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Research Article

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Atom Economy Green Synthesis in Organic Chemistry

Jaya Pandey, Shivi Singh, Ragini Dubey*

Department of Chemistry, Amity School of Applied Sciences, Amity University, Lucknow, Uttar Pradesh, India

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ABSTRACT

Atom economy is a fundamental concept in green synthesis in organic chemistry. It refers to the efficiency of a chemical reaction in utilizing the atoms present in the starting materials to form the desired product, while minimizing the generation of waste products. Its integration into reaction design and synthetic strategies can foster innovation while driving chemical processes towards environmental friendliness. A higher atom economy indicates a more sustainable and environmentally friendly reaction. This research article embarks on an exploration of atom-economical reactions within the realm of green chemistry. Various examples and methods are presented to illustrate the implementation of atom economy in organic synthesis. The atom-efficient reactions ranging from click chemistry to coupling reactions have been explained in this review.

Keywords: Green chemistry, Atom economy, Click chemistry, Coupling reactions, Sustainable

INTRODUCTION

Atom economy is a fundamental principle in green chemistry, emphasizing the efficient utilization of atoms in chemical reactions to minimize waste production. The concept of atom economy was introduced by in 1995, highlighting the importance of designing reactions that maximize the incorporation of starting materials into the desired product [1]. Atom economy, also known as the atom efficiency or atom utilization, is a measure of how effectively the atoms in the reactants are utilized in the formation of desired products [2]. It quantifies the proportion of atoms in the reactants that end up in the desired product, thus reflecting the efficiency of the synthesis process. Green chemistry principles, including atom economy, have gained increasing attention in recent years due to the growing concern for environmental sustainability and the need for more efficient and sustainable synthetic methods [3]. Green chemistry aims to minimize waste, energy consumption, and the use of hazardous substances while maximizing efficiency and the use of renewable resources [4]. In the realm of modern organic chemistry, the paradigm shift towards sustainability and environmental responsibility has sparked the rise of green chemistry principles [5]. At the forefront of this transformation is the concept of atom economy, a pivotal measure of reaction efficiency that encapsulates the wise utilization of resources and minimization of waste. Throughout this exploration of atom economy in green reactions, we have delved into its significance, calculation, and application in various organic transformations [6]. Barry Trost and Roger Sheldon encapsulates the notion of utilizing atoms judiciously and avoiding wasteful byproducts. It is a quantitative measure for chemical processes emphasizing on the importance of utilizing as many atoms from the starting materials as possible in the final product, thereby minimizing the generation of waste [7].

The calculation provides a quantitative assessment of the efficiency of the reactants to the product transformation in terms of atom utilization (Figure 1) [8].

$$\mathrm{A} + \mathrm{B} \xrightarrow[\text{Solvents. Catalysis}]{\text{Reagents}} \mathrm{C} + \mathrm{D}$$

$$\%\ \text{Atom Economy} = \frac{\mathrm{GMW(C)}}{\mathrm{GMW(A+B)}} \times 100\ \%$$

Figure 1: Equation for calculation of atom economy.

Calculation of the atom economy is the ratio of the molecular weight of the desired product to the total molecular weight of all the reactants, expressed as a percentage [9]. A higher atom economy indicates a more efficient use of atoms and resources, while a lower atom economy suggests that a significant portion of the starting materials ends up as waste or byproducts (Figures 2 and 3).

$$\text{Reaction Yield} = \frac{\text{quantity of product isolated}}{\text{theoretical quantity of product}} \times 100\ \%$$

$$\text{Atom Economy} = \frac{\text{molecular wt. of desired product}}{\text{molecular wt. of all products}} \times 100\ \%$$

Figure 2: Atom economy versus reaction yield.

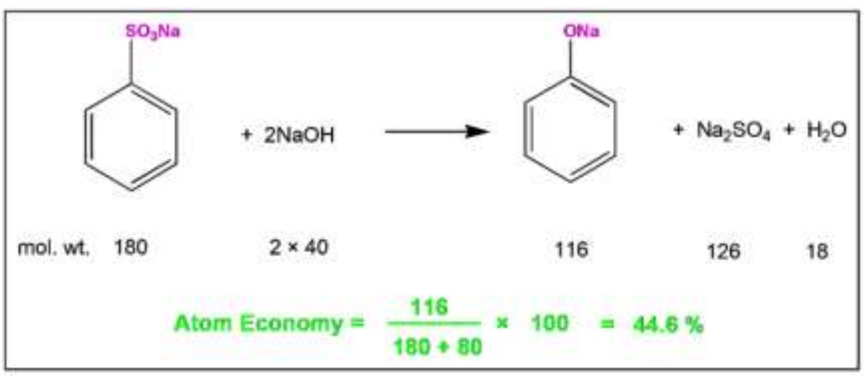

Figure 3: Atom economy example.

MATERIALS AND METHODS

Addition reactions

Addition reactions are the reactions involving combination of one or more reactants to form a larger single product [10]. Addition reactions are crucial for atom economical green synthesis, since they allow for new chemical bonds to be formed without generating a lot of waste [11]. These reactions exemplify the principles of green chemistry by efficiently using atoms and minimizing waste generation, ultimately contributing to more sustainable synthetic processes [12].

Diels Alder reaction: The Diels Alder reaction is a chemical process that combines a conjugated diene and a dienophile to create a cyclohexene ring. It enables the formation of compounds while minimizing the production of waste. By employing this reaction, chemists can contribute to sustainable and environmentally friendly chemical synthesis [13].

To illustrate the atom economy in the Diels-Alder reaction, let's consider the synthesis of a common compound, cyclohexene [14]. This reaction involves the reaction between 1,3-butadiene and ethene, resulting in the formation of cyclohexene. To assess the efficiency of this reaction we can calculate its atom economy by comparing the number of atoms in the starting materials with those in the desired product [15]. In this case both 1,3 butadiene and ethene contain four carbon atoms each resulting in eight carbon atoms in total within the reactants. The desired product, cyclohexene also consists of eight carbon atoms [16]. Therefore, this reaction exhibits 100% atom economy since all carbon atoms from the reactants are integrated into the product (Figure 4).

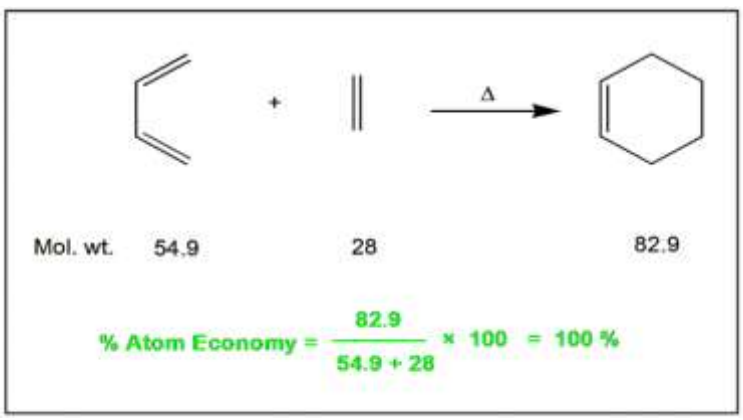

Figure 4: Atom economy of Diels Alder reaction.

Catalytic hydrogenation: In catalytic hydrogenation, a catalyst is used to facilitate the addition of Hydrogen (H_2) to unsaturated organic compounds [17]. Catalytic hydrogenation plays an important role in green chemistry by improving atom economy and reducing waste [18]. It allows inorganic compounds to be converted into highly complex compounds, contributing to the development of sustainable medicines. Catalytic hydrogenation using transition metal catalysts such as platinum, palladium and nickel provides a versatile and environmentally friendly method for greening [19].

One example of catalytic hydrogenation in green synthesis is the conversion of alkenes to alkanes. Alkenes are unsaturated hydrocarbons with carbon-carbon double bonds. Catalytic hydration of alkenes breaks the double bond and adds a hydrogen atom, resulting in an alkane [20]. For example, catalytic hydrogenation of ethene using a platinum catalyst produces ethane. This process reflects the principle of nuclear economy as all the atoms in the reactants end up in the desired product without generating waste or by-products (Figure 5).

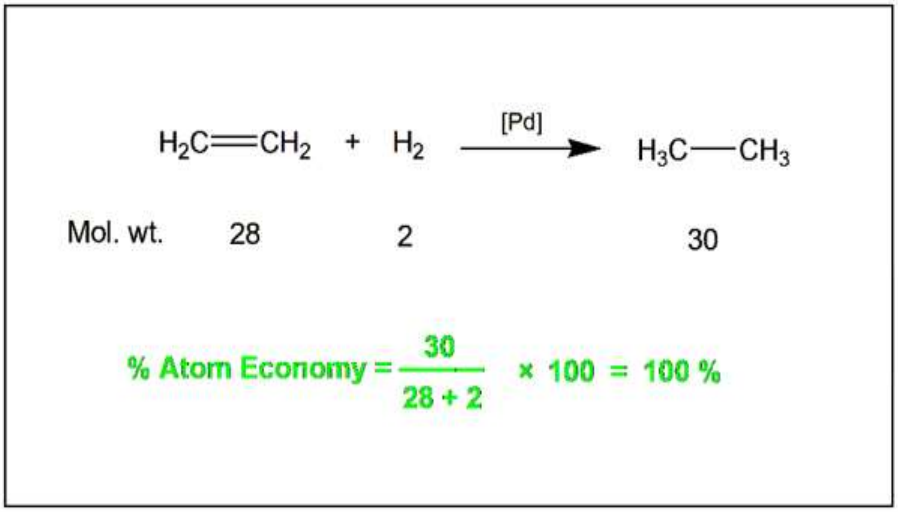

Figure 5: Atom economy of catalytic hydrogenation of alkenes.

Another example is the synthesis of alcohol by the reduction of carbonyl groups such as aldehydes and ketones. Catalytic hydrogenation of benzaldehyde with hydrogen gas in the presence of a palladium catalyst gave phenol. This modification is an important step in the synthesis of a variety of drugs, as it allows the introduction of hydroxyl groups without the need for aggressive reducing agents (Figure 6).

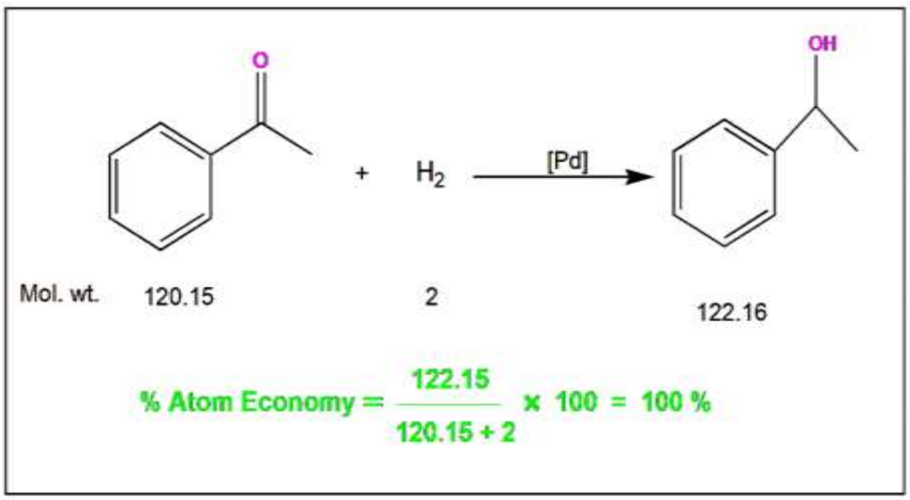

Figure 6: Atom economy of catalytic reduction of carbonyl group.

Coupling reactions: Coupling reactions play a crucial role in green synthesis by promoting atom economy, which refers to the efficient utilization of atoms in a chemical transformation. Some coupling reactions, such as the Suzuki-Miyaura cross-coupling and Heck reactions, are often considered to have relatively high atom economy. These reactions involve the formation of new carbon-carbon or carbon-heteroatom bonds and are known for their selectivity, efficiency, and minimal generation of byproducts (Figure 7).

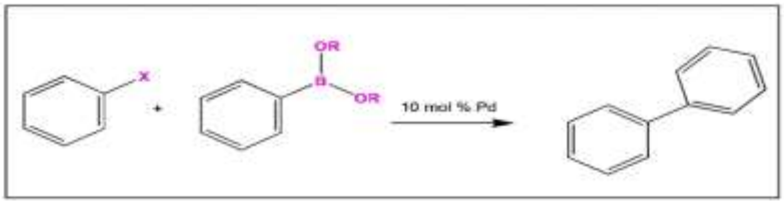

Figure 7: Example of coupling reaction.

Heck reaction: The Heck reaction is widely recognized as a highly atomic economic process due to its efficiency of adding a large fraction of the atoms of the reactants to the final product while minimizing waste generation so. An aryl or vinyl halide forming a carbon bond with both an alkene or an alkyne is effectively added to the final product, forming additional carbon-carbon bonds. The reaction apparently uses a carbon-carbon double or triple bond in the form of an alkene or alkyne, and a carbon-halogen bond in the form of an aryl or vinyl halide (Figure 8).

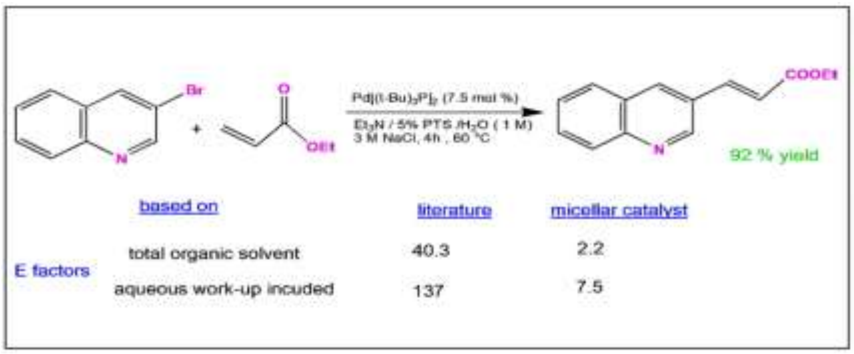

Figure 8: Example of heck reaction.

Suzuki-Miyaura cross-coupling reaction: Suzuki cross-coupling reaction is an organic reaction of an organohalide with an organoborane to give a cohesive product with a palladium catalyst and base Suzuki-Miyaura reaction A new carbon-carbon bond between an aryl or vinyl boronic acid and an aryl or vinyl halide is formed. This bond formation is atomically effective, because the carbon atoms of the reactants are added directly to the material (Figure 9).

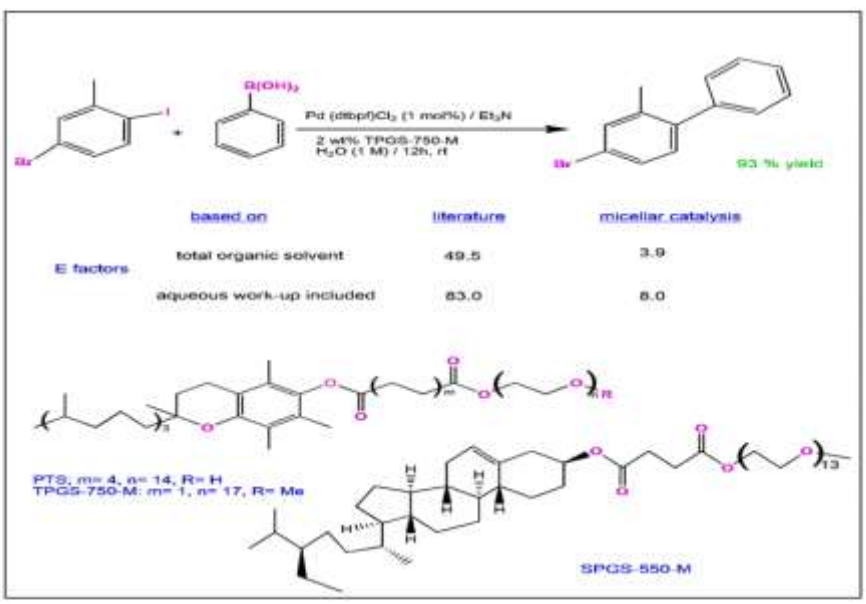

Figure 9: Example of Suzuki-Miyaura cross-coupling reaction.

RESULTS AND DISCUSSION

Click chemistry reactions

Click chemistry refers to a set of highly efficient, selective, and versatile reactions that are widely used in green synthesis due to their excellent atom economy. These reactions are characterized by their simplicity, high yield, and minimal byproduct formation. The term Click chemistry was coined by Nobel laureate K. Barry Sharpless to describe reactions that are efficient, selective, and easily applicable across various fields of chemistry.

Copper-Catalyzed Azide-Alkyne Cycloaddition (CuAAC): These reactions have high atom economy because they proceed rapidly and selectively and minimal side products. The CuAAC reaction involves the reaction between an azide-functionalized compound and an alkyne-functionalized compound, typically in the presence of a copper(I) catalyst and a reducing agent. This reaction leads to the formation of a triazole ring, and it has become a cornerstone of click chemistry due to its high efficiency and compatibility with various functional groups (Figure 10).

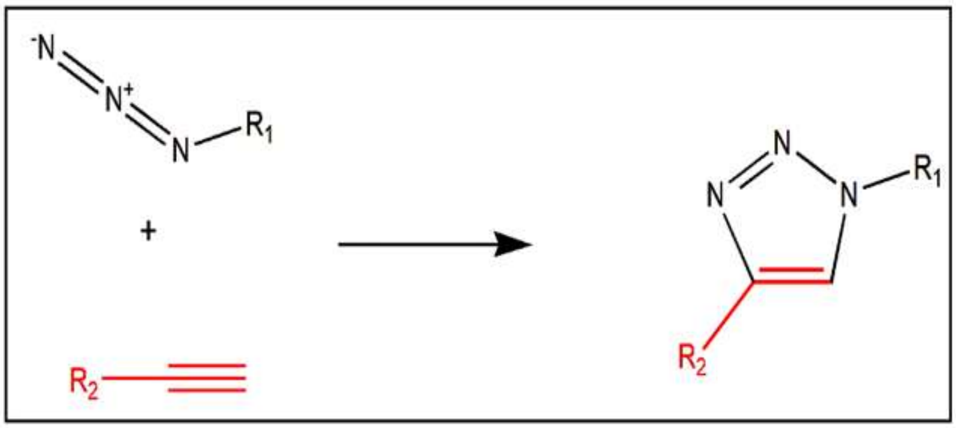

Figure 10: Copper-Catalyzed Azide-Alkyne Cycloaddition (CuAAC).

Solid-phase synthesis

Solid-phase synthesis is a powerful technique in green chemistry that increases the economics of nuclear by reducing waste by reducing the use of solvents. Complex catalyst organic reactions use a variety of substances as catalysts for reagents, catalysts, or reagents. These materials provide a stable matrix in which the reaction takes place, facilitating the separation, purification, and sometimes recycling of the components. In polystyrene and other resins, Polyethylene Glycol (PEG) resin functional groups can be attached to the resin surface to form anchoring reagents or catalysts Organic reactions use silica gel, polyacrylamide beads, zeolites, clays, such as montmorillonite or kaolinite.

Solid-phase synthesis provides a green and efficient method for chemical synthesis by reducing the use of solvents, facilitates purification, and enables the synthesis of complex molecules it is widely used in the pharmaceutical and biotechnology industries.

Peptide synthesis: A linker is attached to a complex of amino acids, usually using a conserved functional group. The peptide chain is formed by the sequential addition of amino acids, activating each amino acid to function on a stable substrate. Excess reagents and by-products are easily removed by washing. Column chromatography requires no other chemically demanding purification methods. The final peptide is cleaved from the solid support and can be further purified and characterized (Figure 11).

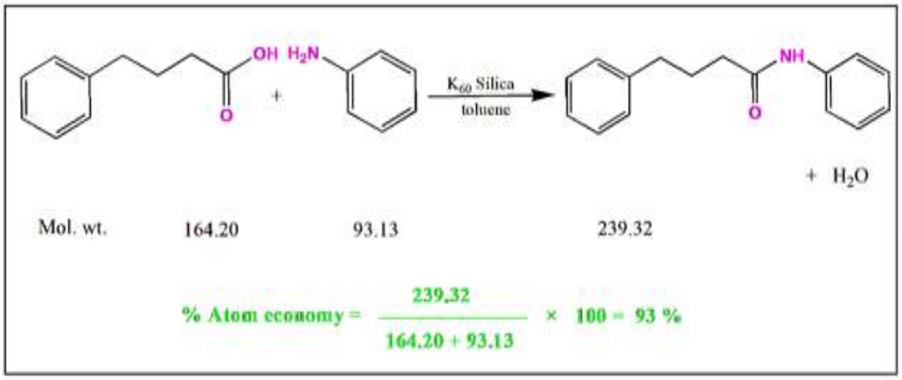

Figure 11: Atom economy of solid phase synthesis.

Rearrangement reactions

Rearrangement reactions involve the redistribution of atoms within a molecule to form new bonds and structural isomers. The atom economy calculation considers the extent to which atoms are conserved during the rearrangement process, reflecting the principles of green chemistry and resource efficiency.

Benzilic acid rearrangement: The rearrangement of benzylic acid is another system involving the conversion of ketones, particularly benzyl, into α-hydroxy acids, known as benzylic acids This reaction is catalysed by a base, usually an alkali metal hydroxide or alkoxide. The rearrangement is achieved by the displacement of the α-hydrogen atom and the subsequent formation of new carbon-carbon bonds.

This process exhibits high atomic economy because no atoms are destroyed or destroyed during the transition. First, it allows the use of readily available starting materials such as benzyl, reducing the need for complex and expensive precursors. Furthermore, the process can be carried out under mild conditions, usually at ambient temperature and pressure, with reduced energy requirements. Furthermore, the use of non-toxic and environmentally friendly raw materials such as alkali metal hydroxides or alkoxides contributes to the greening of all these raw materials (Figure 12).

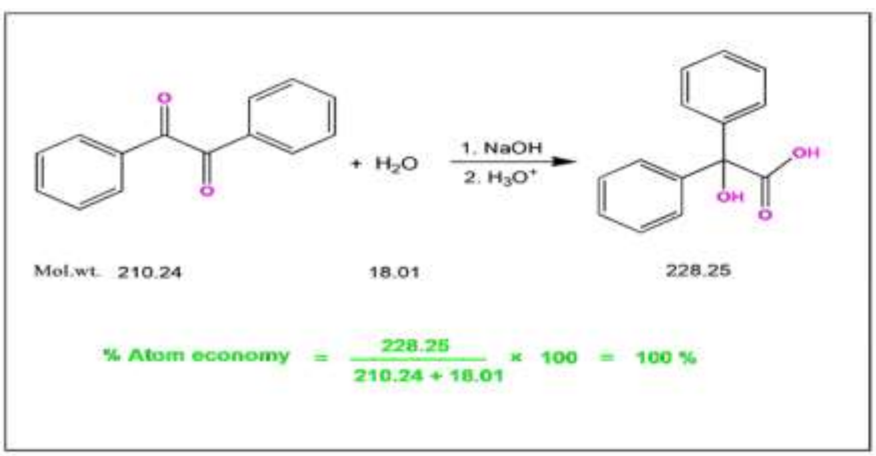

Figure 12: Atom economy of Benzilic acid rearrangement.

Claisen rearrangement: The Claisen rearrangement is a valuable tool in organic synthesis allowing atomic economic green synthesis of various compounds. This rearrangement involves the migration of an alkyl or aryl group from one carbonyl compound to another, resulting in a β-keto ester or β-diketone First discovered by the German chemist Rainer Ludwig Claisen in the late 19th century in the 19th century.

The Claisen rearrangement is particularly useful for the synthesis of complex organic compounds because of its high atomic efficiency. It allows new carbon-carbon bonds to be formed without the need for additional synthesis or waste treatment. By optimizing the use of starting materials, this process contributes to the principles of green chemistry (Figure 13).

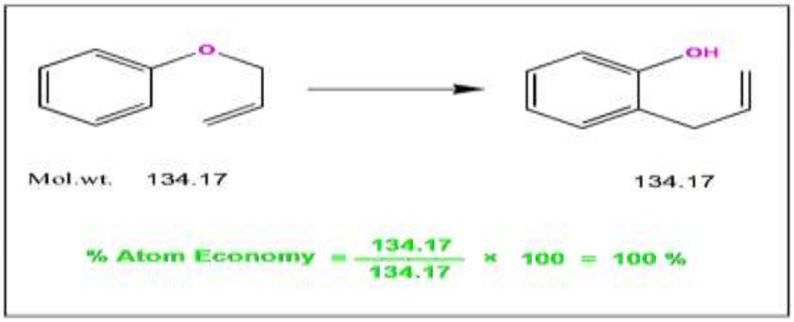

Figure 13: Atom economy of claisen rearrangement.

Beckmann rearrangement: A Beckman rearrangement is a powerful transformation in which the oxime functional group is changed to an amide or nitrile function. This process proceeds by migrating a nitrogen atom from one carbon atom to another in the oxime moiety. The resulting products are valuable raw materials for pharmaceutical, agrochemical, and material science applications.

The main advantage of Beckman's rearrangement is its high atomic economy because it requires only one reagent, an oxime, readily available in aldehyde or ketone and hydroxylamine. The rearrangement procedure ensures that atoms in the first step will all be included in the final product, making it an environmentally friendly manufacturing process.

To illustrate the practical application of Beckmann's new system in green production, let us consider the conversion of cyclohexanone oxime to caprolactam. The conversion begins with treatment of cyclohexanone with hydroxylamine hydrochloride to give cyclohexanone oxime. This oxime is then subjected to Beckman rearrangement conditions, often using an acidic catalyst such as sulfuric acid. The rearrangement displaces the nitrogen atom, resulting in a highly reactive isocyanate intermediate. This intermediate reacts rapidly with water to give caprolactam (Figure 14).

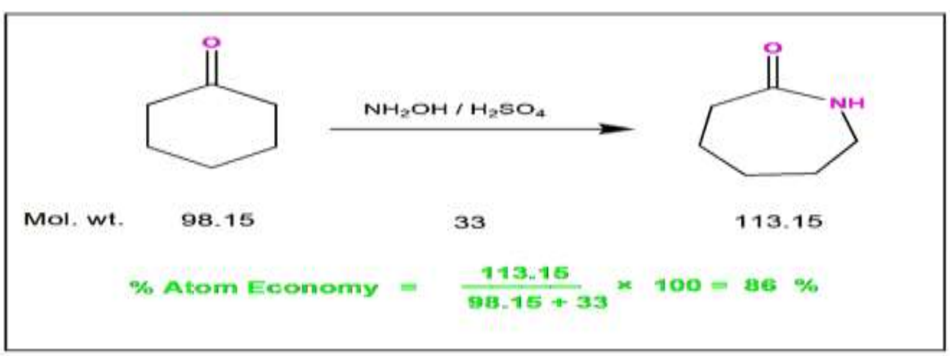

Figure 14: Atom economy of Beckmann rearrangement.

CONCLUSION

The concept of atom economy is essential in the design and application of atom-economical and selective organic transformations. These transformations aim to maximize the incorporation of atoms from starting materials into the final product, thereby reducing waste and improving resource efficiency. However, further research and education are needed to fully exploit the potential of atom economy in organic synthesis and to develop new strategies for improving atom efficiency in chemical reactions.

The concept of atom economy, which focuses on maximizing the incorporation of atoms from starting materials to minimize waste and by-products, has gained worldwide attention, and been accepted by in recent years. In the 1990's, green chemistry emerged as a key strategy for more efficient nuclear chemistry. Recently, research on various practices used in the production of natural products has shown that the nuclear economy is associated with the high intensity of these processes but the importance of the nuclear economy on nature cannot be overestimated in the production of less. The atom economy not only plays an important role in reducing waste but also ensures the efficiency and sustainability of production processes.

In conclusion, atom economy and green synthesis play an important role in the development of sustainable and environmentally friendly biochemicals. By maximizing atomic consumption and minimizing waste, these principles aim to reduce the environmental impacts of chemical reactions. atom economy can be enhanced using processes such as catalysis, renewable feedstocks and solvent optimization, leading to greener and more sustainable production processes.

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