Sustainable Catalysis: Zeolites and Bio-Waste Derived Catalysts

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Abstract:- The research delves into sustainable and efficient catalytic systems using zeolites and bio-waste-derived materials. Fully understanding the very high environmental and economic costs of traditional catalysts, the research would be oriented to the design of innovative alternatives. The synthesis and characterization of zeolites having a special pore structure for use in different catalytic aspects, most specifically hydrocracking, and the production of biofuels, are highlighted. At the same time, bio-waste-derived catalysts through the development by pyrolysis and other processes gained dual benefit by waste management and resource uses. The obtained catalysts were tested in their performance in test reactions such as the Biginelli reaction for the synthesis of renewable plastic and biodiesel production from waste cooking oil. The hypothesis is, therefore, that these newly designed catalysts, upon careful optimization, can realize activities and selectivities at high values while allowing effective reusability. This will significantly help push forward sustainable chemistry methods used today and, as a result, be relevant for a greener industrial environment.

Keywords:- *Zeolites, Bio-Waste-Derived Catalysts, Sustainable Chemistry, Hydrocracking, Biodiesel Production, Renewable Plastics, Catalytic Systems, Pyrolysis, Waste Management, Resource Utilization*

I. INTRODUCTION

Crystalline aluminosilicates, usually referred to as zeolites, possess a highly ordered porous framework. Their applications have extensively been utilized over a very long period in the petrochemical industry for both refining and synthesis purposes. With this particular microporous nature, however, some limits are intrinsically set to diffusion and accessibility. Much effort has placed emphasis on mesoporous zeolites that possess superior mass transfer rates, and hence higher catalytic performance.

Nowadays, there is extensive interest in carrying out research on nonconventional and environmentally friendly catalysts derived from bio-waste. They are renewable and economically feasible for catalysis: banana flower petals, tree leaves, eggshells, and animal bones. The bioconversion of these waste materials into active catalysts could help reduce waste production and assist in a circular economy.

This review represents the efficiency of different zeolites and various catalysts, which were prepared from bio-waste in many industrial applications. The discussion will cover the methods of synthesizing and characterizing mesoporous zeolites, the preparation and catalytic properties of various catalysts obtained from bio-waste, and prospects of these materials for application in sustainable chemical manufacture.

II. ZEOLITE CRYSTALS

Zeolites are aluminosilicate microporous minerals with a highly ordered crystalline structure. In general, the framework of zeolites consists of connected tetrahedral structures of silicon and aluminum atoms. The overall structure of zeolites is crystalline with pores of definite diameters. Throughout their production history, these were used in the refining and petrochemical industry to make fuels and chemicals. Due to the small width of the micropores, the diffusion is confined only to the surface of the crystal.

The high-quality, high-performance mesoporous zeolites were synthesized for the goal of them becoming more cost-effective and scalable. In the last decade, there has been large work on conversion of zeolites to mesoporous crystals.

There are diverse applications of zeolites in the petrochemical industry.

➢ *Hydrocracking and Zeolites:*

Hydrocracking is a procedure that converts heavy compounds to lower boiling point compounds under the presence of hydrogen and a catalyst. Hydrocracking is widely applied in petrochemical industries in the conversion of heavy oils into lighter fuels. It can still be used further to get the by-products of the previously stated reaction into smaller, high-valued products.

Mesoporous (or hierarchical) zeolites are capable of this catalysis, "They possessed optimal textural properties, uniform pore distribution and enhanced-stability characteristics. Of great catalytic importance is their porosity network that is susceptible to unrestricted diffusion of reactants and the resulting products". The zeolites can also be used to convert the crude oils obtained by pyrolysis of solid municipal waste which contains heavy hydrocarbons due to food leftovers and plastics.

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Hydrocracking also shows promise in the production of biofuels, especially from non-edible vegetable oils which would decrease the pressure on the supply chain while also being a viable alternative to conventional fuels.

"Zeolites are widely preferred over other supports because of their stronger acidity, higher thermal and hydro-thermal stability, higher resistance to sulfur and nitrogencompounds, reduced coke production tendency and higher regeneration capability".

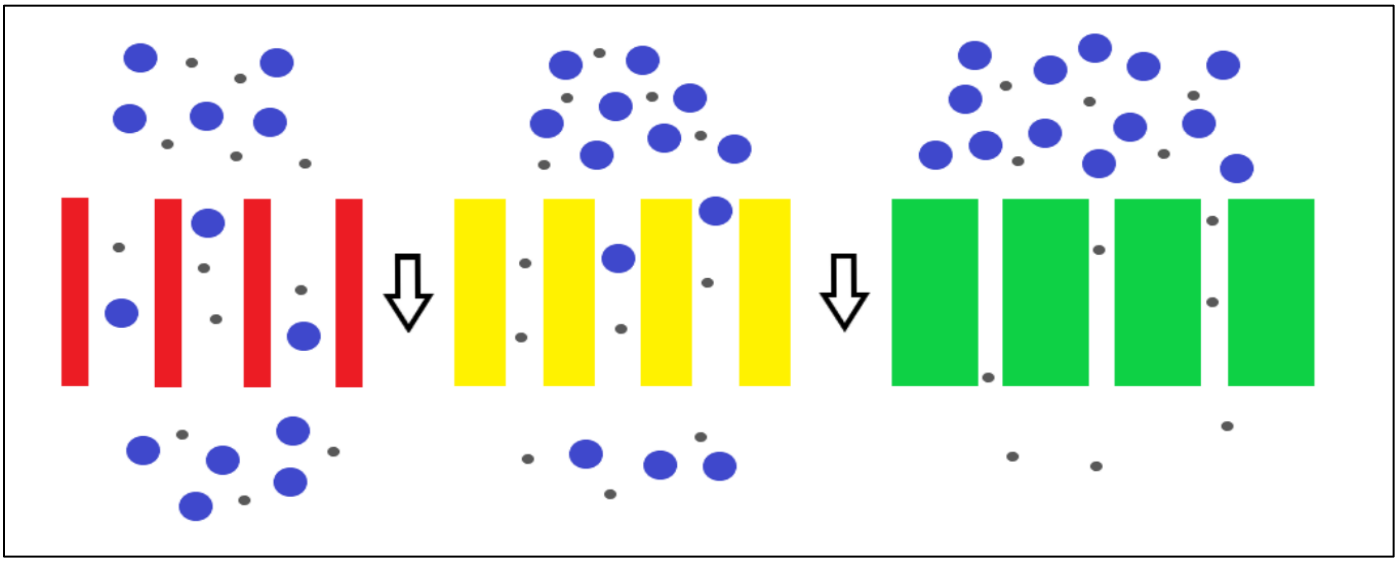

Fig 1: Schematic Illustration of the Diffusion of Molecules within Macropores (Red), Mesopores (Yellow), and Micropores (Green) of a Zeolite. [7]

The microporosity helps for the use of the zeolite as a sieve, but it has diffusion limitations and thus results in slower reaction rates . The diffusion limitations also resulted in the conversion of reagents into undesired by-products and blocked the micropores, causing the catalyst rendered unusable. To avoid this, hierarchical mesoporous (having pores of size 2 to 50 nm according to IUPAC) were developed. It was also found that shortening the diffusion path also increases the catalyst's lifespan and reusability. However, production of such mesoporous zeolites was a challenge that has seen strides in recent years with scientists developing energy and time efficient ways of making mesoporous zeolites.

III. BIO-WASTE CATALYSTS

Recent research has explored the potential of bio-waste derived catalysts for various applications. These catalysts, derived from materials such as banana flower petals, tree leaves, eggshells, and animal bones, offer sustainable and cost-effective solutions for a range of chemical processes.

The following sections will delve into specific examples of bio-waste derived catalysts, highlighting their preparation methods, catalytic properties, and potential applications.

➢ *Banana Flower Petal Ash*

In another study, Ikbal Lashkar et al. approached the potential use of banana flower petal ash (Musa acuminata) as an efficient catalyst for biodiesel production from waste cooking oil. The catalyst was prepared easily by open-air burning, and its catalytic activity with regard to the transesterification reaction at room temperature was tested. In this context, response surface methodology coupled with a particle swarm optimization algorithm was used to optimize key reaction parameters of the catalyst concentration, methanol-to-oil molar ratio, and reaction time. The ash catalyst was characterized for its chemical composition and morphology using different analytical techniques. These results therefore show reusability, renewability, and strong activity of the catalyst, hence very promising for efficient, economic, and environmentally friendly biodiesel production.

➢ *Highly Porous Carbon from Waste Leaves*

Highly porous carbon which was derived from waste tree leaves was used as a low-cost carbon based bifunctional electrocatalyst in a sodium-air cell. Its catalytic activity was improved by doping it with nitrogen and sulfur. The N-doped HPC showed bifunctional catalytic activity with an onset potential of 0.95V at a current density of 6.31 mA cm-2. The Na-Air battery with HPC showed a round trip efficiency of ~83% over 30 cycles.

➢ *Fe3O4-APTES-Glu-lipase*

Devi Rajan et al. investigated the hydrolysis of castor oil into ricinoleic acid using a Pseudomonas guariconensis lipase immobilized on activated ferromagnetic nanoparticles via glutaraldehyde cross-linking. The synthesized nanoparticles were characterized using Fourier Transform Infrared Spectroscopy (FTIR) and Dynamic Light Scattering (DLS). The optimized reaction conditions, determined through response surface methodology, yielded a maximum conversion of 62.5 ± 0.76% at 40°C, pH 9, a water-to-oil ratio of 4:1, and a biocatalyst loading of 4% w/w. Notably, the biocatalyst exhibited significant stability, with minimal loss of activity after six consecutive reuse cycles. The produced ricinoleic acid is a valuable commodity with applications in various industries, including the production of printer ink, pigments, and textile finishes.

➢ *CaO-900*

A waste eggshell-derived catalyst was reported with high efficiency to selectively hydrogenate bio-based cinnamaldehyde to cinnamyl alcohol with a 97% yield at 30 °C. Complete conversion of CAL could be achieved to 3-phenylpropanol through adjustment of the reaction time and temperature. The predominance of the catalytic performance of CaO-900 over others could be attributed to the high alkalinity and relative large specific surface area. Both experimental in situ Raman and theoretical calculations pointed out that the priority of hydrosilylation toward CAL played a crucial role in the control of product distribution. Besides, good recyclability of the CaO-900 catalyst was observed.

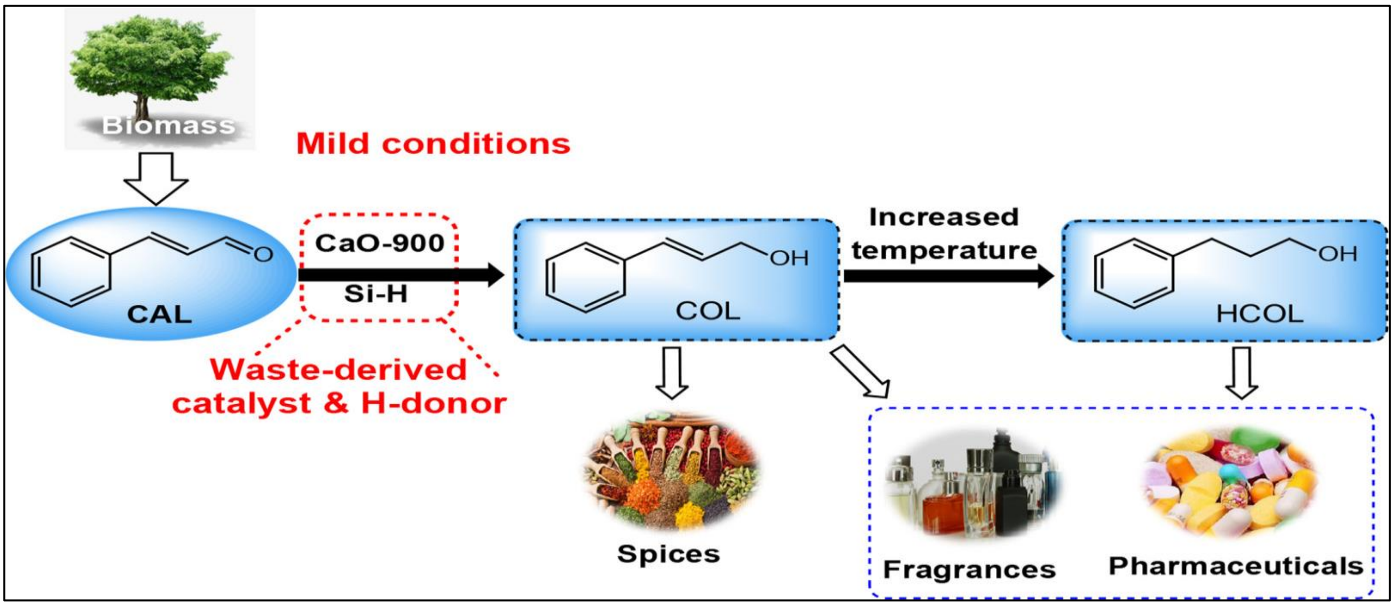

Fig 2: Graphic Organizer to Show use of CaO-900 Catalyst

To produce the CaO-900 catalyst waste eggshells were collected and washed in distilled water to remove dust and impurities. After that, the cleaned eggshells were dried in a drying chest at 80 °C for 24 h and calcined at 500–900 °C for 0.5–4 h in an air atmosphere. The obtained catalysts are denoted as CaO-T, where T is calcination temperature.

Typical catalysts derived from bio-waste involve calcination of waste materials, such as agricultural residues, eggshell, and animal bone, to yield calcium oxide (CaO) or other active elements. This type of catalyst is characterized by the following:

- Surface Area: Normally below that of mesoporous materials, in the range of 10-200 m^2/g.
- Pore Size: Although not unique, the pore size typically ranges from 2–50 nm, depending upon the source of bio-waste used or the preparation technique involved.
- Catalytic Activity: Very effective for biodiesel production, typically in the range of 85–98%.

IV. CONCLUSION

In conclusion, this work shows various paths for the utilization of zeolites and bio-waste-derived materials as innovative sustainable catalysts in industries. This search for greener and more efficient catalytic systems helps answer the societal concern of reducing the negative environmental and economic impacts usually caused by conventional catalysts. Intrinsic pore structures of zeolites and the diversity of bio-wass-derived catalysts open promising avenues toward applications in hydrocracking, biodiesel production, and renewable plastic synthesis. A primary objective of this research is to focus on the synthesis and characterization of new zeolite crystals, develop advanced photocatalytic systems, and convert bio-wastes into catalytically active materials to yield catalysts of very high activity, selectivity, and reusability. This is in line with the greater goals of sustainable chemistry and efficient resource use, opening the way to an environmentally cleaner and more cost-effective future in catalysis.

FUTURE OPPORTUNITIES

- Optimizing catalyst performance through improving the synthesis conditions and structural properties of zeolites and bio-waste-based catalysts for improving the activity, selectivity, and stability performance in various reactions.
- Industrial Scale-up and Applications: Researchers can the scalability and practical application of these catalysts in industry through pilot-scale evaluations of economic viability and operational efficiency.
- Broader Range of Bio-Wastes: Other bio-waste materials need to be investigated to further broaden the variety of sources for catalysts and research their catalytic potential for even more sustainable resource utilisation.

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