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CONVERSION OF INDUSTRIAL LIGNIN INTO VALUE-ADDED PRODUCTS THROUGH CATALYTIC PROCESSING

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ABSTRACT

The industrial lignin is a widely available aromatic biopolymer produced as a key by-product of pulp, paper and other lignocellulosic industries, while its conversion to high-value-added products is not yet developed. In the current work the conversion of industrial lignin to valuable aromatic chemicals was studied via catalytic processing using a heterogeneous catalyst under process conditions. The effect of temperature (220-280°C) and catalyst loading (0-5 wt%) on the conversion of lignin was analyzed using lignin conversion, liquid-product yield, yield of aromatic monomers and solid-residue formation as main performance indices. It was found that the increase in temperature results in increased lignin conversion, i.e., the lignin conversion increases from 52.4% at 220°C up to 78.6% at 260°C and 81.2% at 280°C, while liquid-product yield and yield of aromatic monomers decrease at 280°C. Thus, the optimal temperature was defined as 260°C, at which 78.6% of lignin conversion, 52.4% of liquid-product yield and 31.8% of yield of aromatic monomers were achieved. Increase in catalyst loading was found to result in better performance, while 5 wt% of catalyst resulted in the highest conversion and product yield. At optimized catalytic conditions the increase in lignin conversion from 41.7% to 78.6%, liquid-product yield from 25.3% to 52.4%, aromatic monomer yield from 12.6% to 31.8% and reduction in solid-residue formation from 56.8% to 26.5% compared to non-catalytic processing were observed. Phenolic compounds were determined as main products, followed by guaiacol-type compounds, oxygenated aromatics and syringol-type compounds. Thus, the results revealed that catalytic processing allows to effectively depolymerize the industrial lignin and convert it into valuable aromatic chemicals.

Keywords: *Industrial lignin; Catalytic processing; Lignin depolymerisation; Value-added products; Aromatic chemicals; Biomass valorisation.*

1. INTRODUCTION

The industrial lignin represents a plentiful aromatic biopolymer extracted as one of the key waste streams from the pulp and paper industry along with other related industries. High carbon content and unique aromatic composition of lignin make it a good choice to serve as a renewable raw material for production of various chemicals and materials. However, at present lignin is mainly used as a source of energy. Thus, lignin conversion to chemicals can optimize resource use and enhance biorefinery potential.

Catalytic conversion can serve as an efficient method for lignin valorization since catalysts can enhance the cleavage of lignin inter-unit bonds and assist in producing low molecular weight aromatic products. Various phenolic products including phenols, guaiacols, syringols, aromatic aldehydes/ketones and alcohols can be produced via controlled catalytic de-polymerization. The effectiveness of this technique is highly dependent upon reaction temperature and amount of catalyst used since high reaction severity can result in secondary polymerization and production of residues.

Therefore, the present study investigated the catalytic transformation of industrial lignin at various reaction temperatures and catalyst concentrations. Lignin transformation efficiency, yield of liquid product, yield of aromatic monomers and solid residue formation were taken into consideration as the primary indicators of process performance. Catalytic and non-catalytic processing of lignin was compared to evaluate the feasibility of catalytic process optimization.

1.1 Objectives of the Study

The study was undertaken with the following objectives:

- To assess the catalytic conversion of industrially obtained lignin into value-added aromatic compounds.
- To examine the influence of reaction temperature and catalyst dosage on lignin conversion, yields of products formed and the generation of residues.
- To isolate the aromatic compounds produced and to compare the catalytic process optimised against non-catalytic processing.

2. LITERATURE REVIEW

Jing et al. (2019) authors evaluated catalytic methods used to convert lignocellulosic biomass into value-added chemicals and liquid fuels. They noted that catalytic systems made it possible to break down and transform lignocellulosic materials into simpler molecules and fuel components. It was found that catalyst selection and reaction parameters played a crucial role in the efficiency of catalytic conversion of

lignocellulosic materials. Their results have proved that catalytic conversion of lignocellulosic biomass could be an efficient method for obtaining economically valuable products. Their findings had demonstrated that well-controlled catalytic conversion could provide an effective pathway for producing economically valuable products from lignocellulosic feedstocks.

Jiju et al. (2025) conducted a study on the recent technological advances and industrial uses in relation to the utilisation of lignin based on the concepts of sustainability. Lignin was referred to as one of the major sources of renewable carbon, which offered high prospects for generating high value-added compounds, materials, and industrial products. According to the authors, traditionally, the utilisation of lignin was associated with the application of relatively low-value products, while with the development of technology, there had been an increased interest in the production of high-value products using lignin.

Singh et al. (2024) reviewed the current research on the catalytic depolymerization of lignin for the production of high-value products by means of ionic liquids and deep eutectic solvents. Based on their findings, it became clear that such advanced solvent systems have increased the solubility of lignin and enabled the breakdown of the complex lignin structure, thus allowing for an easier access of lignin to the catalytic conversion process. It was also noted that the appropriate combinations of catalysts with ionic liquids and deep eutectic solvents resulted in the formation of high-value aromatic compounds and increased conversion yields. The study also highlighted the importance of controlling catalyst and solvent conditions to influence product distribution and minimise undesirable reactions.

3. METHODOLOGY

The research conducted a process-based experiment to assess the catalytic transformation of lignin from industrial sources into valuable chemicals. The impacts of the variables such as temperature and the catalyst loading were evaluated using the lignin conversion rate, product yield, monomer yield, and residue formation.

3.1 Research Design

A process-based experimental method was employed for the investigation of the catalytic transformation of industrial lignin into valuable chemicals. This investigation assessed the influence of temperature and catalyst loadings on the conversion of lignin, liquid product yield, aromatic monomer yield, and residue formation.

3.2 Industrial Lignin Preparation

The lignin from industry was the main raw material used. The industrial lignin was dried to avoid moisture changes, milled to get a uniform particle size and then homogenized. The resulting mixture was kept dry for future use.

3.3 Catalytic Processing Conditions

Catalytic conversion was carried out by employing a heterogeneous catalytic process with the help of a closed high-pressure reactor. The weight percent of the catalyst used in the experiment was changed to 0, 1, 3, and 5%. The temperature of the reaction was kept constant at 220, 240, 260, and 280°C. The reaction time was maintained at 2 hours for comparative evaluation.

3.4 Product Recovery and Characterisation

After the reaction was complete, the reactor was cooled down, and the products were fractioned between the solid and liquid parts using filtration. The liquid part of the reaction was analysed for value-added aromatic compounds, whereas the solid part was dried and weighed for residual mass determination. The most significant product groups include phenolic compounds, guaiacol compounds, syringol compounds, aromatic aldehydes/ketones, aromatic alcohols, and others.

3.5 Determination of Conversion and Product Yield

Lignin conversion was calculated from the initial and residual lignin quantities:

$$Lignin\ Conversion\ (\%) = \frac{Initial\ Lignin\ Mass - Residual\ Lignin\ Mass}{Initial\ Lignin\ Mass} \times 100$$

Liquid-product yield was calculated as:

$$Lignin\ Product\ Yield\ (\%) = \frac{Mass\ of\ Liquid\ Product}{Initial\ Lignin\ Mass} \times 100$$

Residue formation was determined using:

$$Residue\ Formation\ (\%) = \frac{Mass\ of\ Liquid\ Product}{Initial\ Lignin\ Mass} \times 100$$

The aromatic monomers were quantified by taking the amount of aromatic monomers obtained per unit of lignin feed.

3.6 Optimisation of Processing Conditions

The effect of reaction temperature and catalyst loading on the process was evaluated with the aid of lignin conversion, yield of liquid products, yield of aromatic monomers, and formation of residues. The condition offering the best compromise in terms of conversion and formation of valuable products was selected as the optimal condition. According to the selected data, 260 °C was the best temperature, and 5 wt% was the best catalyst loading.

3.7 Comparative Data Analysis

The optimized catalytic condition was compared with the non-catalytic condition in order to determine the efficiency of catalytic processing. Percentage improvement is given by:

$$Improvement\ (\%) = \frac{Optimised\ Value - Baseline\ Value}{Baseline\ Value} \times 100$$

The percent reduction in terms of residue formation was done against the non-catalyst conditions. Tables and graphs were used to show the effects of temperature and loading on the catalysts.

4. RESULTS AND DISCUSSION

The findings showed that catalytic process had considerable effects on the transformation of industrial lignin. Reaction temperature and catalyst amount were observed to impact the decomposition of lignin and production of liquids and aromatics.

4.1 Effect of Reaction Temperature on Lignin Conversion

The effects of reaction temperatures on the catalytic conversion of lignin are presented in Table 1 and Figure 1. The variables used for the analysis were lignin conversion, product yield in liquid form, aromatic monomers yield, and solid residue formation.

Table 1: Effect of Reaction Temperature on Catalytic Lignin Conversion

Reaction Temperature (°C)	Lignin Conversion (%)	Liquid Product Yield (%)	Aromatic Monomer Yield (%)	Solid Residue (%)
220	52.4	31.6	17.8	48.3
240	64.8	40.7	24.9	38.1

260	78.6	52.4	31.8	26.5
280	81.2	49.1	27.6	24.7

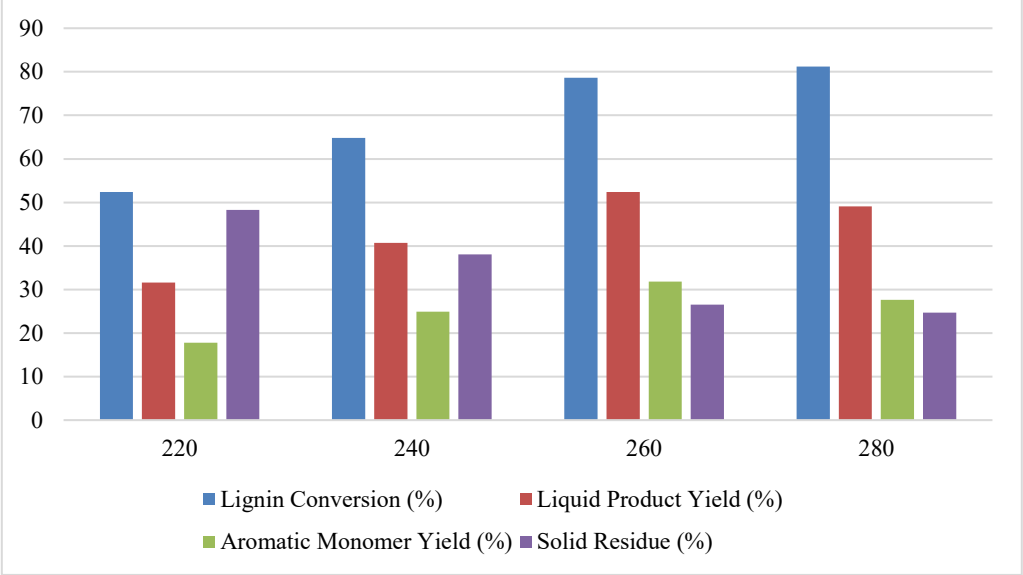


Figure 1: Graphical Representation of Effect of Reaction Temperature on Catalytic Lignin Conversion

The findings revealed that an increase in the reaction temperature usually resulted in an improvement in lignin conversion. The rate of lignin conversion increased from 52.4% at 220°C to 64.8% at 240°C and 78.6% at 260°C; it was further increased to 81.2% at 280°C. The yield of liquid products increased from 31.6% to 52.4% when there was an increase in reaction temperature from 220°C to 260°C, but it reduced to 49.1% at 280°C. Likewise, the yield of aromatic monomers achieved its maximum value at 260°C, which was 31.8%, and it was reduced to 27.6% at 280°C. The solid residue was reduced from 48.3% to 24.7%. It appears that the most optimum temperature was 260°C since the most favourable balance between lignin conversion and value-added product formation, while the higher temperature mainly increased conversion without improving the desired product yields.

4.2 Effect of Catalyst Loading

Table 2 and Figure 2 depict the influence of various amounts of catalysts on the catalytic degradation of industrial lignin. The parameters considered are lignin conversion, yield of liquid products, aromatic monomers yield, and the yield of residue at different catalyst loadings.

Table 2: Effect of Catalyst Loading on Lignin Conversion and Product Yield

Catalyst Loading (wt%)	Lignin Conversion (%)	Liquid Product Yield (%)	Aromatic Monomer Yield (%)	Residue Formation (%)
0	41.7	25.3	12.6	56.8
1	58.9	35.8	19.7	42.4
3	74.6	48.7	29.5	28.7
5	78.6	52.4	31.8	26.5

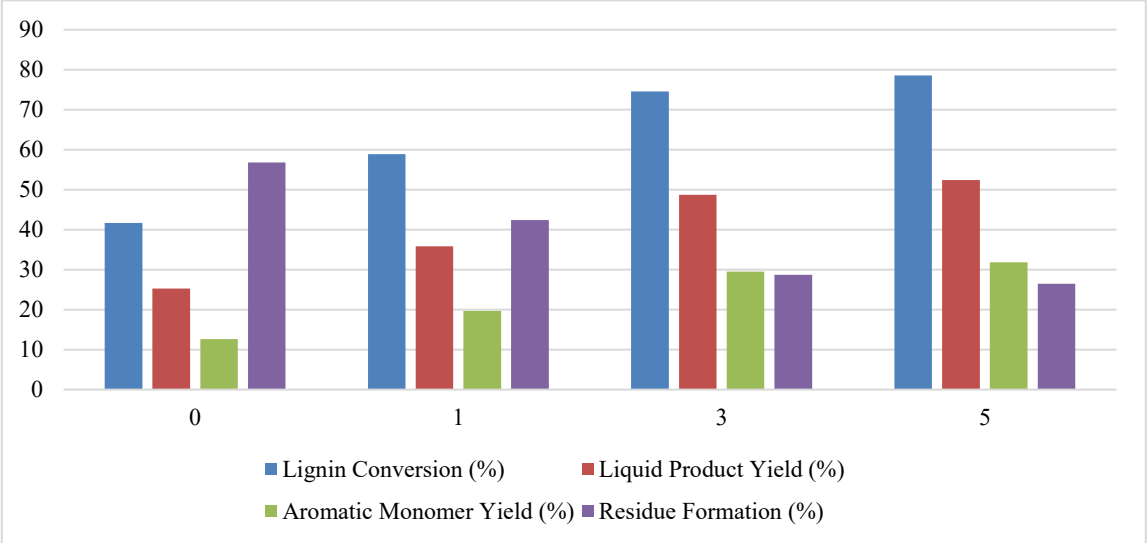


Figure 2: Graphical Representation of Effect of Catalyst Loading on Lignin Conversion and Product Yield

The results demonstrated a significant increase in lignin conversion with an increase in the amount of the catalyst used. The lignin conversion percentage rose from 41.7% in the absence of the catalyst to 58.9%, 74.6% and 78.6% with the usage of 1, 3 and 5 wt% of catalyst, respectively. At the same time, the yield of liquid products increased from 25.3% to 52.4%, while that of aromatic monomers increased from 12.6% to 31.8%. On the other hand, the amount of residues generated reduced significantly from 56.8% to 26.5% with an increase in the use of catalyst to 5 wt%. These findings indicated that increasing catalyst loading enhanced lignin depolymerisation and promoted the formation of desirable liquid and aromatic products, with 5 wt% showing the highest overall catalytic performance among the conditions evaluated.

4.3 Distribution of Value-Added Products

Table 3 and Figure 3 show the distribution of various value-added product groups produced by the optimum catalytic reaction condition. The distribution of product was analyzed based on individual product yield and the share of the liquid product fraction.

Table 3: Representative Distribution of Value-Added Products under Optimum Conditions

Product Group	Yield (%)	Share of Liquid Products (%)
Phenolic compounds	13.2	25.2
Guaiacol-type compounds	8.7	16.6
Syringol-type compounds	5.9	11.3
Aromatic aldehydes/ketones	4.8	9.2
Aromatic alcohols	3.6	6.9
Other oxygenated aromatics	8.4	16.0
Unidentified/low-molecular-weight products	7.8	14.9
Total	**52.4**	**100.0**

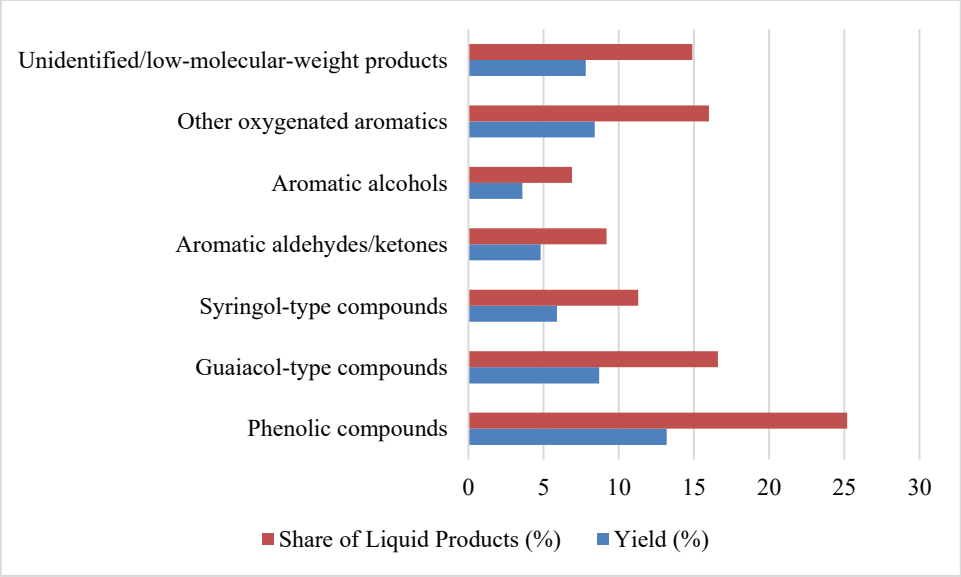


Figure 3: Graphical Representation of Representative Distribution of Value-Added Products under Optimum Conditions

The findings indicated that the phenolic compounds were the highest product class with a yield of 13.2% and making up 25.2% of all liquid products. The guaiacol type compounds had a yield of 8.7% (16.6%), while the other oxygenated aromatics and the syringol-type compounds made up 8.4% (16.0%) and 5.9% (11.3%), respectively. The yield of the aromatic aldehydes/ketones was 4.8% (9.2%), while that of the aromatic alcohols was 3.6% (6.9%). The unidentified or low-molecular weight products made up 7.8% (14.9%). In total, the yield of the liquid products was 52.4%, indicating that catalytic processing generated a diverse range of potentially value-added aromatic products, with phenolic compounds being the predominant identified fraction.

4.4 Comparison of Non-Catalytic and Catalytic Processing

The comparison between non-catalytic process and catalytic process optimized for the treatment of industrial lignin is illustrated in Table 4 and Figure 4. Lignin conversion, liquid yield, aromatic monomer yield, solid formation, and aromatic products selectivity were considered.

Table 4: Comparative Performance of Non-Catalytic and Optimised Catalytic Processing

Performance Indicator	Non-Catalytic	Optimised Catalytic	Improvement
Lignin conversion (%)	41.7	78.6	88.5%
Liquid-product yield (%)	25.3	52.4	107.1%
Aromatic monomer yield (%)	12.6	31.8	152.4%
Solid residue (%)	56.8	26.5	−53.3%
Aromatic-product selectivity (%)	49.8	60.7	21.9%

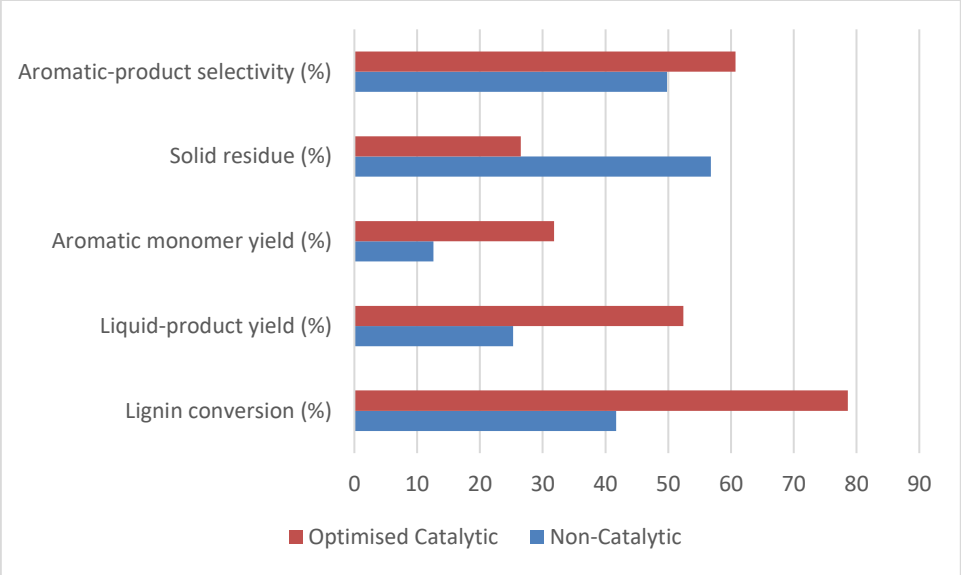


Figure 4: Graphical Representation of Comparative Performance of Non-Catalytic and Optimised Catalytic Processing

It is evident that there were notable improvements in catalytic processing. Conversion of lignin increased from 41.7% to 78.6%, which translates to an 88.5% increase. Yield of liquid products increased from 25.3% to 52.4%, which was 107.1% improvement, whereas yield of aromatic monomers had the highest improvement, rising from 12.6% to 31.8% (152.4%). Solid residues on the other hand reduced from 56.8% to 26.5%, translating into 53.3% reduction. Selectivity of aromatic products improved from 49.8% to 60.7%, which was 21.9% improvement. Clearly, the results demonstrated that there was a marked improvement in catalytic compared to non-catalytic processing.

4.5 Discussion

Catalytic processing led to improvement in lignin conversion and product formation. Operating temperature of 260°C yielded a better compromise between lignin conversion and formation of aromatic monomers, whereas increase in catalyst concentration increased depolymerization and decreased solid residue formation.

With the optimized catalytic processing method, there was an increase in lignin conversion from 41.7% to 78.6% and aromatic monomer production from 12.6% to 31.8% and decrease in solid residue formation from 56.8% to 26.5%. Phenolic compounds were the major identified products, confirming the potential of catalytic processing for lignin valorisation.

5. CONCLUSION

The findings of the research confirmed that the catalytic processing was a promising method for enhancing conversion and valorization of industrial lignin to obtain valuable aromatic products. It was found out that reaction temperature and catalyst loading had significant effects on lignin depolymerization, product formation, and residue production. In terms of reaction temperature, 260°C was found to be the optimal condition in respect to lignin conversion and product formation, while in respect to catalyst loading, 5 wt% was found to be the best catalyst dosage. Under the optimized catalytic condition, lignin conversion increased from 41.7% to 78.6%, liquid-product yield increased from 25.3% to 52.4%, and aromatic monomer yield significantly increased from 12.6% to 31.8% in comparison with the non-catalytic processing. At the same time, the amount of solid residue decreased from 56.8% to 26.5%, which showed more efficient use of the lignin material. Among the groups of products obtained, phenolic compounds were the dominant product, guaiacol type compounds were second, other oxygenated aromatics were third, and syringol type compounds were fourth. Overall, catalytic processing showed considerable potential for transforming industrial lignin from a predominantly low-value residue into a renewable source of value-added chemicals and supporting the development of more sustainable and resource-efficient biorefinery processes.

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