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Green Chemistry Approaches for the Sustainable Synthesis of Organic Compounds

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Abstract* Organic synthesis is a cornerstone field in chemistry to aid in drug development, agrochemistry, polymer, material and industry useful chemical products; nevertheless conventional synthetic pathways frequently rely on dangerous chemical reagents, toxic solvents, highly energy dependent reaction circumstances, inefficient strategies which create large amounts of chemical waste raising major environmental, economic and safety concerns limiting the feasibility of long term sustainable chemical processes; consequently growing needs to produce materials environmentally friendly initiated development of principles of green chemistry for designed new chemical processes to reduce the waste amount, usage of toxic reagents, improve the overall mass intensity as well as explore alternative cleaner approaches without diminishing chemical yields; This conceptual paper reports the strategies to achieve environment friendly synthetic approach on new pathways to organic compounds by combination of several advanced concepts as: catalytic processes, biomass derived feedstocks, solvent free synthesis, biocatalysis, microwave assisted synthesis, ultrasound mediated reactions and continuous flow chemistry; In proposed method it will be evaluated according to efficiency on the basis of sustainability parameters as atom economy, mass intensity of the reaction, decrease of consumed energy, catalyst recyclability, low toxicity, exploitation of raw materials which are coming from sources of nature such as biomass etc.; Also environmentally favorable media like water, ion fluids, deep eutectic solvents should be chosen over common organic media to mitigate chemical contamination and health hazards; Cooperation between catalytic chemistry and new reactions methods will offer benefits like higher selectivity, decrease of side products, operational costs reduction, scale up to large industrial applications and application of modern simulation methods would improve a predictable capability as to find reaction condition to provide higher efficiencies and green conditions; The benefits to be offered to use of this scheme of concept is to shift conventional production from traditional towards more sustainable way of conducting organic chemistry, aiming an optimal balance between efficiency, environment, profit and industrial feasibility ultimately contribute to the development of future

Keywords: Green chemistry, Sustainable synthesis, Organic reactions, Catalysis, Renewable resources, Biocatalysis, Solvent-free chemistry, Environmental sustainability

I. INTRODUCTION AND BACKGROUND RELATED TO THE STUDY

The chemical sciences have undergone a paradigm shift with the advent of green chemistry as the fundamental goal is to develop chemical products and processes that have no detrimental effects and the minimized potential for negative impacts associated with the manufacture and use of the product, and the associated industrial production processes-the chemical synthesis itself is designed and improved while being cost-effective, to provide suitable yields with good chemical performance characteristics and beneficial societal effects (Anastas & Warner, 1998), to the traditional reaction development in which product generation is the only concern without considering impact to the environment. Chemical waste is minimized by applying preventative policies to all phases of chemical processes involving a wide range of issues including, "reducing waste, safer solvents and reactions, use of renewables, increased energy efficiency, improved atoms utilization", etc. Historically, green chemistry evolved in response to the growing environmental concern over increasing levels of chemical waste being disposed from industrial processes and limitation to traditional approaches to pollution control strategies around the end of 20th century especially after establishing the concepts of pollution prevention and publication of twelve principles by Anastas and Warner in 1998 which has laid down a systematic methodology on designing environmental benign chemical technology (Anastas & Warner, 1998). These twelve principles provide a set of guidelines and inspirations to chemical research, which have encouraged chemists to go

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beyond the approaches of end-of-pipe waste treatment into molecule and process design in which prevent pollutions before they occur. Green chemistry has received much more important as all the sections of modern chemical industries from pharmaceuticals, agrochemicals and polymers sectors to specialty chemical industry heavily depend on organic synthesis to yield all the fine chemicals required with traditional approaches that consume much amount of solvents, stochiometric reagents and large portion of energy input, which inevitably cause enormous of waste, CO 2 output, occupational diseases and human health damage (Sheldon, 2007). So green chemistry is becoming a pivotal strategy toward innovation in all relevant industrial sectors by applying energy efficient transformation, catalysis, renewable resources, safe solvents, better atom economy as the tool toward the development of safe and green industry. Organic synthesis is particularly important research area for green chemistry to cover for its being a cornerstone to make a large number of value-added products through the multi-step sequences from a starting material to a final product, and this process often causes enormous consumption of materials and energy; thus, making green alternative of current processes a critical scientific and industrial challenge for society and mankind (Dunn, 2012). The relation between chemistry and sustainability is determined by chemical activities having impact on resources availability, eco-system and human safety as well as energy consumption. So, for present chemistry, one has to consider, in chemical research process development, besides the molecular functionality and performance of molecules; also, on life cycle assessment (LCA) and life cycles (CLCA), and sustainability will eventually be driven by such research endeavors. Catalytic transformations, biocatalysis, solvent-free chemistry, microwave accelerated synthesis, continuous flow reaction, new sources of materials from bio-resource and life cycle analyses are potential avenues explored by researcher around the world with promising results and substantial potential to minimize ecologic foot print without compromising reaction efficiency and selectivity (Clark, 2018). As increasing awareness is triggered by ever worsening environmental pollution, people are seeking alternatives by governments that require industries to adapt chemical synthesis into safer processes while the whole industry requires efficient reaction and synthesis design from atom to economy, toward developing socially acceptable products (Sheldon, 2007), thus to reduce reliance on hazardous reagents, toxic solvents and enormous energy as well as organic wastes, toward achieving economically and environmentally acceptable processes, so green chemistry has become an indispensable framework guiding sustainable organic synthesis research.

Environmental Challenges in Conventional Organic Synthesis

Traditional methods of organic synthesis provide vital routes to compounds such as pharmaceuticals, pesticides, polymers and fine chemicals. Many conventional synthetic operations however cause significant environmental problems including poor use of resources, use of toxic materials and hazardous chemicals, unnecessary production of waste and energy requirements, prompting an urgent need for greener and more sustainable operations. A key problem with conventional synthesis is the generation of chemical waste often arising from multi-step sequences of reactions, overuse of reagents, protection groups, poor conversions of reactions and the formation of many undesired byproducts, reducing process yields and exacerbating environmental problems. Atom economy is a problem because large numbers of atoms from the starting materials end up as waste, and this means they cannot contribute to the mass of the final product, making subsequent steps in the process a necessity in order to dispose of or process wasted materials (Sheldon, 2007). Conventional synthetic operations in organic synthesis typically consist of the consumption of reactants to form a product together with large amounts of waste in contrast to the intent of greener chemistry to convert a large proportion of the starting material's atoms into a target molecule using effective design, processes including catalytic ones, efficient sequences and improved reactions to reduce waste formation (Trost, 1991). Extensive use of toxic organic solvents including benzene, chloroform, dichloromethane etc are commonly used in organic reactions for example as the medium, extractant or as purification agents and are detrimental to the health of man or cause exposure to those employed in processes. These substances may also lead to harmful emissions that contribute to the increasing atmospheric and occupational hazard.

Solvent usage presents a serious issue when referring to the sustainability of any chemical process, as it commonly comprises the largest percentage in terms of material consumed, and subsequently wasted especially in pharmaceutical production (Henderson et al., 2011). As well as wastage there may be further problematic environmental aspects of conventional reactions requiring extended heating times of up to several hours or days and thus high temperatures and large amounts of energy for consumption which increases the associated costs and overall CO2 emitted when producing chemicals and these reaction conditions may influence negatively the sustainability (Anastas & Zimmerman, 2003). The problems of waste generation, use of toxic organic solvents and energy demand suggest that more sustainable synthetic processes will be required in the form of chemical reactions utilizing catalysts, solvent-free conditions, renewable raw materials, biocatalysis, microwave and a flow-based production method. By implementing a selection or combinations of green organic synthesis strategies there can be opportunity to improve efficiency and safety of chemical process together with environmentally friendly operations for the future needs of industry and society.

Importance of Sustainable Organic Synthesis

The role of sustainable organic synthesis is of utmost importance in modern day chemistry and industry today, since it offers procedures for synthesis of useful organic molecules that result in diminished pollution, better reaction efficiencies and sustainability of resources; Conventional synthesis techniques usually depend on use of hazardous substances and excessive amounts of energy to proceed in relatively inefficient reaction pathways, contrary to a new trend towards synthetic chemistry using more "environment-friendly" procedures that combine chemical performance with environmentally friendly and economically competitive characteristics; Among the most important advantages of the sustainable organic synthesis we find that it limits environment pollution by minimizing generation of waste by applying a higher atom economy as well as more efficient catalytic transformations and consequently less amount of chemical contaminants released into environment from the chemical manufacturing processes (Anastas & Warner, 1998); Furthermore it increases occupational and environment safety by eliminating the use of toxically harmful reagents and harmful organic solvents and the need to utilize chemically robust and environmentally Persistent substances, but substituting with benign substitutes such as renewable solvents, bio-catalysis, recyclable catalysts and less harmful systems of reaction which results in the reduction of dangers among researchers, professionals of industry and people surrounding them (Clark, 2018); Cost benefits may also be drawn from the use of sustainable synthetic technologies as the production costs could decrease through high yield of reactions, lower consumption of material, simplistic procedures of purification, cheaper and easier treatment of the produced waste and improved usage of catalysts; Incorporating a renewable feed or a resource to achieve sustainable synthesis, a step towards sustainability, constitutes one of the main and remarkable aspects of sustainable chemistry, for example usage of plant based substrates instead of finite oil related resources in chemistry ensures sustainability of materials and a switch towards circular chemistry systems (Sheldon, 2014); The pharmaceutical, the polymer, the agrochemical and the fine chemical industries benefit from sustainable organic synthesis because their research and industrial practices adhere to environmental regulations. Reduced emissions as well as enhanced resource efficiency make use of chemical manufacturing process that increase competitiveness among their sustainable chemical producers; Novel synthesis technologies like using continuous flow system of reactions or microwave supported catalysis, photochemistry reactions, and enzymatic synthesis; and efficient choice of a greener solvent system that reduce a high percentage of pollution, may assist in creating a more environmentally compliant chemical synthesis process (Jimnez-Gonzlez et al., 2012); Therefore, sustainable organic synthesis is not merely necessary environmentally, but it constitutes an innovation that bridges chemical productivity with efficiency and environmentalism.

II. RESEARCH PROBLEM RELATED TO THE STUDY

Notwithstanding the considerable progress in organic synthesis and chemical manufacture, still, these classical synthetic methods suffer from the environmental, economic and safety problems concerning to toxic reagents and solvents, non-renewable resources and their uses, inefficient pathways, harsh conditions of reactions, and high consumption of energy in the process. Such challenges lead to serious need for sustainable chemistry that could offer to solve above mentioned problems with high synthetic efficiency in organic transformations (Sheldon, 2007); a majority of chemical waste arises from chemical reactions, of which pharmaceutical and fine chemical industries are prominent due to the multi-step synthesis, purification process and low atom efficiency of reactions. These processes are not environmentally friendlier and cause an increase in production cost (Sheldon, 2007). Besides the environmental waste, working with volatile organic compounds and toxicated solvents cause serious problems related to worker's safety, working environment and earth's pollution and consequently the alternative greener solvent and reaction mediums are needed (Henderson et al., 2011); the processes are power intensive such as heating energy required, long reaction time and high temperature contribute in increasing amount of carbon emission from chemical processes and making chemical reactions unsustainable (Anastas & Zimmerman, 2003). While green chemistry serves as a scientific base to address problems mentioned in context above, real implementation of this concept in organic synthesis is faced with problems namely catalytic development, readily available renewable resources, scalability, cost effectiveness, integration with industry. Therefore, it is research problem statement considered in the following concept which will deal with the development and assessing new chemical synthetic routes in a cleaner and energy efficient way in terms of sustainability of products, minimizing by-products and avoiding toxicity.

III. RESEARCH OBJECTIVES

The conceptual study aims:

1. To analyze principles of green chemistry in organic synthesis.
2. To evaluate sustainable synthetic methodologies.
3. To explore catalytic approaches for efficient transformations.
4. To investigate renewable raw materials for chemical production.
5. To propose environmentally friendly strategies for future organic synthesis.

IV. LITERATURE REVIEW

Historical Development of Green Chemistry

The history of green chemistry is a significant transition from traditional approaches of pollution control toward proactive techniques that prevent the formation of waste, toxicity, and contamination through efficient molecular and process design. With extensive industrial growth and increasing reliance on chemical processes in the twentieth century, hazards such as pollution-generating waste products, toxic emissions, depleted non-renewable resources and environmental contamination drew awareness of society and were later prompted for the development of government regulations where control and treatment of pollution were first considered rather than its prevention (Anastas & Warner, 1998). The initial transition toward sustainability can be witnessed as far back as the late twentieth century through the U.S. Pollution Prevention Act of 1990, in which pollution prevention was declared a national policy issue where an endeavor to reduce at source or prior to its occurrence, was favored and hence prompted more prevention of potential waste generation in chemical practices to take place (United States Environmental Protection Agency [EPA], 1990). Following on these issues, green chemistry was subsequently established in the 1990s by Paul Anastas and John Warner, authors of the twelve principles of green chemistry introduced in 1998, in an aim to assist the production of chemical products and processes with minimal use or creation of hazardous substances and greater environmental compatibility as well as efficiency and safety (Anastas & Warner, 1998); these principles include prevention of waste, atom economy, safe chemical synthesis, renewable feedstocks, energy efficiency, catalytic processes and environment preferable solvents, that offer a series of guidance to the modern chemists in achieving green synthetic processes, where in the modern time green chemistry has grown into an interdisciplinary science composed of topics varying across different fields such as organic chemistry, catalysis, materials chemistry, bio-technology, chemical engineering and industrial manufacturing (Clark, 2018); and therefore the history of green chemistry is a scientific transformation from the concept of managing environmental pollution toward preventing their source, which was achieved through responsible utilization of resource to construct a more sustainably developed world.

Principles of Green Chemistry

Green chemistry principles and approaches provide a rational framework to advance sustainability of chemical synthesis. With these fundamental concepts as guidance, chemists can be guided and fostered to establish the optimal routes to most resource-efficient, less environmentally dangerous and chemically safe processes that enhance chemical synthesis. Of which the design of reactions with an absence of waste through "waste prevention" and with efficient use of reactant material, which "atom economy" refers to as the measure of amount of reactant molecule that ends up in product, and using appropriate "safe solvents" that are generally the largest volume component. Waste prevention aims to minimize formation of chemical waste at source, and prevent reliance on expensive and energy-consuming processes, for effective post disposal processes of waste generated and minimize pollution to environments (Anastas & Warner, 1998). Atom economy is a crucial definition which measure how many of reaction atom is being utilize in reaction and encourage scientists to develop chemist-safe ways with "high atom economy". High atom economy is believed to favor minimized generation of undesired by-product and hence to increase sustainability in reactions (Trost, 1991). Safer solvent choice in green synthesis is of significant important due to solvents often hold major position both on consumption and production of waste, especially when referring to its consumption in production process where its used often high percentage. For example, pharmaceutical factories especially in using safe solvent which has less toxic and ecologically damaging impact. "Green" solvents such as water, ethanol, SCCO2 and ionic liquid are popular in reactions to benefit both less pollution, safer environment and potential to be recycled; while also support some chemistry transformations in their reaction conditions. Green chemistry principle enable scientist and industries develop safer, higher efficient and reduce hazardous chemical usage in synthesis of organic matter in order to produce environment-friendly product.

Green Catalytic Approaches

Green catalytic strategies have been developed as one of the very crucial methods of Green organic synthesis as because they improve the rate and selectivity of a reaction; consequently, they require only sub stoichiometric amount of material used and a catalyst allows transformations to occur under much milder and more environmentally benign conditions (Sheldon, 2007); consequently, catalysis provides essential tools to develop greener organic syntheses by reducing the consumption of energy, formation of by products as well as improved efficiency for industrial and laboratory syntheses (Sheldon, 2007); In the modern day organic synthesis metal catalysis has gained tremendous success as the organo-transformations through the use of transition metals such as palladium, copper and iron complexes are made to work very efficiently for C-C as well as C-Hetero atom bond formation under selective catalytic cycles, thereby affording complex organic molecules in an efficient manner, compared to stoichiometric methods; Various palladium mediated coupling reactions like cross-coupling methods have found abundant applications in synthesis of pharmaceutically and materially relevant organic molecules while copper as well as iron has more economical and efficient choices as compared to palladium considering their availability and less harmful environmental effect (Bostrm et al., 2018); apart from metal systems, the use of small organic molecules based catalysts without metal is the prime objective of organocatalytic to bring about desired transformations in various reactions in a green manner. Amines, proline derivatives work as suitable catalysts by being metals-free thus circumventing the issue of metal contaminants. Toxicity and purification complexity in target molecules (Dalko & Moisan, 2004); Biocatalysis in conjunction with enzymes and microorganisms has proven itself to be efficient, clean and sustainable synthesis route with mild temperatures, aq. Condition etc. As biocatalysts perform reaction in eco-benign milieu and with high selectivity (chemo, regio, stereoselectivity) (Bornscheuer et al., 2012); hence the integration of metal catalysts, organ catalysts and biocatalysts together lead a comprehensive solution in pursuing green organic synthesis.

Applications of Green Organic Synthesis

Green organic synthesis has become paramount to many industrial sectors owing to its environmentally acceptable methods for the synthesis of commercially valuable chemicals by increasing efficiency for their synthesis, minimizing the amount of wastage, use of toxic materials and energy consumption; the approaches of green synthesis play a crucial role to efficiently synthesize drug molecules and the active pharmaceutical ingredients (APIs) in the pharmaceutical sector by improving the selectivity of the reaction, minimizing waste solvent, reduction in the number of processing steps and development of relatively much safe process paths resulting in better economic and environmental results (Dunn, 2012); The catalysts, sustainable solvents and modern organic processing methods like continuous-flow chemistry and effective synthetic routes have acquired greater importance for pharmaceutical manufacturing companies as sustainable manufacturing solutions; In the polymer sector green organic synthesis offers methods to produce sustainable and biodegradable polymers and materials by using renewable inputs, eco-friendly monomers and effective polymerisation routes thus enabling the industry to depend less on the fossil resources and avoiding long-term accumulation of pollutants in the environment (Sheldon, 2014); Agrochemical sector similarly gains immense use by designing and manufacturing more suitable and safe pesticides and other agrochemicals with better selectivity to produce fewer residues from pollution sources resulting in greater sustainability to environment and reduction in soil and water resources (Clark, 2018); As a whole the technological approach toward economic development without jeopardizing with the nature is the technological green organic synthesis which integrates chemical and environmental efficiency along with resource efficient processes.

V. SIGNIFICANCE OF THE STUDY

The scientific, environmental, and industrial significance of the study on green chemical processes for sustainable organic synthesis lies in its providing of a comprehensive blueprint on how the design of chemical production processes can be improved via strategies of green chemistry, reaction innovation and conscientious consumption of chemicals. From a scientific view, green synthesis is of great importance due to new synthetic principles of catalyzed efficiency with renewable chemicals; it can significantly contribute to the advancement of green synthesis methods and will broaden synthetic possibility for future. (Anastas & Warner, 1998) Environmentally, implementing green chemistry method offers a number of substantial improvements in decreasing the extent of chemical pollution, producing fewer chemical wastes, minimizing usage of dangerous chemicals and green, etc (Sheldon, 2007) It also includes development of many other less dangerous chemicals used. Industrial scale adoption of the clean manufacturing techniques of synthesis in an ideal scenario could further enable companies to attain better resource efficiency; reduction of production costs; and strict regulatory compliances etc (Clark, 2018)

VI. LIMITATIONS OF THE STUDY

While the alternative paths of green chemistry may look very promising and sustainable for organic synthesis, there remain a number of limitations and bottlenecks that need to be overcome before they can be adopted at the industrial level. Namely: the high price and lack of availability of some novel catalysts such as complex metals catalysts, biocatalysts or designed systems make them uneconomical at industrial scales, especially when compared with well-established and less expensive alternatives Sheldon, 2014. While successfully conducted a sustainability experiment in laboratory settings, scaling up these processes can prove a difficult task due to heat and mass transfer changes and requirement of different controls; renewable raw materials may not be consistently available in term of quantity and composition, hence renewable feedstock can be at high demand in other industries, conflicting its possible use for organic synthesis (Clark, 2018). Catalysis separation, recovery and re-use still represent technical problems which strongly impact process economics and environmental impact; indeed, the technology developed needs large scale verification to demonstrate it is viable, safe and environmentally sustainable.

VII. FUTURE PERSPECTIVES

An increasing reliance on artificial intelligence (AI), the increasing impact of renewable carbon chemistry, advanced catalysis strategies and circular chemistry: AI may drive future growth of sustainable organic synthesis through predictive synthesis and conditions optimization, thereby speeding up green chemistry approaches via prediction of outcomes of reactions as well as optimizing of conditions, coupled with rapid analysis of complicated chemical data (Lavecchia, 2015); renewable carbon strategies, centered on applications of CO2 and biomass, will enable shifting from dependency on petrochemicals and increase the opportunities to sustainable chemical production (Sheldon, 2014); advanced catalysis, exemplified by nano- and photocatalysts, provides excellent efficiency, higher selectivity and energetic saving through effective strategies (Bhanage & Arai, 2001); chemical recycling and waste-to-resource are central part of circular chemistry that tries to create close-loop systems to minimize resources consumption and environmental pollution (Clark, 2018).

VIII. CONCLUSION

In the field of modern chemical science, sustainable organic synthesis is addressed to develop safer, greener, and more efficient chemical process to provide the necessary materials for production industry with least harmful effects on environment. The applications of principles of green chemistry for the improvement of traditionally synthetic methodology has shown the capabilities to transform to the cleaner, more effective approach in organic synthesis through various ways of reduce the waste, enhance efficiency in using of sources, minimize the consumption of dangerous chemical materials, and to encourage reasonable design on chemical reactions (Anastas & Warner, 1998). Catalytic technologies, such as metal catalysis, organocatalytic and biocatalysis; help greatly in sustainable synthesis due to their characters such as enhance selectivity, reduce energy consumption, transform substrate to product with less negative effects. And sustainable raw materials, including bio-derivatives and utilize of CO2 and among others, serve as the alternative and renewable carbon sources other than limited finite fossils resource (Sheldon, 2014). Moreover, the integration of innovative technologies, including continuous-flow processing, computational chemistry, AI assistance optimizes process and advanced reaction engineering techniques also provide a new trend to tackle chemical industry sustainability problems from the perspective of enhanced efficiency, increased capability for production and reduced environmental burden (Clark, 2018). Effective conjunction among chemistry, engineering science, computation science, industry technologies and also those developing of new materials are key factors for realization the organic sustainable synthesis in the future which can satisfy the environmental problems from natural resource limitation and pollution during production and use, and therefore build green organic chemistry for both of science & innovation and economic profit.

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