photopolymerization of a liquid resin at the bottom of a fluid reservoir. Most resins are produced from acrylate species due to the ability of fast polymerization at ambient temperature. The formulation of these resins is crucial as it affects every step of the process from the printing parameters to the properties of the final object. To reduce use of fossil-based materials in resin synthesis, there is high interest in using compatible bio-based compounds in photopolymerization from renewable resources. The main benefits of bio-based materials are that they are easy to process, meet technological, functional, and durability needs, while also being more bio-compatible, easier to recycle, and potentially cheaper.

Lignin presents a compelling alternative. It commonly produced as a byproduct in pulp and paper mills, with over 70 million metric tons yearly from wood delignification for pulp and paper manufacturing (Li and Takkellapati, 2018). In addition, it is the second most abundant natural polymer on Earth, it accounts for approximately 30 % of organic carbon in the biosphere (Moretti et al., 2021). Kraft pulping is dominant process in delignification processes as Kraft lignin accounts for over 85 % of technical lignin generated globally (Ashokkumar et al., 2022; Schubert, 2020; Vásquez-Garay et al., 2021). Kraft lignin itself is a complex, three-dimensional polymer (Argyropoulos et al., 2023). Its renewable nature, along with its intrinsic properties such as high thermal stability, chemical resistance, and antioxidant capabilities, makes lignin an attractive candidate for replacing petroleum-derived resins in various applications (Li et al., 2021). Despite its abundance and intrinsic properties, lignin is underutilized, with the majority being burned as low-value fuel (Chauhan et al., 2022). Recent advancements in chemical processing, particularly the modification of lignin using have highlighted its potential as a sustainable feedstock for high-value applications, including 3D printing resins (Chmely et al., 2023; Jeong et al., 2024; Jiang et al., 2020; Zhang et al., 2024)

Efforts to develop lignin-based resins for photopolymerization processes like SLA have shown that lignin's UV absorption properties and mechanical reinforcement capabilities can enhance the performance of 3D-printed parts (Ebers et al., 2021; Sutton et al., 2021). However, challenges remain in optimizing lignin's integration into resins, particularly in improving its miscibility and ensuring mechanical performance comparable to petroleum-based counterparts. Recent research demonstrates that chemical modifications, such as modified directly by acylation with methacrylic anhydride enhance lignin's compatibility with photopolymers enabling higher lignin content in resins without compromising the quality of printed parts (Wan et al., 2023). The blending of modified kraft lignin in epoxy resin can show improved degradation potential in resultant resin, addressing disposal challenges for wind turbine blade (Celiktas et al., 2019).

Given the potential of new sustainable resins to reduce the environmental impact of 3D printing, it is critical to evaluate their economic viability and sustainability through techno-economic analysis (TEA) and life cycle assessment (LCA). TEA provides insights into the costs associated with producing lignin-integrated resins, including raw material price, processing expenses, and scalability, while LCA assesses the life-cycle environmental impacts, such as greenhouse gas emissions, energy use, and waste generation throughout the resin's life cycle (Dysert et al., 2016; "ISO 14040:2006,"). Together, these assessments provide a comprehensive understanding of both the economic and environmental implications of integrating lignin-based resins into industrial 3D printing applications.

This study aims to conduct a TEA and LCA of lignin-incorporated resins for 3D printing, focusing on their economic feasibility and environmental impact to replace petroleum-derived resins in SLA and DLP technologies. By analyzing the costs and environmental impacts of producing lignin-incorporated resins, we seek to determine their feasibility for large-scale industrial production and use. Additionally, we will explore the effect of change in the lignin quantity in resin formulation in potential global warming (GW) impacts. The findings from this study will provide valuable insights into the viability of lignin-based resins as sustainable alternatives in additive manufacturing, contributing to the broader goal of acting as climate change mitigation strategy by reducing the environmental impact of the 3D printing industry.

2. Method

In this study, kraft lignin fractionation is carried out followed by lignin modification. After lignin is modified with methacrylic anhydride, blending of modified lignin with commercial resin results in sustainable resin. This process followed the methodology outlined in the research conducted by Chmely et al. (Chmely et al., 2023). A detailed process model for making bio-based resin for 3D printing was created and simulated using SuperPro Designer v12 software ("Intelligen, Inc.,"; 2023) to gather material and energy balance data for TEA and LCA with modification for scale up of process. Table S1 and Fig S2 present the price per unit of different materials and process flow diagram used for the preparation of resin derived from commercial resin and modified kraft lignin, modeled in SuperPro Designer. The study adopted for North America used a utilization rate of 330 working days per year, which mirrors the operational pattern of real-world industrial processing, operating 24 h per day. Mass and energy balances, process flow compositions, and equipment configurations were carried out considering 10 MT(Metric Ton)/batch production capacity for the lignin-based resin. The LCA analysis was conducted using SimaPro 9.4 software ("PRé Sustainability," 2024), with data sourced from the US EI and USLCI databases ("DATASMART," 2024).

2.1. Process description

The following section outlined the process used for depolymerization of kraft lignin, and synthesis of resin.

2.1.1. Fractionation of kraft lignin into low and high molecular weight lignin

In this study, the fractionation of kraft lignin was performed to separate the material into low molecular weight (low-MW) and high molecular weight (high-MW) fractions. The fractionation process employed acetone as the solvent, which effectively separates the lignin into soluble low-MW fractions and insoluble high-MW fractions (Argyropoulos et al., 2023). A 10 % (w/v) suspension of kraft lignin in acetone was prepared, and the mixture was stirred for 1 h at room temperature. The mixture was then centrifuged at 5000 rpm for 15 min to separate the soluble low-MW lignin (80 %) from the insoluble high-MW fraction. The high-MW lignin fraction (20 %) was dried for 6 h in a spray dryer. The optimized solvent recovery rate for acetone was 99 %, making the process both cost-effective and environmentally sustainable.

The low-MW lignin was recovered by evaporating the acetone under reduced pressure, followed by treating sulfuric acid for removal of impurities. The mixture was further cleaned through a Plate and frame filtration followed by washing in centrifuge operation. The low-MW lignin, which is more soluble in organic solvents, was then used for chemical modification through methacrylic anhydride, while the high-MW lignin left the system.

This fractionation process allowed for the utilization of lignin fractions with specific molecular weight distributions, which is essential for tailoring the properties of lignin-based materials for applications such as 3D printing resins. The low-MW fraction demonstrated enhanced solubility and processability, making it ideal for blending with photopolymer resins. For the lignin modification step, at 90°C for one hour, methacrylic anhydride was used in equal ratio of hydroxyl group (OH-) present in low molecular weight lignin (For 8.2 mol of OH- in 1 kg of lignin, 8.2 mol of methacrylic anhydride was used) in presence of 4-

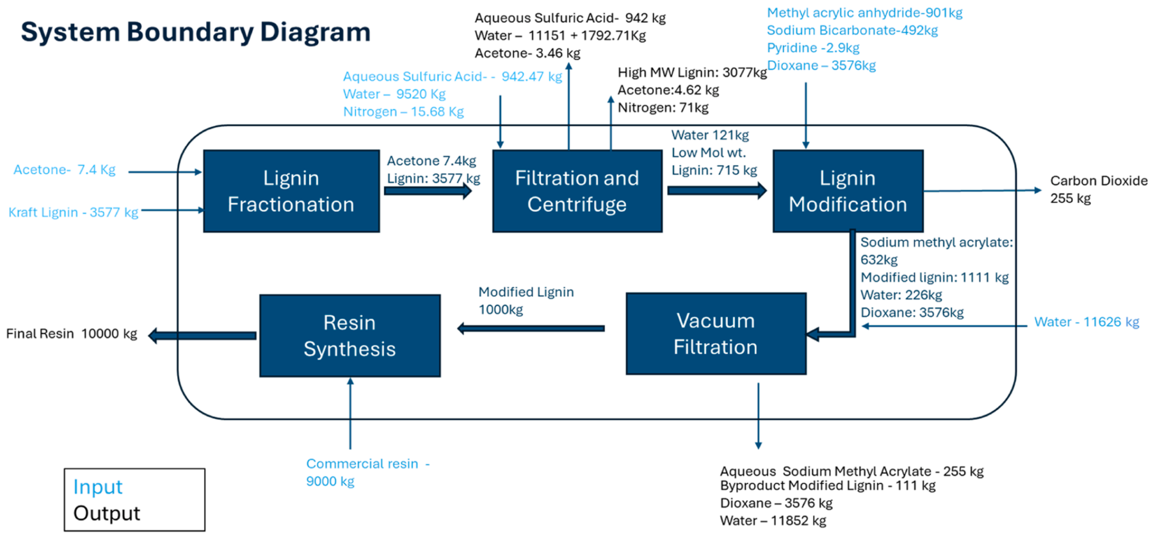


Fig. 1. System boundary for cradle-to-gate production of lignin-based resin, 10,000 kg.

(dimethylamino) pyridine (DMAP) as catalyst in dioxane as a solvent (five time more by wt% than low molecular weight lignin). In this system, the esterification of lignin's –OH by methacrylic anhydride occurs (Eq:1) in tandem with the neutralization of the acid-byproduct by sodium bicarbonate (Eq:2). For each reactive –OH on the lignin (abbreviated as L–OH), the two steps can be written as follows:

$$CH_2{=}C(CH_3)–COOH + NaHCO_3 \rightarrow CH_2{=}C(CH_3)–COO^- Na^+ + CO_2 + H_2O \quad (1)$$

$$L–OH + CH_2{=}C(CH_3)–COOCO–C(CH_3){=}CH_2 + NaHCO_3 \rightarrow L–OCOC(CH_3){=}CH_2 + CH_2{=}C(CH_3)–COO^- Na^+ + CO_2 + H_2O \quad (2)$$

The reaction was optimized so that ~100 % of the lignin hydroxyl groups were converted into methacrylate functionalities. This reaction scheme explains how the methacrylation improves the resin compatibility of lignin (by introducing polymerizable double bonds) and shows how side-products are reacted through in situ neutralization. After the reaction was completed, reaction mixture quenched with saturated aqueous sodium bicarbonate. In this step, the main product of modified low-MW kraft lignin and byproducts such as sodium methacrylate, CO_2 and water were formed. After cooling reaction, CO_2 was vented out and aqueous sodium methacrylate and THF were separated in rotary vacuum filter operation.

2.1.2. *Resin synthesis*

For the resin formulation, the modified low-MW kraft lignin was blended with a commercially available UV-curable photopolymer resin in varying concentrations (5 %, 10 %, 20 % and 30 % w/w). The blending process was carried out in a planetary mixer at 2000 rpm for 30 min to ensure homogeneity and uniform dispersion of lignin within the resin matrix. This blending process was carried out with complete conversion of commercial resin with modified lignin to resultant sustainable resin During this process, lignin's role as a photo initiator was noted, as it contributed to the curing properties of the resin by aiding the photopolymerization process, as reported in previous studies (Sutton et al., 2021). The process was operated in batch mode, with 1320 batches processed annually and each batch maintained for a 6-h residence time.

2.2. *Economic analysis*

This study performed a TEA using the American Association of Cost Engineers (AACE) methodology, with an estimated accuracy range of ± 30 % (Dysert et al., 2016). The proposed structural resin production plant was modeled to be in North America, with a total annual labor requirement of 22,587 h with 13,201 MT annual resin production capacity. This labor was distributed among 11 operators working onsite for 330 operational days per year, with hourly wage rates of $34.50/hr for operators. The purchased equipment was assumed to have no salvage value at the end of its useful life (Turton et al., 2008). The project was modeled over a 25-year operational lifetime, with a construction period of 12 months and a startup phase lasting 2 months.

SuperPro Designer v12 software was utilized to estimate the equipment purchase costs, while other economic assumptions were based on traditional plant design and economics for chemical engineering projects (Kobe, 1958). The minimum and maximum price for chemicals is gathered across the commercial sellers, and an average price was calculated (Table S1). The total capital cost investment (C(TC)) was determined by adding the direct fixed capital cost (CDF), working capital (CW), and startup costs (CS), as shown in Eq. (1):

$$C(TC) = C(DF) + C(W) + C(S) \quad (3)$$

Using Eq. (2), the annual operating costs (C(AO)) for the plant were broken down into utility cost (C(U)), materials cost (C(M)), facilities cost (C(F)), and labor cost (C(L)), with all underlying economic assumptions derived from the SuperPro Designer database:

$$C(AO) = C(U) + C(M) + C(F) + C(L) \quad (4)$$

2.2.1. *Scenario analysis*

The economic factors influence on profitability were assessed using an analysis focused on cost related to capital investment, modified low-MW kraft lignin's percentage contribution in resin, and scale of plant size for different scenario and sensitivity analyses were conducted. The base-case scenario considered a plant scale of 10 MT/batch, and different scenarios considered: 1. Comparing the use of different scales of plant. 2. Comparison of lignin percentage in the resin formulation. and 3. Comparison of resin unit production price with industrial resin.

For the sensitivity analysis, parameters such as materials cost and labor cost were selected based on their potential impact on product value. This enabled a comprehensive evaluation of how these factors could influence the profitability of the resin for 3D printing production process. The schematic presentation of material flows within the process and system boundary is shown in Fig. 1. Inventory data of kraft lignin was collected from literature with mass allocation approach used because of multiple products produced (Culbertson et al., 2016; ISO

Table 1
Economic analysis results for five commercial-scale production of resin, cradle-to-gate.

Scale (MT/ batch)	Total capital investment (Million $)	Annual operating cost ($)	Unit Production Cost ($/kg)	Minimum Selling Price ($/kg)
2	22.80	104.22	39.47	39.96
4	34.60	205.12	38.84	39.29
10	67.86	507.31	38.43	38.85
20	121.10	1010.47	38.27	38.68
30	173.42	1513.42	38.21	38.63

2006b).

2.3. Life cycle assessment

2.3.1. Goal and scope definition

The goal of the present study was to quantify the life-cycle environmental impact of resin production from lignin and commercial epoxy resin for 3D printing.

2.3.2. Functional unit

According to the ISO 14040 standard, the functional unit (FU) provides a reference point for environmental inputs and outputs flowing across the system boundary. In the present study, 1 kg of resin production was selected as the FU ("ISO 14040:2006").

2.3.3. System boundary

In this study, a cradle-to-gate LCA was conducted to evaluate the life-cycle environmental impacts associated with the production of resin for 3D printing. The system boundary included all upstream and onsite processes, capturing inputs such as electricity, chemicals, and water, and outputs like resin, used solvents, and water. These system boundaries were defined to encompass the key stages of production from raw material extraction to the final resin output, excluding downstream activities like product use and disposal (Fig. 1). The system boundary for the LCA was carefully delineated to ensure the inclusion of all relevant processes contributing to the overall environmental footprint. This approach allowed for a focused comparison of the environmental impacts of the production phase alone, which is crucial for determining the sustainability of resin manufacturing in the context of 3D printing. The tool for reduction and assessment of chemicals and other environmental impacts (TRACI) impact category method with US 2008 normalization was used to estimate the life-cycle environmental impacts (Bare, 2012). The impact categories were ozone depletion (kg chlorofluorocarbons-11eq), global warming (kg CO_2 eq), smog (kg O_3 eq), acidification (kg SO_2 eq), eutrophication (kg N eq), carcinogens (CTUh), non-carcinogens (CTUh), respiratory effects (kg PM2.5 eq), ecotoxicity (CTUe), and fossil fuel depletion (MJ surplus). In experimental process and process modelling, methacrylic anhydride was used, but methyl acrylate was a substitute material for LCA analysis due to unavailability of original compound in LCA database. The selection of methyl acrylate was based on both molecules that are reactive ester monomers used for monomer synthesis. In the LCA database it provides the closest possible approximation to methacrylic anhydride.

The system boundary assumes that the kraft lignin was produced using a chlorine-free bleaching process from southern pine at a mill located in the southern United States ("N.C.," 2023). The life cycle inventory (LCI) for kraft lignin included all processes required for its production via the bleached kraft process. By structuring the system boundaries in this manner, the study provided a clear framework for quantifying the environmental performance of the resin production process, ensuring that key contributors to environmental impacts were captured and assessed comprehensively.

3. Results and discussion

3.1. Techno-economic analysis

The material balance for optimized process model use in techno-economic analysis is shown in Fig. 1. The power required in optimized process for resin was 0.003 kWh per kg at $0.078/kW-h with maximum consumption (~40 %) in centrifuge operation.

The economic analysis for various production scales (Table 1) at

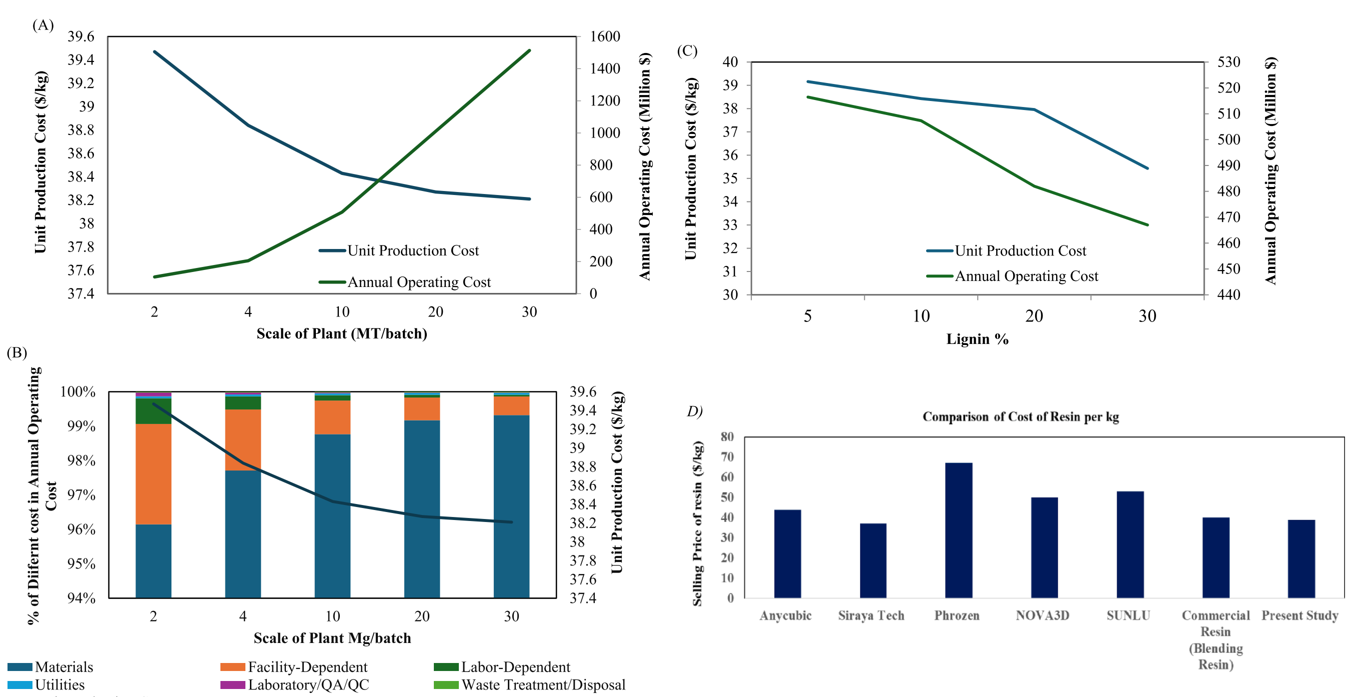


Fig. 2. The change in the unit production costs for a blended resin for 3D printing for the following scenarios: A) Different plant scales, B) Different costs in annual operating cost for different plant scales, C) Different lignin usage (%), and D) Different cost of commercial resin.

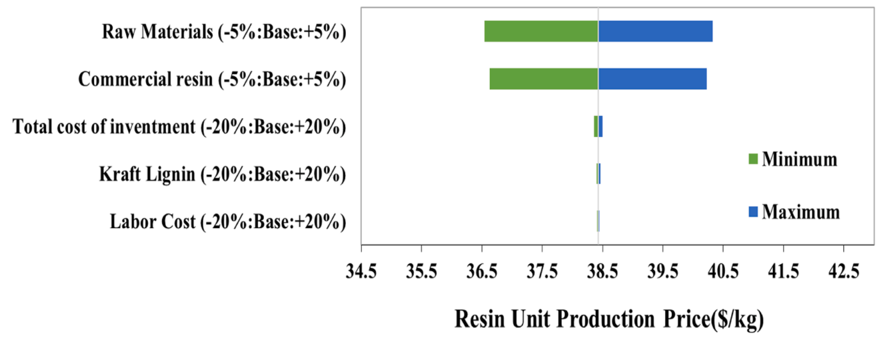


Fig. 3. Unit production cost effect on different parameters for resin production plant, 10 MT/batch.

constant blending ratio of 9:1 (commercial resin: low-MW modified kraft lignin) reveals that total capital investment ranges from $22.80 million for a 2 MT/batch facility to $173.42 million for a 30 MT/batch facility, with direct fixed costs as the predominant contribution. We simulated 1320 batches annually with 6 hr resident time with total operating hours of 7920. As the batch size increased, equipment size and materials requirement increased with constant batch duration and effect unit production price (Fig. 2A). Annual operating expenses rose significantly, from $101 million for the smallest facility to $1527 million for the largest, with material costs representing nearly 99 % of the total. The change in lignin usage affects unit production price (Fig. 2B). Facility-dependent costs contributed little, around 3 % and 1 % for smaller and larger facilities, respectively (Fig. 2C). These findings highlight material usage as the primary cost contributor in resin production. Notably, minimum selling price (MSP) declined from $39.96/kg at 2 MT/batch to $38.63/kg at 30 MT/batch as facility scale increased, assuming a 10 % internal rate of return for MSP estimation.

In the transition from laboratory-scale operations to a 10 MT pilot-scale process, the durations for lignin fractionation, drying, and lignin modification were systematically varied to evaluate their impact on the minimum selling price (MSP) of the resin. The results, presented in Fig. S3 and Fig. S4, indicate that the drying duration must be limited to less than ~24 h while maintaining other reaction parameters at baseline conditions to ensure the product's resin's MSP remains below the commercial benchmark of $40/kg. A similar analysis for lignin modification suggests that a duration of 22 h is maximum to achieve a competitive MSP, aligning with commercial resin pricing.

The commercial epoxy resin, which is blended with lignin to create the base resin, contributes the most to the annual operating costs. This is because it serves as a primary feedstock in the production of sustainable resin (Fig. 2C). Fractionation of kraft lignin process required low-cost material and small amounts of low-MW lignin required in the blending process. Utility costs were relatively small compared to materials costs because the sustainable lignin-based resin production process does not require high temperature or pressure. The MSP of resultant blended resin of $38.85/kg from ratio of modified kraft lignin and commercial resin is 1:9 was less than commercial resin of $40/kg. The cost of conventional industrial resin for 3D printing is between $30/kg and $70 /kg (Fig. 3) ("ANYCUBIC," 2024; "NOVA3D," 2024; "Phrozen," 2024; "SainSmart," 2024; "Siraya Tech," 2024; "SUNLU," 2024). In comparison to that, MSP of lignin-incorporated resin in this study was $38.85/kg for scale of 10MT/batch at 10 % internal rate of return.

3.1.1. Scenario analysis results

In Fig. 2, this study found the impact of uncertainty on annual operating cost from different scale of plant (A), different percentage of lignin usage (B), change in contribution of material cost for different plant scale (C).

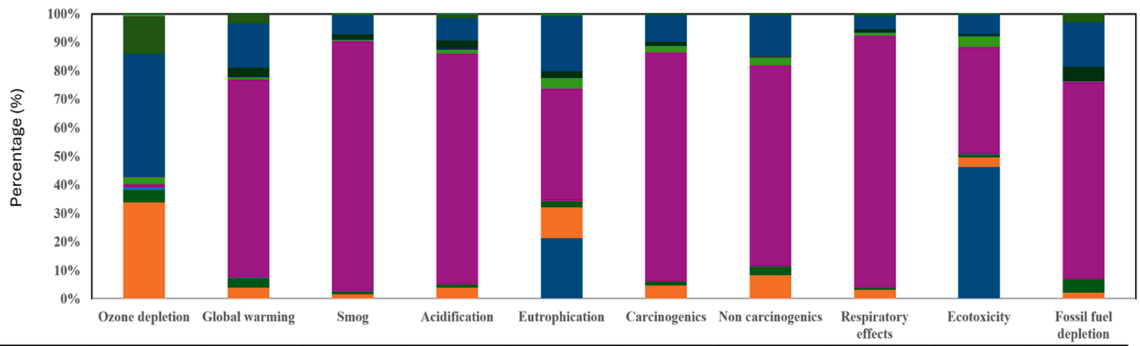
Fig. 2A detail the variations in unit production costs across four different plant scales, demonstrating that increasing the plant size from 2 MT to 30 MT led to substantially higher capital and operational expenses but with a relatively small reduction in unit costs. Specifically, scaling from 2 MT/batch to 10 MT/batch decreased unit production costs by approximately $1/kg, driven largely by economies of scale in facility dependent cost for equipment and infrastructure utilization. At the 10 MT/batch level, the annual operating cost reached $507 million, while the unit production cost stood at $38.43/kg. At 20 MT/batch, the unit production cost only marginally decreased by $0.16/kg to $38.27/kg, with an associated operating expense of $1.010 billion. Similarly, at the 30 MT/batch level, the unit production cost per kilogram reduces further to $38.21/kg, but this slight reduction required a significantly larger operating budget of $1.513 billion annually. Beyond the 10 MT scale, however, further increases in capacity to 20 MT and 30 MT provided little impact on unit cost reductions due to proportional increases in material requirements, which remain the dominant expense. Fig. 2B illustrates that, while absolute capital investment escalates from $22.8 million (2 MT/batch) to $173.42 million (30 MT/batch), raw material costs dominate expenses at all scales—surpassing 95–99 % of annual operating outlays. This imbalance causes the relative share of utilities, labor, and facility-dependent expenses to shrink even as capacity grows, resulting in only modest per-unit savings (about $1–$2/kg) despite substantial capital expenditures. Consequently, although scale-up does lower the minimum selling price from $39.96/kg at 2 MT/batch to $38.63/kg at 30 MT/batch—raw material usage remains the primary cost driver, reducing the direct impact of capital investment on final resin price.

Table 2
Molecular weight distributions of fractionated lignin from different solvents.

	Mn	*Mw*	*D*	Ref
Present Study-Acetone	1959	2135	1.09	
EtOH	1173	2100	1.8	(Jiang et al., 2020)
MeOH	1480	2961	2	
Methyl Ethyl Ketone	1192	2174	1.8	

M_n: Number Average Molecular Weight, M_w: Weight Average Molecular Weight

In an extended scenario analysis (Fig. 2C), adjusting the proportion of modified kraft lignin in the resin synthesis notably impacted production costs. When the modified lignin content was increased incrementally from 5 % to 30 %, the unit production costs decreased from $39.16/kg to $35.43/kg. These values indicated that a higher proportion of lignin substitution not only helped lower material expenses but also directly affected the resin's molecular weight distribution shown in Table 2. Specifically, as the lignin percentage increased, there is a cost-saving potential due to the lower price of Kraft lignin compared to traditional feedstock materials. Currently, increasing lignin content more than 10 % showed changes in properties involve inconsistent curing, poor dispersion, increase viscosity (Zhang et al., 2021). The new development in lignin modification technique of lignin, use of different lignin-derived polymers and nano-dispersion technique have potential to increase lignin content in resin. These analysis suggests that increasing lignin content could make resin production more



	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Total	8.67467E-08	6.6473812	0.681906	0.037388	0.005528	3.24E-07	1.04E-06	0.00517197	46.64427	16.636699
■ Resin	0	0	0	0	0.001183	0	0	0	21.61624	0
■ Kraft Lignin	2.94559E-08	0.2658198	0.01166	0.001492	0.000596	1.52E-08	8.66E-08	0.00016976	1.51531	0.3670737
■ Methyl acrylate	3.71462E-09	0.2264535	0.007082	0.000434	0.000117	4.96E-09	3.16E-08	3.4872E-05	0.500385	0.7966279
■ Pyridine-compounds	7.13113E-10	0.0024634	0.000113	9.33E-06	4.8E-06	1.28E-10	8.94E-10	7.2666E-07	0.038856	0.0047026
■ Epoxy resin	1.12816E-09	4.6280725	0.598068	0.03028	0.00218	2.61E-07	7.33E-07	0.00457065	17.59537	11.49732
■ Sodium bicarbonate	2.00279E-09	0.0463028	0.003343	0.000483	0.000201	6.94E-09	2.67E-08	5.5501E-05	1.699291	0.0271733
■ Sulfuric acid	2.93994E-11	0.0266859	0.002026	0.000284	7.86E-06	2.37E-10	3.55E-09	3.107E-06	0.180466	0.0257869
■ Water(Process)	3.29219E-11	0.0007141	3.11E-05	2.76E-06	1.3E-06	7.88E-11	2.04E-10	2.5013E-07	0.004233	0.0008477
■ Acetone	6.4227E-11	0.1994055	0.010226	0.000909	0.000119	4.28E-09	2.84E-09	5.9016E-05	0.23756	0.8344088
■ Dioxane	3.74315E-08	1.0262675	0.045055	0.002951	0.001067	3.01E-08	1.46E-07	0.00022823	3.107645	2.5933046
■ Nitrogen	2.37877E-11	0.0005835	2.07E-05	2.29E-06	1.16E-06	2.13E-11	7.72E-11	1.4453E-07	0.00174	0.0007561
■ Steam	1.1515E-08	0.2120987	0.003881	0.000493	2E-05	1.29E-09	4.18E-09	4.6822E-05	0.10706	0.4708326
■ Well water(Cooling)	6.31991E-12	0.0001456	6.55E-06	7.68E-07	4.46E-07	7.41E-12	2.52E-11	4.5224E-08	0.000607	9.461E-05
■ Electricity mix eGRIS 2022/US US-EI U	1.08047E-10	0.0015555	6.39E-05	9.71E-06	2.29E-06	4.4E-11	1.62E-10	6.4824E-07	0.003617	0.0025433
■ Heating water, domestic/US	5.20992E-10	0.0108129	0.000331	3.6E-05	2.66E-05	4.32E-10	2.02E-09	2.1989E-06	0.035887	0.015227

Fig. 4. Life cycle assessment contributions for cradle-to-gate production of 1 kg of blended resin for 3D printing (average of 30 batches).

economically viable at larger scales while simultaneously enhancing the material's sustainability properties by incorporating more renewable components (Argyropoulos et al., 2023; Demuner et al., 2019; Poveda-Giraldo et al., 2021).

As indicated in Table 2, the fractionation of kraft lignin using acetone yields a lignin fraction with a lower weight-averaged MW and reduced dispersion (D). The use of acetone is beneficial, as a lignin fraction with a lower MW generally exhibits enhanced solubility in organic solvents, attributable to decreased branching and reduced chain entanglement (Sameni et al., 2017). This characteristic is anticipated to improve the dispersion of modified lignin in photoactive, hydrophobic resins for 3D printing. In different analysis, we observe that, production cost of resin is \$36.05/kg when we used direct kraft lignin without modification. Comparative scenario analyses further demonstrate that lignin fractionated to low molecular weights using different solvents results in a broader molecular weight distribution, which influences resin properties. If these altered properties remain within the acceptable range for targeted applications, it is projected that the resin price will be around ~ \$36.1/kg. This scenario analysis underscores that the flexibility in using different solvents for lower molecular weight lignin has a substantial effect on the minimum selling price.

3.1.2. Sensitivity analysis results

The sensitivity analysis provides critical insight into how variations in key parameters affect the unit production cost, highlighting which factors exert the most significant influence on the overall process economics. A ± 5 % variation in raw material costs including commercial resin results in a change from a minimum of \$36.54/kg to a maximum of \$40.32/kg. This range, nearly a \$3.78/kg difference, underscores the sensitivity of production cost to fluctuations in material pricing. Similarly, when only commercial resin prices are varied by ± 5 %, the unit production cost shifts from \$36.63/kg to \$40.23/kg. This close correlation not only confirms that commercial resin is a major component within the raw materials category but also emphasizes its role as a primary cost driver. A wider variation in total cost of investment (TCI) of ± 20 % shows a narrow production cost range of \$38.36/kg to \$38.50/kg, indicating minimal sensitivity. Similarly, adjustments in kraft lignin costs by ± 20 % led to minimal shifts in unit production costs, decreasing to \$38.4/kg with a 20 % reduction in lignin cost and increasing to \$38.46/kg with a 20 % increase. Labor cost changes also exhibit minor impacts, with a 20 % increase in labor costs resulting in a maximum unit production cost of \$38.45/kg, whereas a 20 % reduction in labor expense brings the unit production cost down marginally to \$38.41/kg. In comparison, the sensitivity analysis shows that other factors such as total cost of investment, Kraft lignin, and labor cost have a comparatively limited effect on the unit production cost. This limited effect suggests that capital investment fluctuations have relatively less impact on the cost structure, likely due to capital cost spreading over the facility's lifespan. A production capacity of 10 MT/batch, yielding a unit cost of \$38.43/kg and MSP of \$38.85/kg, was chosen as the base line for further scenario analysis and associated LCA (see below).

3.2. Life cycle assessment for resin production

The cradle-to-gate LCA of blended resin production process was estimated using Simapro software by adopting the methodology mentioned in Section 2. A LCA of resin includes lignin fractionation to produce low-MW lignin to analyze the environmental impacts across the entire process. From kraft lignin fractionation, and resin formulation, focusing on key areas like energy consumption, greenhouse gas emissions, water usage, and potential waste generation at each stage, with significant impacts likely stemming from the chosen blending commercial resin, fractionation method, solvent usage, and energy requirements for the fractionation process to achieve low-MW lignin. So, apportioning all the impact of the production process to resin and no impact to the high molecular weight lignin is inappropriate. We applied mass allocation for resin and high molecular weight lignin of 76.46 % and 23.54 % respectively (Table S2).

Life cycle assessment (LCA) of resin production using different solvent uses in lignin modification is essential for adaptation of production method of resin at commercial production but not explored well (Moretti et al., 2021). We conducted various scenario analyses for evaluating the sustainable production of resin, referencing methodologies utilized in previous studies (Ahire et al., 2024). In this study, different percentages of lignin after modification for blending with commercial resin were also evaluated (Table S4).

When conducting an LCA on a highly efficient solvent recycling system with a closed-loop process, we allocated the environmental impacts associated with solvent production solely to the initial production stage, i.e. when the solvent first entered the system, and then only accounted for the energy consumption and minor losses incurred during subsequent recycling cycles within the closed loop (front-loaded). The nitrogen used for drying was small in quantity and showed little impact on contribution to GW impact.

We used a base case of 10MT/batch of blended resin, since acetone solvent remained within the system and was continuously recycled. Thus, the environmental burden of producing the solvent was largest at the initial stage, while accounting for make-up acetone in each recycling cycle. Due to use and recycling of solvent in each batch process, the chemical properties of solvent change. This affects and limit the quantity of the solvent that may be recycled. We consider that acetone present in the system for recirculation was used for 30 cycles or batches. The amount of solvent recycled in each batch was 31,442 kg per batch. In scenario of 10 % lignin blended (Table S4), where we included all solvent usage including recycle for first batch process, the GW impact of resin for first batch was 12.39 kg CO_2 eq (Table S4, Lignin % Batch: 10 % 1) and for other 29 batches were 6.44 kg CO_2 eq (Table S4, Lignin % Batch: 10 %29). These led to an average GW impact of 6.64 kg CO_2 eq/kg. This GW impact is slightly lower than a commercial epoxy resin of 6.72 kg CO_2 eq/kg resin (Table S1). The use of methyl acrylate contributed 3.51 % to GW impact, this minimal effect suggests the substitution is reasonable.

Table S2 summarizes materials and energy inputs require per kg of blended resin in the process of producing at an industrial 10 MT/batch scale. Water constituted the largest input (2.65 kg) going into the production of resin, followed by commercial resin (0.9 kg). Similarly, the process consumed 0.003 kWh of electricity and 1.06 kg of steam power in producing 1 kg of resin. The solvent usage and modified low-MW lignin remained in waste flow was considered in the chemical waste and organic waste category, respectively. The aqueous sodium methyl acrylate was considered as hazardous waste in waste flows. For water uses after batch, it is considered that it will be recycled.

Fig. 4 shows the total emissions in terms of climate change and fossil depletion are 6.6 kg CO_2 eq. and 16.6 MJ per kg of blended resin production. In contribution of different factors, epoxy resin contributed the maximum (71.8 %), followed by dioxane as solvent (15.9 %), and then use of kraft lignin (4.12 %). The commercial epoxy resin remains the largest contributor to the overall environmental burden, accounting for approximately 71–72 % of both GW and fossil fuel depletion impacts. This is primarily due to the energy-intensive nature of producing fossil-derived epoxy resins, which rely on non-renewable feedstocks. Even though lignin partially substitutes for epoxy resin, the fossil-based fraction continues to dominate the GW impact at 6.64 kg CO_2 eq/kg—only marginally lower than the 6.72 kg CO_2 eq/kg for conventional resin. This finding indicates that further reductions in environmental impacts will require not only increasing the lignin content but also rethinking or further optimizing the fossil-based resin component. Dioxane contributes about 15.9 % to GWP and similarly affects fossil fuel depletion, ozone depletion, and eutrophication categories. Although solvent recovery systems help mitigate its impact, the residual environmental burden underscores the need for improved recovery efficiency or the identification of alternative solvents with lower environmental impacts. Exploring bio-based or less toxic solvents may further reduce the overall environmental footprint. Kraft lignin contributes a relatively small share (around 4.12 % to GW), which highlights the inherent environmental advantage of incorporating renewable, bio-based material. However, the processing steps required to fractionate and chemically modify the lignin introduce additional energy consumption and ancillary impacts. These additional inputs, while minor compared to fossil-based components, become more significant when scaling up the process or further increasing lignin content. Thus, optimizing the fractionation and modification processes is essential to fully capitalize on the benefits of lignin without incurring substantial extra environmental costs.

Methylene diphenyl diisocyanate (MDI) play an important role in creating polyurethane materials used in some 3D printing applications, has GW impact of 6.92 kg CO_2eq /kg (US-EI 2.2). Unsaturated polyester resins are used in composite 3D printing, particularly when combined with fiber reinforcements. It has GW impact of 7.6 kg CO_2 eq/kg (Chard et al., 2019).

A similar trend was also followed in terms of fossil fuel depletion where epoxy resin contributed the maximum (72.7 %) followed by dioxane solvent usage (16.4 %). The third most contribution for fossil fuel depletion was use of methyl acrylate (5 %). Upon further analysis, it was observed that the major contributor in terms of climate change (61 %) and fossil depletion (74 %) was epoxy resin. In the ozone depletion impact category, highest contribution was dioxane (43.2 %) followed by kraft lignin (34.2 %). The negative impact of usage of solvents in the resin synthesis process was obvious, especially due to the negative contribution of dioxane in the eutrophication (19.7 %) and non-carcinogenic (14.1 %) categories. The impact from contribution of epoxy resin decreased as percent of modified kraft lignin in final resin. In this scenario, the amount of dioxane solvent used for kraft lignin modification increases, resulting in a smaller reduction in the negative impact from epoxy resin use. This observation shows that further research is needed to lower usage of dioxane solvent through process optimization and exploration of alternative solvent with less environmental burdens (Libretti et al., 2024). We evaluated the use of alternative safe solvent to dioxane with tetrahydrofuran in life cycle assessment, the GW impact of resin was increased to 7.39 kg CO_2 eq/kg due to higher GW impact of tetrahydrofuran (6.48 kgCO_2 eq/kg) than dioxane (3.75 kgCO_2 eq/kg).

In the present LCA analysis, commercial epoxy resin consistently emerged as the primary contributor to GW impact, principally due to its fossil-based feedstocks and energy-intensive production route. This impact persisted even when lignin partially replaced the commercial resin, signifying a strong need to further optimize or substitute fossil-derived components. Meanwhile, solvents (e.g., dioxane, acetone), although partially recovered, remained substantial contributors to ozone depletion, toxicity, and eutrophication indicating that enhancements in solvent recovery or the adoption of alternative solvents hold considerable potential for impact reduction. Finally, the fractionation and modification of lignin, while lowering reliance on fossil-based precursors, introduced additional energy consumption and byproduct streams, underscoring the importance of balancing increased lignin incorporation with overall process efficiency. Extending the assessment to include end-of-life scenarios and circular recovery pathways could further refine these conclusions, thereby guiding future efforts in developing low-impact resin systems for additive manufacturing.

The sensitivity analysis of the global warming (GW) impact for resin production highlights the influence of key input variables, including acetone, dioxane, steam, and sulfuric acid usage. An increase in acetone consumption by 20 % to 6.68 kg results in a higher GW impact, whereas a 20 % reduction lowers it to 6.60 gCO_2 eq. per kg of SAF, indicating a moderate contribution to overall emissions. Similarly, dioxane usage exhibits notable sensitivity, with a 20 % increase to 6.85 kg leading to a higher GW impact, while a 20 % reduction to 6.43 kg decreases emissions accordingly. Steam consumption also affects the GW impact, with a 20 % increase to 6.69 kg resulting in slightly higher emissions, whereas a 20 % reduction to 6.59 kg lowers the impact, suggesting a

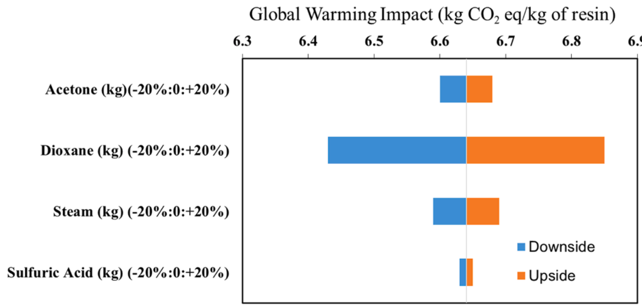


Fig. 5. Sensitivity analysis of the impact of global warming impact of blended resin production.

moderate influence on SAF production emissions. In contrast, variations in sulfuric acid usage have a minimal effect on the GW impact, with changes ranging from 6.63 to 6.65 gCO_2 eq. per kg of SAF. These findings underscore the importance of optimizing acetone and dioxane consumption to minimize emissions while recognizing that steam and sulfuric acid have relatively lower impacts on the overall carbon footprint of blended resin production (Fig. 5).

3.2.1. Uncertainty analysis

Life cycle assessment results are used to inform decision-making, so it is crucial to quantify their uncertainty. We employed a Monte Carlo simulation for 10 % modified lignin in blended resin with inventory shown in Table 2 to understand the influence of data uncertainty on specific impact categories. For each process, the Monte Carlo analyses involved 1000 simulations, resulting from combinations of assorted values of included LCI parameters. We evaluated uncertainty by examining the spread of values in relation to their average. The results showed lower the standard error of mean, thus more reliable results. In Table 3, we present the key findings of our uncertainty analysis, including mean values, standard deviation (representing variability), and other pertinent metrics. The highest uncertainty was observed for the non-carcinogenic impact category and carcinogenic impact category. Carcinogenic category has a high CV (Coefficient of Variation) of 55.543, the SEM (Standard deviation of the sample distribution of the mean) is very small (5.79E-09), suggesting that the mean is still estimated with reasonable precision despite the high variability. The GW impact results varied between 6.37 and 6.98 kg CO_2 eq per kg at both ends of the confidence interval (2.5 %–97.5 %). The results showed that the uncertainty for GW impact and other impact categories considered were low, confirming the reliability of our dataset and demonstrating that variations in data selection and inherent data variability do not exert a significant influence on the examined impact categories (Giuliana et al., 2022). The variation in durations for lignin fractionation, drying, and lignin modification during the scale-up from laboratory to commercial scale resulted in minor changes in electricity consumption. However, this variation does not significantly affect the GW impact of the resin.

3.2.2. Cumulative energy demand (Lower heating value (LHV))

The analysis of cumulative energy demand (CED) reveals that non-renewable fossil energy significantly dominates the process, contributing 111 MJ to the total energy input (Table S5). Among the assessed inputs, epoxy resin emerges as the largest contributor to fossil energy demand, accounting for 76.15 MJ, which underscores the energy-intensive nature of its production. Similarly, the synthesis of methyl acrylate (5.11 MJ) (substitute for methacrylic anhydride) and the dioxane (18.2 MJ) also represent notable contributions, reflecting the substantial energy requirements for raw material production and operational processes. In contrast, non-renewable nuclear energy accounts for 10.9 MJ, with key contributors being methyl acrylate and electricity generation. This reliance on fossil and nuclear energy highlights the inherent energy burden of conventional chemical inputs and utility requirements, necessitating targeted interventions to reduce the reliance on non-renewable energy sources.

In contrast to fossil energy, renewable energy sources provide a modest share of the total CED, with renewable biomass contributing 16.4 MJ, primarily driven by kraft lignin (16.1 MJ). This finding emphasizes the relatively lower environmental footprint of incorporating lignin as a renewable material, particularly compared to conventional petroleum-derived inputs. Other renewable energy sources, such as wind, solar, geothermal (0.19 MJ), and water (1.17 MJ), make minimal contributions, indicating the limited integration of these sources in the current process. The renewable energy inputs reflect the potential for further optimization by enhancing the reliance on bio-based feedstocks and incorporating renewable electricity systems. By increasing the proportion of lignin-derived components and leveraging closed-loop solvent recovery systems, the process could achieve substantial reductions in non-renewable energy demand and overall environmental impacts.

4. Conclusion

This study conducted comprehensive economic and environmental analyses of resin production using sustainable kraft lignin as a bio-based alternative in commercial resin formulations. By employing a detailed process model across plant scales from 2 MT/batch to 30 MT/batch, we found that unit production costs for the resin reached $38.43/kg at a 10 MT/batch scale, with the minimum cost of $38.21/kg at 30MT/batch scale. The environmental assessment indicates that the new lignin-based blended resin production process achieved a GW impact of 6.64 kg CO_2 eq/kg, which is in similar range to conventional epoxy resin at 6.72 kg CO_2 eq/kg. Additionally, the cost analysis revealed that the price of commercial epoxy resin was a significant driver of production costs and a major contributor to the GW impact of the blended resin. These findings highlight both the economic feasibility and environmental promise of lignin-based resin for 3D printing applications. This research

Table 3
Uncertainty analysis of cradle-to-gate life-cycle environmental impacts of blended resin production per 1 kg.

Impact category	Unit	Mean	Median	SD	CV	2.5 %	97.5 %	SEM
Ozone depletion	kg CFC 11eq	8.62E 08	8.31E 08	1.71E 08	19.78528	6.06E 08	1.27E 07	5.39E 10
Global warming	kg CO_2 eq	6.646891	6.641366	0.152108	2.288412	6.372284	6.983801	0.00481
Smog	kg O_3 eq	0.68209	0.681386	0.006406	0.939229	0.671558	0.69726	0.000203
Acidification	kg SO_2 eq	0.037408	0.037322	0.000706	1.887849	0.036374	0.039041	2.23E 05
Eutrophication	kg N eq	0.005482	0.005079	0.001573	28.69237	0.004111	0.009591	4.97E 05
Carcinogenics	CTUh	3.3E 07	2.87E 07	1.83E 07	55.54331	1.25E 07	8E 07	5.79E 09
Non carcinogenics	CTUh	1.03E 06	9.7E 07	3.56E 07	34.50527	8.43E 07	1.57E 06	1.13E 08
Respiratory effects	kg PM2.5 eq	0.005172	0.005165	5.48E 05	1.058855	0.005085	0.005308	1.73E 06
Ecotoxicity	CTUe	47.03354	44.74582	12.07148	25.66568	36.00276	72.09421	0.381734
Fossil fuel depletion	MJ surplus	16.62861	16.59909	0.494022	2.970914	15.76317	17.72655	0.015622

Note: SD: Standard Deviation, CV: Coefficient of Variation, CV unit is in %. SEM: Standard Error of the Mean (SEM) (standard deviation of the sample distribution of the mean).

contributes to advancing sustainable resin manufacturing, aligning with future goals for environmentally conscious material production.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2025.120803.

Data availability

No data was used for the research described in the article.

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