Selenium Catalysts

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Green Chemistry with Selenium Reagents: Development of Efficient Catalytic Reactions

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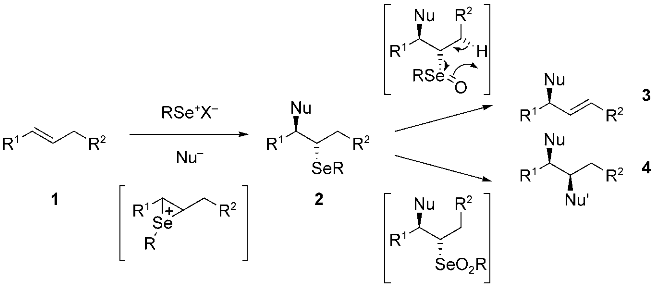
Applications of selenium reagents in organic chemistry have developed rapidly over the past years, and comprehensive reviews on this area have appeared.[1] Rather new, however, is the use of selenium-based catalysts in organic synthesis. We highlight new developments in organoselenium catalysis and in particular the use of selenium electrophiles and organoselenium compounds in carbonylation reactions and the oxidation of alkenes and carbonyl compounds. The use of organoselenium ligands for metal-catalyzed processes is not covered here; the topic has been reviewed recently elsewhere.[1f] Also their potential as efficient mimetics for selenoenzymes will not be discussed.[2] In this Highlight we will focus on the catalytic use of selenium electrophiles for selenenylations and halogenations as well as the use of perseleninic acids as catalytic oxidants for various substrates.

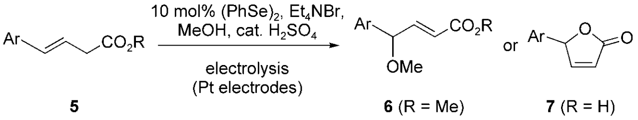
The use of electrophilic selenium reagents is a very versatile strategy for functionalizing alkenes **1**. To avoid the use of stoichiometric amounts of selenium reagents, researchers have sought for analogous catalytic methods. Selenenylation–deselenenylation sequences involve two steps: the initial selenofunctionalization is followed by oxidation of the organoselenium moiety in **2**, which allows the regeneration of the reagent through β elimination giving **3** or substitution to provide **4** (Scheme 1). Various reagents can be used to activate the selenide moiety in **2** to undergo elimination or substitution. The most explored approach involves oxidation with an excess of persulfate.[3] The oxidant is initially responsible for the generation of the electrophilic selenenylating agent from the corresponding diselenide and then for the oxidation of the selenium moiety in **2** allowing the regeneration of the catalyst. This approach proved to be useful for functionalizations such as hydroxylations, alkoxylations, and cyclizations, and when chiral nonracemic diselenides were used, interesting levels of stereoselectivity were reached.[3]



Scheme 1. Selenenylation of alkenes followed by elimination or substitution.

Depending on the substrate **5**, either an addition–elimination sequence to yield **6** or a cyclization–elimination sequence to give **7** is possible by using an electrochemical procedure (Scheme 2).[4] The reaction is initiated by anodic oxidation of bromide to bromine. The latter reacts with the diselenide to afford the arylselenenyl bromide, which promotes the selenofunctionalization. Subsequent elimination of the selenium moiety via a tetravalent selenium compound gives the products **6** or **7** and regenerates the arylselenenyl bromide. Alternatively, hypervalent iodine reagents such as [bis(trifluoroacetoxy)iodo]benzene can be used as oxidants, in combination with catalytic amounts (5 mol %) of diselenides, to effect the conversion of butenoic acids **5** (R = H) to the corresponding butenolides **7** in yields of up to 95 %.[5] In a diselenide-catalyzed dihydroxylation of alkenes with ammonium persulfate as the oxidant both nucleophiles are hydroxy groups and diols of type **4** (Nu = Nu' = OH) are obtained.[6]

Arylseleninic acids **8**[7] and also selenoxides[8] can be used as catalysts for the oxidation of bromide with hydrogen peroxide to hypobromite and bromine in a two-phase reaction



Scheme 2. Electrochemically driven selenenylation–elimination sequence.

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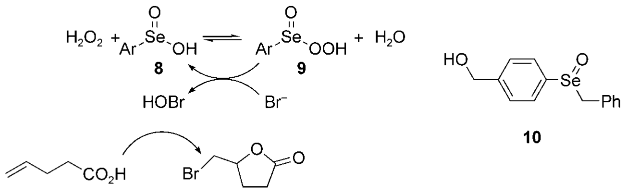


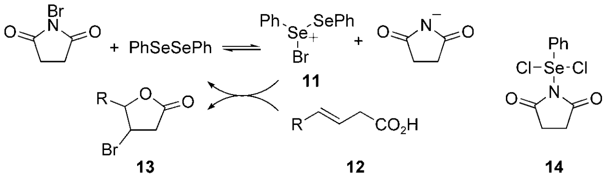
Scheme 3. Selenium-catalyzed oxidation of bromide for bromolactonizations.

mixture. The mechanism (Scheme 3) involves the formation of perselenenic acid **9** which is responsible for the bromide oxidation. Bromocyclizations of unsaturated acids or alcohols can be performed with catalyst **8** in the presence of sodium bromide and hydrogen peroxide generating the cyclic products in high yields. Similarly, the electrophilic bromination of activated aromatic substrates can be performed.

Detty and co-workers also demonstrated that dendrimeric polyphenyl selenides can catalyze the oxidation of bromide with hydrogen peroxide for subsequent reactions with alkenes.[9] A dendrimer with twelve PhSe groups showed an autocatalytic effect between the selenium moieties and resulted in turnover numbers of $>60\,000$. The reaction is initiated by the bromonium cation generated in the uncatalyzed background reaction.[10] More recently, the same group reported that the easily recoverable selenoxide **10** can be sequestered in a halide-permeable xerogel, which serves as an impressive catalyst for the brominations of arenes and for bromolactonizations.[11]

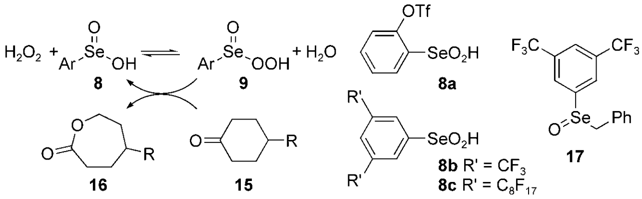
N-Halosuccinimides such as *N*-bromosuccinimide (NBS) and *N*-chlorosuccinimide (NCS) can also be used as halogen sources in organoselenium-catalyzed oxidative halogenations. Selenium catalysts react by enhancing the electrophilicity of the oxidized halogen compounds, and the mechanisms involve an electrophilic halogenation. Tunge et al. reported halolactonizations,[12a,b] α-halogenations of ketones,[12c] and allylic halogenations.[12d] Diphenyl diselenide proved to be the most active and selective catalyst for the bromolactonization of **12** to **13** with NBS (Scheme 4).[12a] In the proposed mechanism the electrophilic NBS is activated by nucleophilic attack of PhSeSePh; it was suggested that the Se−Se bond is not cleaved by NBS during the reaction. The oxidized selenium halide **11** is then capable of cyclizing the alkene while the selenium derivative remains coordinated to bromine during the formation of the lactone ring.

In a similar way, the chlorination of β-ketoesters with NCS can be catalyzed by 5 mol % PhSeCl via a reactive, tetracoordinate intermediate **14**.[12c] The chemoselecivity of the chlorination of α,β-unsaturated ketones can be controlled by the solvent, affording either the allyl chloride or a vinyl chloride product after elimination of the selenium moiety.[12] Polymer-bound selenenyl bromide derivatives have been used for efficient allylic chlorinations.[13] Recently, also the synthesis of iodohydrins from alkenes catalyzed by diphenyl diselenide in the presence of *N*-iodosuccinimide and water has been described.[14]



Scheme 4. Selenium-catalyzed bromolactonization. R = H, Ph, alkyl.

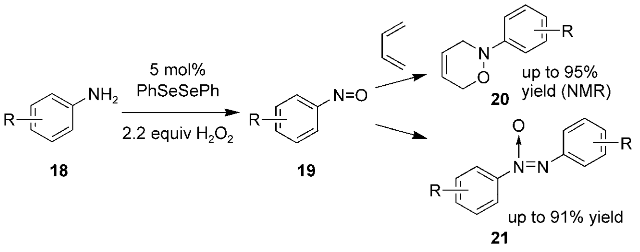
Organic peracids are used as common reagents in the Baeyer–Villiger oxidation. Their synthesis can involve safety issues, and waste acids must be disposed of after the reaction. The use of hydrogen peroxide with a catalyst has emerged as a clean alternative. Recently, Ichikawa and co-workers described the novel seleninic acid **8a** as a catalyst for the Baeyer–Villiger oxidation.[15] Reaction with hydrogen peroxide generates the peracid, which reacts with ketones **15** to yield the corresponding lactones **16** in high yields (Scheme 5).



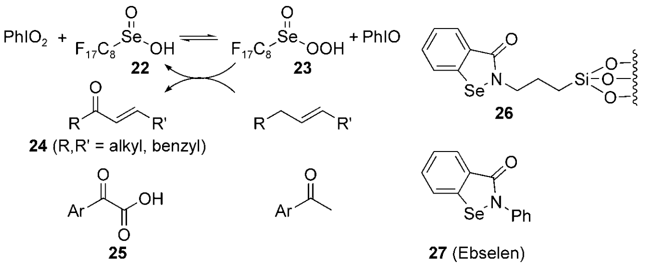
Scheme 5. Baeyer–Villiger oxidation catalyzed by seleninic acids.

The synthesis of 3,5-bis(perfluoroalkyl)phenyl seleninic acids **8b** and **8c** as recyclable catalysts for oxidation reactions with hydrogen peroxide was described by Sheldon and co-workers.[16] These catalysts can be used for oxidations under monophasic, as well as fluorous biphasic and fluorous triphasic reaction conditions. Baeyer–Villiger reactions, oxidations of aldehydes to carboxylic acids, and even cleavages of 1,2-dicarbonyl compounds have been described. Attempts to perform asymmetric Baeyer–Villiger oxidations using chiral organoselenium catalysts resulted in only minor selectivities (e.r. up to 60:40).[17] Aryl alkyl selenoxides such as **17** can also be used as precatalysts for the Baeyer–Villiger oxidation.[18] Catalyst **17** can also be employed in the epoxidation of various alkenes in good yields. Perseleninic acids, generated from diphenyl diselenide and hydrogen peroxide, can also be used for the oxidation of primary aromatic amines **18** to aromatic nitroso compounds **19**.[19] The nitroso compounds **19** can be used in a one-pot hetero-Diels–Alder reaction with conjugated dienes to form oxazines **20**[19a] as well as for the simple and efficient preparation of azoxyarenes **21** (Scheme 6).[19b]

An easily accessible fluorous seleninic acid **22** was employed by Crich and Zou as the catalyst in allylic oxidations leading to α,β-unsaturated carbonyl derivatives **24** in good yields (Scheme 7).[20a] A recent report shows that the same catalyst can be used for the efficient oxidation of aryl alkyl ketones to ketoacids **25**, and even benzylic methylene groups can be oxidized to the corresponding ketones.[20b] The highly electron-deficient seleninic acid is an easy-to-handle, effective catalyst when used in conjunction with a hypervalent iodine oxidant. An easily removable, silica-supported organoselenium catalyst **26** was introduced for the oxidation of alkylarenes, aromatic aldehydes, and sulfoxides using *tert*-butyl hydroperoxide as oxidant.[21] The



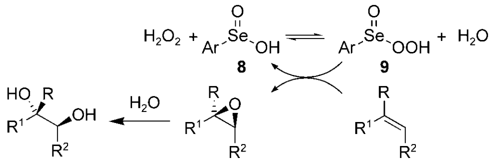
Scheme 6. Synthesis of nitroso derivatives **19** catalyzed by perseleninic acids.



Scheme 7. Allylic oxidation and oxidation of ketones catalyzed by perseleninic acids.

reaction and substrate selectivities are similar to those of Ebselen (**27**), an established organoselenium catalyst.

Selenium-catalyzed epoxidations are already established,[22] but the combination with a subsequent ring-opening reaction leading to dihydroxylated products was developed recently.[23] The alkene is epoxidized by the perseleninic acid and the epoxide is opened by an S_N2-type reaction (Scheme 8). The stereocontrol in these reactions depends on the steric and electronic properties of the substrate. The oxidations which use selenium dioxide are not affected by other functionalities in the substrate.



Scheme 8. Alkene dihydroxylation by epoxidation of alkenes catalyzed by perseleninic acids. R = Ph, Me, *n*Pr; R^1 = H, Ph, Me; R^2 = H, Me, *n*Pr.

These recent developments in selenium-based catalytic methods clearly demonstrate that new and alternative strategies remain to be discovered for the facile functionalization of different substrates.

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