

FUTURISTIC TRENDS AND OPPORTUNITIES IN ORGANIC SYNTHESIS-ASYMMETRIC ORGANOCATALYSIS

Abstract

Organic synthesis is the art and science of constructing organic molecules and has an enormous impact on human life and their well-being. It has benefitted the society by providing nutritional supplements, medicines, vitamins, cosmetics, high energy fuels, polymers and plastics to name a few. This discipline has also facilitated the emergence and development of other disciplines and technologies namely biology and biotechnology, chemical biology, medicinal chemistry, physics, materials science and nanotechnology. After survey on the recent publications, asymmetric organocatalysis is identified to be the most recent methodologies in the synthesis of organic compounds.

Keywords: Organic synthesis; asymmetric organocatalysis; chemical biology; nanotechnology; medicinal chemistry

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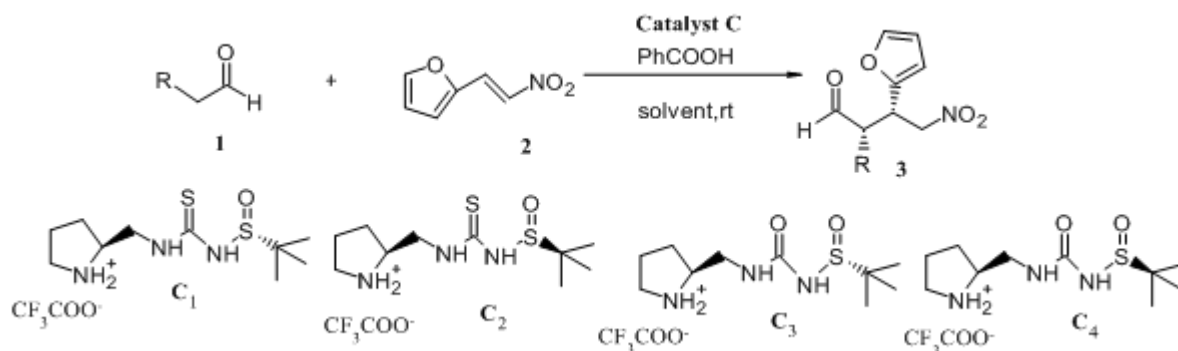
I. INTRODUCTION

The study of organic compounds, their structure, including their synthesis, and application is called organic chemistry [1]. Over the years, there is a tremendous growth in the synthesis of organic molecules, to meet the ever increasing needs of society since the successful synthesis of urea [2] in 1828 by Friedrich Wöhler. Since then many efforts have been put in by the scientific community for the development of new bio-active molecules, novel materials with properties, like bio-compatibility, new catalysts for selective transformations, and so on. This discipline has also **facilitated the emergence and development of other disciplines and technologies** namely biology and biotechnology, chemical biology, medicinal chemistry, physics, materials science and nanotechnology.

The use of organic compounds as catalysts is known from a very long time, but their usage as asymmetric catalysts has become important in the past few decades, due to their selectivity in lots of reactions [3]. Asymmetric organocatalysis has evolved a lot since the earlier work reported using cinchona alkaloids for the reaction between hydrogen cyanide and aldehydic substrate, reported by Breiding and Fiske [4] in 1912. This was followed by various enantioselective important publications of MacMillan and List, which finally resulted in the 2021 Nobel Prize in Chemistry [5]. Being easily available either naturally or synthetically, organocatalysts are hence, easy to obtain, are economical and save time and energy [6]. A variety of efficient, smaller organocatalysts have widened the scope and field of organic synthesis, namely chiral proline derivatives, thioureas, brønsted acids, *N*-heterocyclic carbenes, the quaternary ammonium salts based on cinchona alkaloids [7] etc.

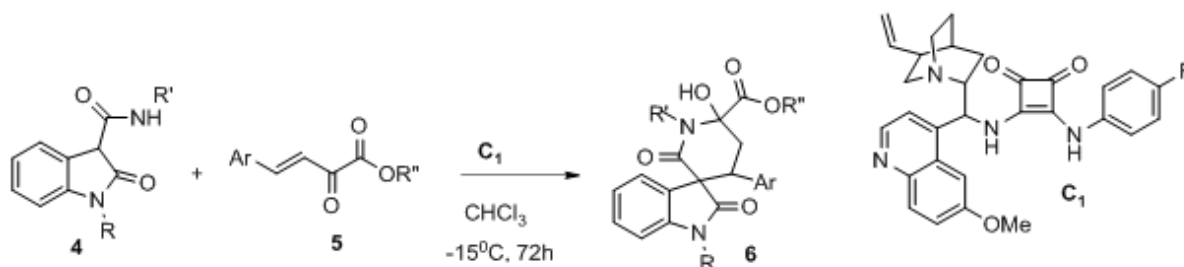
Milder conditions involved in the organocatalysis in comparison to most of the metal catalysts, and their low toxic nature finds them suitable in medicinal chemistry [8]. In addition to the decrease in the activation energy of the reaction, organocatalysis is also important in terms of environment and is a greener technique. As the use of catalysts is involved, which is one of the green chemistry principles, organocatalysis is greener [9] than traditional catalysis. It uses, mainly oxygen-stable reagents, is cheaper and saves energy. Organocatalysis is compatible with various functionalities which are sensitive to other processes—this leads to escape of the protection step, this in turn lowers the overall number of reaction steps. No production of metallic waste and avoidance of metals in the products, finds them applications in medicinal chemistry.

Asymmetric organocatalysis is useful for natural products synthesis, chiral drugs, and bioactive molecules. Šebesta et al. designed four new *N*-sulfinyl-*N*'-(pyrrolidinylmethyl)urea and *N*-sulfinyl-*N*'-(pyrrolidinylmethyl)thiourea bifunctional organocatalysts [10] (**Scheme 1**) and used them for reaction between aldehydes with nitroalkenes (Michael additions) using both solvent less condition and solvent condition. The sulfinylurea catalyst was better than the thiourea catalyst. Upto 98% ee enantioselectivities could be reached easily. The additional chiral center on the sulfur plays only a minor role on the stereoselectivity, which is mainly due to the proline configuration. Using Ball-milling conditions [11], good yields of the Michael products were obtained but enantiomeric purities was less than in solution. DFT calculations proved a dual activation mode, namely enamine activation of aldehydes and hydrogen-bond activation of nitroalkenes.



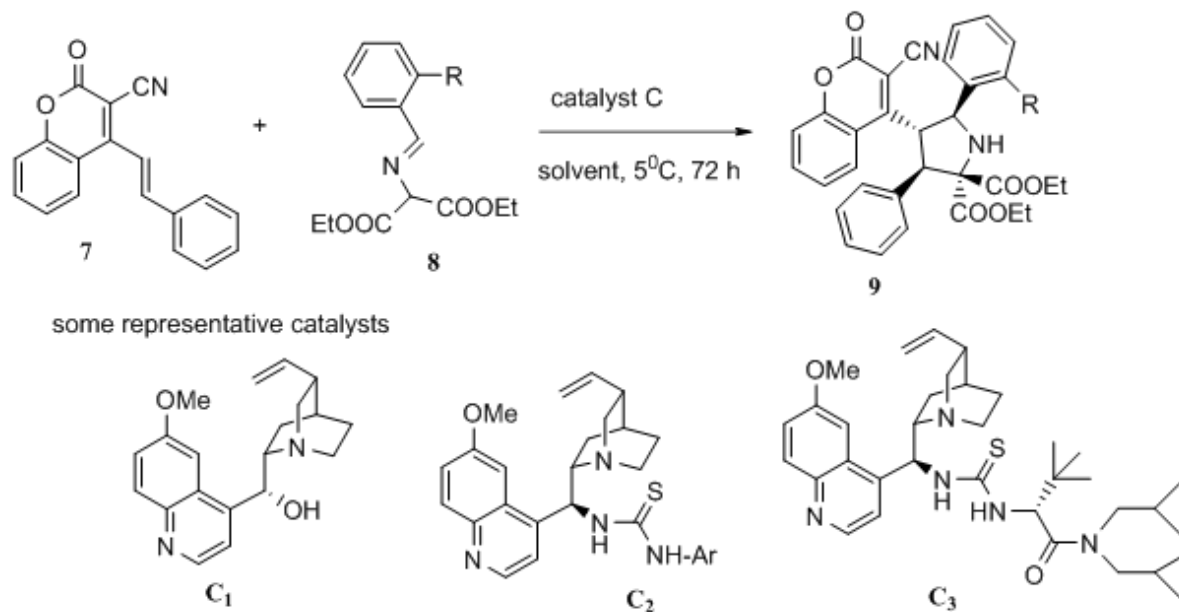
Scheme 1: Michael Addition Reaction of Aldehydes with Nitroalkenes using *N*-sulfinyl-*N'*-(pyrrolidinylmethyl)Urea/Thiourea Bifunctional Organocatalysts.

Zhang [12] et al. published the synthesis of spiro- δ -lactam oxindoles (**Scheme 2**) using organocatalysts and came up with various chiral centers through an annulation reaction. Their method is a metal free, novel, simpler and effective for the synthesis of bioactive spiro- δ -lactam oxindoles involving a wide variety of reactants, with good diastereo/enantioselectivities.



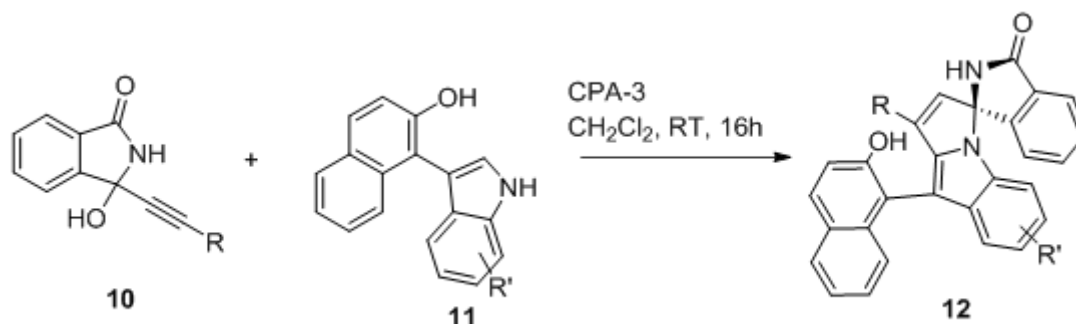
Scheme 2: Building of Bioactive Spiro- δ -Lactam Oxindoles

The (3 + 2)-cycloaddition reaction between cyanocoumarins with imines obtained from salicylaldehyde (**Scheme 3**) is reported by Albrecht group [13] using quinine-derived organocatalyst. Compounds with two biologically important units, were synthesized with good chemical/stereochemical selectivity. Further, some selected transformations of the cycloadducts were also reported.



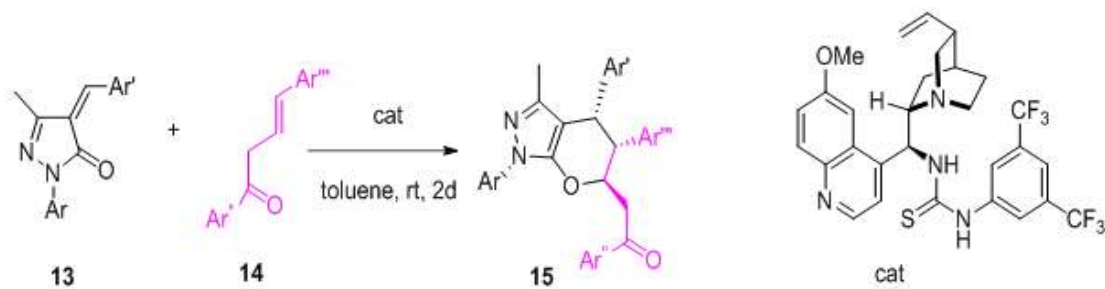
Scheme 3: Cycloaddition reaction between 4-(alk-1-en-1-yl)-3-Cyanocoumarins and Imines.

Introduction of chiral spiro *N,N*-acetal carbon stereocenters and chiral 3-arylindoles [14] (**Scheme 4**) through the (3 + 2) annulation of α -(3-isoindolinonyl) propargylic alcohols with 1-(3-indolyl)naphthalen-2-ols using a chiral phosphoric acid (CPA) was reported by Xia et al., the reaction resulted in pyrrolo[1,2-*a*]indoles in yields upto 77-95% and 73-96% ee.



Scheme 4: Building of Pyrrolo[1,2-*a*]Indoles

Bania [15] group came up with a report on the asymmetric Diels–Alder reaction between alkylidene pyrazolones with allylated ketones (**Scheme 5**). The synthesis was done by a bifunctional thiourea catalyst. The product, tetrahydropyrano[2,3-*c*]pyrazoles were obtained in moderately good yields, with diastereoselectivities/enantioselectivities. They have also reported a decarbonylation reaction as an application.

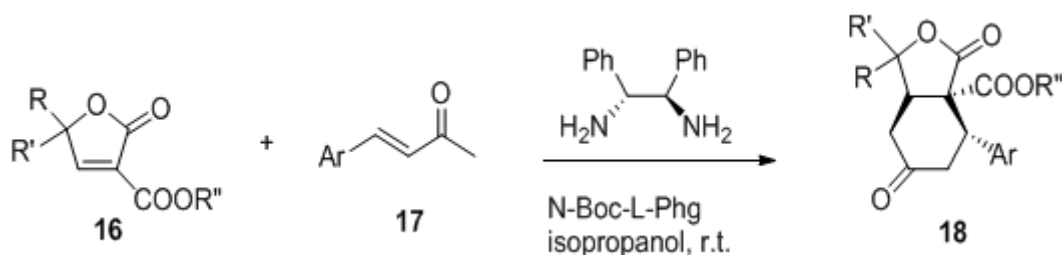


Scheme 5: Diels–Alder Reaction Involving Pyrazolones with Allylated Ketones

Through the aza-Friedel–Crafts reaction, coupling of electron-rich aromatic compounds with imines can be easily and efficiently done for the easy introduction of aminoalkyl groups into the aromatic system. This introduces aza-stereocenters which can then be tuned by organocatalysts. Biswas [16] in his review reported recent work in asymmetric aza-Friedel–Crafts reactions catalyzed by organocatalysts. Sharma coworkers [17] in their article compiled the work published in the last 10 years on the asymmetric aza-Michael reaction of amines and amides using organocatalysts. The authors reported both types of the organocatalysts, those which are acting through non-covalent interactions as well as others which are working through covalent bond formation. The review reported cinchona alkaloids, squaramides, chiral amines, phase-transfer catalysts and chiral bifunctional thioureas, which activate the substrates through hydrogen bond formation. High yields and high enantiomeric excesses were obtained in most of these reactions. N-heterocyclic carbenes and chiral pyrrolidine derivatives on the other hand, acting through covalent bond formation such as the iminium ions with the substrates were also included.

Substituted chiral pyrrolidines are the heterocyclic structural frameworks which are commonly present in bioactive natural and synthetic products [18]. Since the discovery and implementation of organocatalysis, chiral pyrrolidines have taken a leading role as organocatalysts, as they efficiently carry out different enantioselective transformations in an eco friendly way, without using the metals.

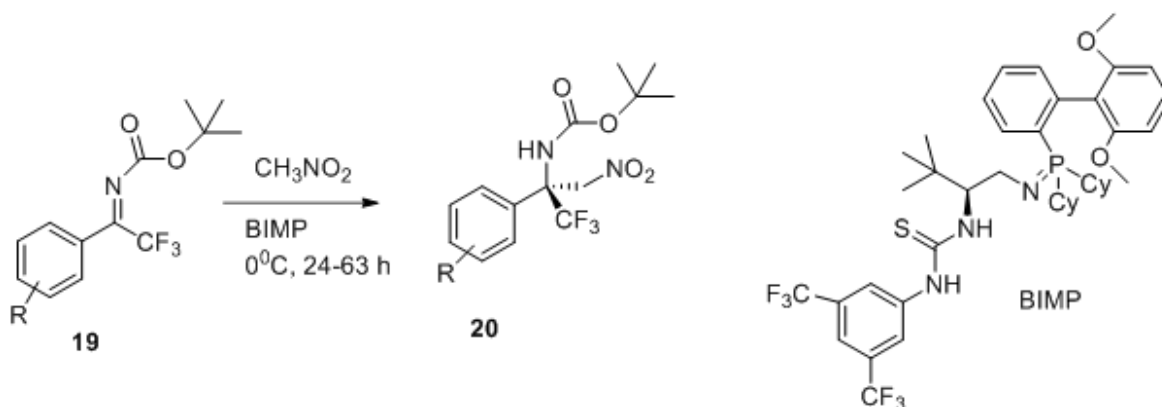
The organocatalyst, chiral spiro (S)-1-benzylspiro[indoline-3,2'-pyrrolidin]-2-one was used to carry out the enantioselective aldol condensation between isatins and acetone, and was reported by Zou coworkers [19], an array of chiral 3-hydroxy-3-(2-oxopropyl)-indolin-2-ones (**Scheme 6**) in excellent yields were synthesized in upto 97% yield and good enantioselectivities (upto 82% ee). Compared to the chiral prolinamide organocatalyst, the enantioselectivities of their catalysts were due to steric control rather than amide NH hydrogen bonding (for enamine organocatalysis). An enantioselective organo-catalyzed reaction for an efficient access under mild conditions to chiral bicyclic γ -butyrolactones in good yields [20], good enantioselectivities/diastereoselectivities has been established by Bai et al. by the reaction of furanones with α,β -unsaturated ketones.



Scheme 6: Synthesis of 3-Hydroxy-3-(2-oxopropyl)-Indolin-2-ones 18

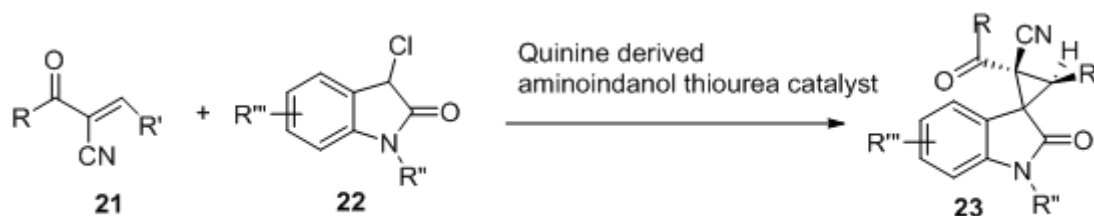
Proline-based organocatalysts are becoming important in organic synthesis, mainly in enantioselective synthesis. Proline and its derivatives are quite effective chiral organocatalysts in aldol reaction, which is one of the most important C-C bond forming reactions in organic synthesis. Numerous, highly efficient, proline-based organocatalysts, including polymer based chiral species, have been reported for aldol reaction. These polymer-supported organocatalysts demonstrated high stability under the reaction conditions and showed the best results, mainly in terms of its recyclability and reusability. These potential and their economic advantages including being greener, have led to the development of many more polymer-supported proline catalysts. Shajahan [21] in their review, published recent findings for asymmetric aldol reactions using various polymer immobilized proline-based chiral organocatalysts. Chemists from Hoffmann-La Roche and Schering AG in 1971, independently carried out intramolecular aldol reaction catalyzed by proline, this transformation is now known as the Hajos–Parrish–Eder–Sauer–Wiechert reaction. List and Barbas came up with a report in 2000 that L-proline can catalyze intermolecular aldol reactions with good enantioselectivities. In that same year, MacMillan reported efficient catalysis by imidazolidinones derived from amino acids on asymmetric Diels–Alder cycloadditions. These two reports sparked the origin of modern asymmetric organocatalysis. An important development in this upcoming field happened in 2005, through the independent work of Jørgensen and Hayashi on the use of diarylprolinol silyl ethers for the asymmetric functionalization of aldehydes. Since the last 20 years, there has been a tremendous development in asymmetric organocatalysis and it has evolved as a very powerful technique for the easy construction of complex molecules. Quintavalla [22] et al. in their review, starting from 2008, focused on the recent developments in the asymmetric synthesis of organocatalysts derived from proline or are related to it.

Organocatalysts, namely thiourea-based iminophosphorane (BIMP) with SPhos- or BIDIME phosphine units were developed and used in the asymmetric addition of nitromethane with *N*-Boc-protected trifluoromethyl aryl ketimines (**Scheme 7**) by Sanz coworkers [23] under mild conditions with no need of additional base. The product, α -Trifluoromethyl β -nitroamines were obtained in 40–82% yields and reaction were 80–95% enantioselective. The catalysts which was obtained from the reaction of a chiral 1,2-amino alcohol-derived thiourea-organoazide with phosphines, caused the aza-Henry reaction on fluorinated ketimines with high enantioselectivity (95% ee). The reaction could be done on a gram scale, with no loss of enantioselectivity. BIMP acted as superbases as well as H-bond donor.



Scheme 7: Reaction between Nitromethane and *N*-Boc-protected Trifluoromethyl aryl Ketimines using Thiourea-Based Iminophosphorane (BIMP) Organocatalysts

Quinine-based aminoindanol-thiourea catalyzed the Michael addition/alkylation reaction of chlorooxindoles with chalcones (**Scheme 8**) and was investigated by Wang coworkers [24]. Novel spirooxindoles condensed cyclopropane were efficiently synthesized in moderate-excellent diastereo-/enantioselectivity and these in turn were further converted to various structural diverse products. Density functional theory calculations conveyed that the intramolecular H-bonding in the catalyst were important for the stereoselectivity.



Scheme 8: Asymmetric Michael addition reaction of Oxindoles and α -cyano Chalcones

Lattanzi [25] in her report discussed their achievements, on the asymmetric synthesis of new three, five, and six membered heterocyclic compounds, also spiro compounds with quaternary chiral centres. Michael and aldol reactions (combinations) enabled them to increase the number of their compounds from thiophenes derivatives and lactones to hybrid scaffolds with heterocyclic units. On combining visible light photocatalysis with organocatalysis, lots of progress is reported in the synthesis. In these reactions, photocatalysts/photosensitizers absorb visible light and induce their photo-excited states which in turn cause activation of unreactive reactants through electron or energy transfer mechanisms, and organocatalysts are involved in controlling the reactivities of the other substrates. Shen et al. in their review [26] discussed the recent findings of reactions involving both, i.e., organocatalysis and photocatalysis in the synthesis of organic compounds. Review by Hughes [27] coworkers reported work in asymmetric organocatalysis from patents since 2018. Cinchona alkaloids as free base as well as quaternary salts, phosphonium salts, proline-based catalysts, and chiral phosphoric acids were reported for catalysis and were discussed. The group also highlighted asymmetric organocatalysis for the synthesis of pharmaceutical

compounds in industries. By taking pregabalin, as an example, Giorgianni et al. in their perspective [28] discussed the importance and role of organocatalysts. Chiral primary α -amino amides, with adjacent enamine bonding site (Bronsted base site), a hydrogen bonding site (Bronsted acid site), and bulky substituents, are important bifunctional organocatalysts for numerous asymmetric organic conversions. Primary α -amino amides are better organocatalysts than other primary amino organocatalysts, like chiral diamines/cinchona-alkaloid-derived primary amines. Also primary α -amino amides are less expensive, easy to produce, stable to air, and allow for the introduction of a variety of functional groups. Recently, Reddy group [29] have published work on the organocatalysis by α -amino amides as well as their derivatives on various reactions namely, aldol reaction, allylation of aldehydes, Strecker reaction, reduction of Aryl imines, Michael tandem reaction, epoxide ring opening, asymmetric hydrogen transfer, hydrosilylation and reaction of aldehydes with N-specific nitrosobenzene.

In their review, Reyes et al. [30] reported the work on the use of organocatalysts for the building of enantioselective products which are of relevance to the medicinal chemists [31] and pharmaceutical companies.

II. CONCLUSION

There had been an enormous development opportunities in the synthesis of organic moieties in the 21st century. Organic synthesis is the art and science of constructing organic molecules and has an enormous impact on human life and their well-being. It has benefitted the society by providing nutritional supplements, medicines, vitamins, cosmetics, high energy fuels, polymers and plastics to name a few. Organic chemistry is a highly innovative discipline. This discipline has also facilitated the emergence and development of other disciplines and technologies namely biology and biotechnology, chemical biology, medicinal chemistry, physics, materials science and nanotechnology. Based on the publication trends, asymmetric organocatalysis in organic synthesis is featured as the most recent trend in organic synthesis. This Chapter aims at discussing some recent, novel and advanced examples showing the multifaceted potential of this upcoming and important field.

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