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En route to metal-mediated and metal-catalysed reactions in water

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This perspective report presents the key approaches for the development of various organometallic reactions in aqueous media. In view of future sustainability, the efficient use of natural resources, such as renewable biomass-based feedstocks, constitutes an important aspect for sustainable chemical industry. The exploration and discovery of efficient organometallic reactions or equivalents in water enrich the toolbox of organic chemists for the direct conversion of biomass-derived feedstocks into high-valued chemicals and the direct modification of biomolecules in their native aqueous environment, which contributes to future sustainability.

Introduction

Carbon-carbon bond formation plays the central role in synthetic organic chemistry. For polar routes, such transformations necessarily involve carbon nucleophiles and electrophiles.¹ One class of the most commonly used nucleophiles is organometallic compounds. Since the discovery of alkylzinc compounds by Frankland from the reaction of iodoalkanes with metallic zinc,² organometallic reagents serving as nucleophiles for organic syntheses have been rapidly evolved both in scope and application.³⁻⁷ The early discoveries of Reformatsky,⁸ Barbier,⁹ Grignard,¹⁰ and Gilman¹¹ are among the important milestones in the development of classical organometallic reactions. Subsequently, there have been great progresses in the use of alkali¹² and other metals since the 1930s. Recently, organometallic reactions catalysed by transition metals have become increasingly important in the synthesis of organic molecules,¹³ underscored by three Nobel Prizes: for palladium-catalysed cross-coupling in 2010,¹⁴⁻¹⁶ olefin metathesis in 2005¹⁷⁻¹⁹ and asymmetric catalysis in 2001²⁰⁻²² within the last decade.

In spite of the enormous progress being made, there are obvious shortcomings for classical organometallic reactions in terms of chemical sustainability, such as the extensive use of organic solvents, stoichiometric metals, moisture and functional group intolerances, which are partially ascribed to the limitation of the historical development of classical reactions from fossil based feedstocks²³ bearing no functional groups and being insoluble in water. Accordingly, classical organic reactions were intuitively developed in fossil originated organic solvents. With the increasing concerns of the depletion of non-renewable fossil resources and the environmental

deterioration,²⁴ developing products from renewable resources and improving resources/energy utilization efficiency are the key measures towards future chemical sustainability.²⁵

Biomass, as a sustainable and renewable feedstock provided by nature could be a practical alternative towards future chemicals.²⁶⁻²⁸ In contrast to the fossil-based feedstocks, biomass-based ones are generally over-functionalized and often soluble or soluble after depolymerisation in water. As a result, further processing is required to adapt them to the reaction conditions that were initially developed for fossil-based classical organometallic reactions in organic solvents. One of the most common strategies for such purposes is the exhaustive protecting group manipulations, which in turn limiting the possibility of using water as solvent and leading to extra steps and waste *etc.* Conversely, exploration of organometallic reactions directly in water could be a possible solution in terms of various functional groups tolerance and direct chemical modification of biomolecules. Hence, exploring such fundamentally novel chemistry would potentially simplify chemical synthesis significantly, improve synthetic efficiency, provide valuable tools for chemical biology, and contribute to the future chemical sustainability²⁹ with respect to atom-economy,³⁰ the E-factor³¹ and step-economy.³²

General design concept

Most classical organometallic compounds are highly polarized as carbanions, which are also strong bases. Consequently, they are unstable towards active protons (moisture or functional groups) and must be synthesized/used under strictly anhydrous/aprotic conditions. Conceptually, the key to developing successful organometallic reactions in water (aqueous media) is to attenuate or prevent the protonation of carbon-metal bond once the organometallic species is generated (eqn (1)).

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Scheme 6 Synthesis of (+)-*N*-acetyl neuraminic acid.

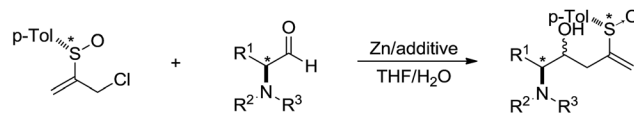
vinylloxiranes, 2-methylenetetrahydrofurans,⁷⁰ trimethylene-methane equivalent,⁷¹ cyclopentane derivatives.⁷² A carbocyclic ring enlargement methodology was also developed (Scheme 7),^{73,74} by using the indium-mediated Barbier-type reaction in water, in which 5-, 6-, 7-, 8-, and 12-membered rings are expanded by two carbon atoms into 7-, 8-, 9-, 10-, and 14-membered ring derivatives respectively. The use of water as a solvent was found to be critical for the success of the reaction and similar ring enlargement in organic solvents was not successful. Such a ring expansion strategy can also be applied to heterocyclic medium ring and⁷⁵ one carbon-ring expansion.⁷⁶

The diastereoselectivity of such reaction was studied in detail by Parquette and co-workers, and found that the free hydroxyl derivatives react with excellent diastereofacial control to give significantly heightened levels of *syn*-1,2-diols and *anti*-diols (Scheme 8).⁷⁷ Relative reactivities were determined in the α -series and the hydroxyl aldehyde proved to be the most reactive substrate. This reactivity ordering suggests that the selectivity stems from chelated intermediates. The rate acceleration observed in water can be heightened by initial acidification. Then they reported a variety of diastereoselective allylations in aqueous conditions and their synthetic applications such as a practical alternative to the Knoevenagel reaction of aliphatic aldehydes, the formation of α -methylene- γ -lactones fused to medium and large rings and the intercalation of multiple carbon atoms between the carbonyls of α -diketones.⁷⁸

In 2002, Delgado and co-workers reported a Barbier-type diastereoselective allylation of α -amino aldehydes with an enantiopure 2-sulfinylallyl building block in aqueous media mediated by zinc (Scheme 9).⁷⁹ High levels of diastereoselection can be achieved from α -amino aldehydes configurationally related to natural α -amino acids.

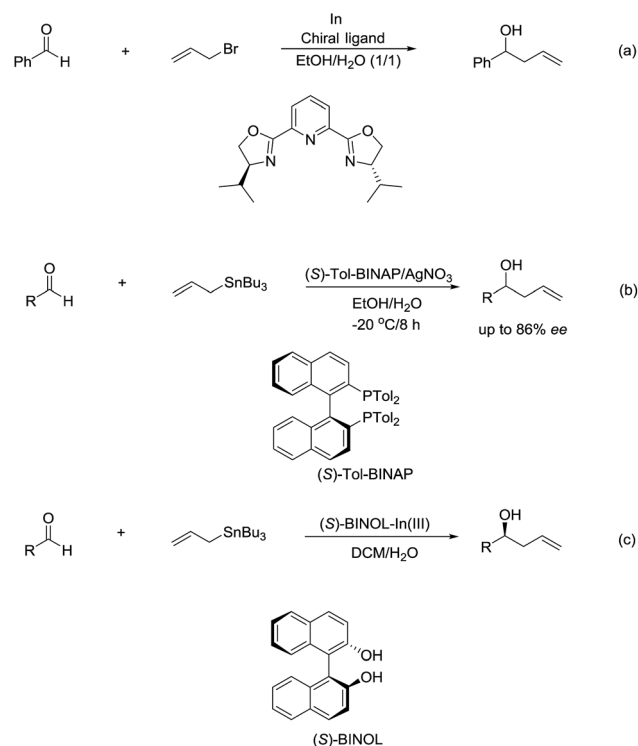


Scheme 7 In-mediated carbocyclic ring expansion in water.

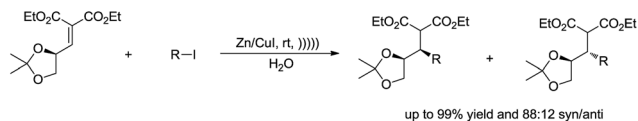
Scheme 8 In-mediated diastereoselective allylation of α -oxy aldehydes in water.Scheme 9 Zinc-mediated Barbier-type diastereoselective allylation of α -amino aldehydes with 2-sulfinylallyl chloride in aqueous media.

The enantioselectivity of such reactions in water was also possible. In 1999, an enantioselective allylation reaction of aldehydes in an aqueous media using chiral pyridine bis(oxazoline) ligand was reported by Loh and co-workers (Scheme 10a).⁸⁰ Subsequently, a AgNO_3 /(*S*)-Tol-BINAP-catalysed enantioselective allylation of aldehydes using allyltributylstannane was achieved by the same group (Scheme 10b).⁸¹ Later, they reported an enantioselective allylation of aldehyde catalysed by a moisture-tolerant chiral (*S*)-BINOL-In(III) complex. The allylation of a variety of aromatic, α,β -unsaturated and aliphatic aldehydes resulted in both moderate to good yields and high enantioselectivities (Scheme 10c).⁸²

In 2003, Kobayashi and co-workers reported a catalytic asymmetric allylation of aldehydes using allyltributyltin in aqueous media *via* the combination of cadmium bromide and chiral diamine ligands. Interestingly, these ligands were found to accelerate the reactions significantly (Scheme 11).⁸³ Later, they reported an In-catalysed allylation of ketone with allyl

Scheme 10 (a) In-mediated enantioselective allylation of aldehydes using chiral pyridine bis(oxazoline) ligand; (b) AgNO_3 /(*S*)-Tol-BINAP-catalysed enantioselective allylation of aldehydes using allyltributylstannane in an aqueous media; (c) In(III)-(*S*)-BINOL complex catalysed enantioselective allylation of aldehyde using allyltributylstannane in an aqueous media.

Perspective



Scheme 22 Zinc-copper couple-mediated diastereoselective addition of alkyl iodides and α,β -unsaturated compounds in water.

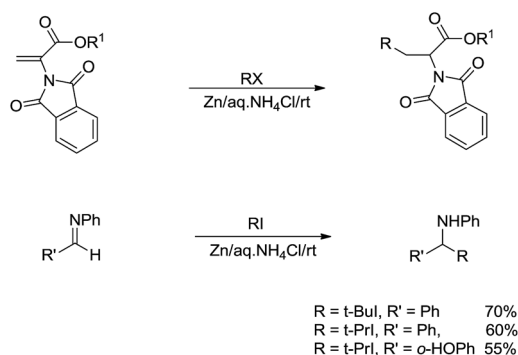
prevent the more facile reversed reaction to break the C-C bonds of the radical addition intermediate. One approach is *via* the stabilization of the radical. Thus, in 2002, Li and co-workers reported a zinc-mediated conjugate addition reaction of alkyl halides to α -phthalimidoacylate derivatives and nucleophilic addition to imines for the efficient synthesis of α -amino acid derivatives and amines in the presence of NH_4Cl in water (Scheme 23). Notably, no reaction was observed in absence of water.¹¹⁶

It is noteworthy that Li and co-workers also reported a magnesium-mediated Barbier-type allylation of aldehyde using water as a sole solvent, which proceeds most likely *via* a radical process on the metal surface (Scheme 24).¹¹⁷

In 2002, Naito and co-workers reported an intermolecular alkyl radical addition to imine derivatives and electron-deficient C-C double bond in aqueous media by using indium as a single-electron-transfer radical initiator (Scheme 25).¹¹⁸ The one-pot reaction provided a convenient method for preparing α -amino acids.

In 2003, they reported an indium-mediated cascade reaction, in which the addition-cyclization-trapping sequences efficiently generated the cyclized products in aqueous media (Scheme 26).¹¹⁹ The substrates bearing vinylsulfonamide and hydrazone proceeded smoothly in aqueous media to provide the functionalized cyclic products.

For the even more challenging Barbier-Grignard-type carbonyl alkylation using unactivated alkyl halides in water,



Scheme 23 Zinc-mediated conjugate addition of alkyl halides to α -phthalimidoacylate and imine derivatives in aqueous media.



Scheme 24 Barbier-Grignard allylation of aldehydes with magnesium in water.



Scheme 25 Indium-mediated alkyl radical addition to imine and phenyl vinyl sulfone derivatives in aqueous media.

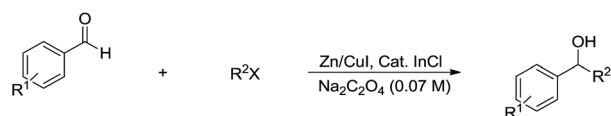


Scheme 26 Indium-mediated radical addition-cyclization-trapping cascade reaction in aqueous media.

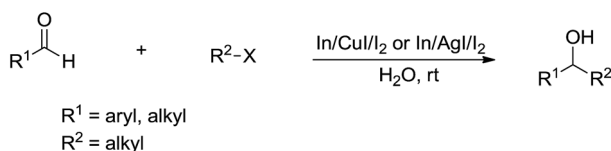
in absence of radical stabilization, the “reductive Lewis acid” concept was used by Li and co-workers successfully, in which conceptually the addition is accompanied by reduction and “free radical intermediate” is not “free” during the reaction progress (Scheme 27).¹²⁰

In 2008, Loh and co-workers further developed this Barbier-Grignard-type alkylation reaction of aldehydes including aliphatic version using unactivated alkyl halides in water catalysed by In/CuI or In/AgI catalysis (Scheme 28).¹²¹ The reactions proceeded more efficiently in water than in organic solvent.

Another type of reactions is the metal-mediated Reformatsky-type reaction. The reaction of a metal with an α -halogen carbonyl compound would generate an organometallic intermediate that can equilibrate between the carbanion form and the enolate form. Like the case of allyl and propargyl, the enolate form would allow the reaction to proceed through a six-membered cyclic transition state and thus could be energetically favorable. Indeed, the reaction of an α -halogen carbonyl compound with an aldehyde in the presence of zinc, tin, or indium in water provided a direct cross-aldol reaction product (Scheme 29).^{122,123} While a direct Reformatsky-type reaction occurred in low yields in the case of aromatic aldehydes were



Scheme 27 Zinc-mediated Barbier-Grignard-type carbonyl alkylation in water.



Scheme 28 In/CuI or In/AgI -mediated alkylation of carbonyls in water.





Scheme 29 Zn, Sn and In-mediated direct cross-aldol reactions of aldehydes and α -halogen carbonyls.

used in water mediated by zinc.¹²⁴ Later Lee and co-workers reported that the reactions of aldehydes or ketones with ethyl bromoacetate in the presence of indium promoted by ultrasound afforded β -hydroxyesters in good to excellent yields under mild conditions.¹²⁵ Bieber and co-workers found that even catalytic amounts of benzoyl peroxide or peracids can greatly enhance the reactions of bromoacetates and aromatic aldehydes, giving satisfactory yields. A radical chain mechanism, initiated by electron abstraction from the organometallic Reformatsky reagent, was proposed (Scheme 30).¹²⁶

The indium-mediated aqueous Reformatsky reaction was successfully applied to the synthesis of α,α -difluoro- β -hydroxy ketones by Welch and co-workers in 2001 (Scheme 31).¹²⁷

Via temporarily stabilization (surfactant) or on water strategy

One strategy that nature frequently adopts to perform reactions in aqueous media is encapsulation *via* lipid bilayer membranes.³⁴ Chemists, in turn, have developed surfactants that can be self-assembled in water to form micelles,¹²⁸ which provide the lipophilic interior to serve, in essence, as the solvent for catalysis. Organic solutes interact with micelles according to their polarity: non-polar solutes are encapsulated in the interior



Scheme 30 Zinc-mediated Reformatsky-type reaction of bromoacetates and aromatic aldehydes and the proposed radical chain mechanism.



Scheme 31 In-mediated synthesis of α,α -difluoro- β -hydroxy ketones in water.

of the micelle, while polar solutes locate themselves at the surface of the micelle and moderately polar molecules would be positioned closer to the polar surface. This compartmentalization of solutes lays the foundation and is responsible for many organic reactions in aqueous media, particularly assisting with organometallic processes, as the lipophilic interior of the surfactants provides the hydrophobic area to temporarily stabilize polar carbon–metal bond and facilitate the chemical transformation, such as in oxidation, reduction and C–C coupling reactions.¹²⁹

Recently, the application of surfactants for aqueous catalysis has been demonstrated in the development of catalytic organometallic reactions in water. For example, in 2004, Kobayashi and co-workers reported a Zn-mediated enantio and diastereoselective, stereospecific Mannich-type reaction in water, in which the surfactant CTAB (cetyltrimethylammonium bromide) significantly improved the yield (Scheme 32).¹³⁰

In 2012, Lipshutz and co-workers reported a copper-catalysed conjugate addition of alkyl halides to enones mediated by zinc in aqueous media using TPGS-750-M as surfactant (Scheme 33).¹³¹ Various cross-coupling reactions catalysed by transition metals in aqueous media using surfactants were also reported by his group.^{132,133}

In 2014, Li and co-workers reported the Rh-catalysed and Zn-mediated Barbier–Grignard-type arylation of aldehydes using unactivated aryl iodides in water, in which the organometallic species could be temporarily stabilized by encapsulation into the lipophilic interior of the surfactant BrijC10 (Scheme 34).¹³⁴

In 2018, Lipshutz and co-workers developed an environmentally responsible, mild method for the synthesis of functionalized 1,3-butadienes *via* Pd-catalysed cross-coupling of substituted allenic esters in water in the presence of the surfactant TPGS-750-M (Scheme 35).¹³⁵ Various sp^2 – sp^2 , sp^2 – sp^2 , and sp^2 – sp^3 coupling reactions were realized and these transformations tolerated broad functional groups.

As for the reactivity of polar organometallic compounds on water, recently Capriati and co-workers reported the nucleophilic addition of Grignard reagents and lithium reagents to γ -



Scheme 32 Zinc-mediated asymmetric Mannich-type reactions in water using CTAB as surfactant.



Scheme 33 Cu-catalysed and zinc-mediated conjugate additions of alkyl halides to enones in aqueous media using TPGS-750-M as surfactant.





Scheme 34 Rh-catalysed and Zn-mediated Barbier–Grignard-type arylation of aldehydes in water using BrijC10 as surfactant.



Scheme 35 Pd-catalysed cross-coupling of substituted allenic esters for the synthesis of functionalized 1,3-butadienes in water in the presence of the surfactant TPGS-750-M.

chloroketone on water at room temperature and under air for efficient formation of THF derivatives, in which water may play an important role as demonstrated by the solvent isotope effect and the control experiments that indicate the strong intermolecular hydrogen bonds jointly with *trans*-phase H-bonding with the substrate, thus (a) shielding the organometallic reagent from competitive protonolysis processes and (b) activating the carbonyl derivative towards nucleophilic addition (Scheme 36a).¹³⁶ Later, they further developed the nucleophilic additions of organolithium and organomagnesium reagents to imines and nitriles using bulk water as a privileged reaction medium, working under air, at room temperature, with vigorous stirring (Scheme 36b).¹³⁷ The significant solvent D/H isotope effect observed for the on-water nucleophilic additions of organolithium compounds to imines suggests the on-water catalysis arises from proton transfer across the organic–water



Scheme 36 (a) Formation of THF derivatives *via* nucleophilic additions of Grignard reagents to γ -chloroketone using on water strategy; (b) on-water addition of organolithium and organomagnesium reagents to imines and nitriles.

interface. The strong intermolecular hydrogen bonds between water molecules may play a key role in disfavoured protonolysis, which occurs extensively in other protic media such as methanol.^{138,139}

Bypass stoichiometric reagents

Via C–H bond activation. The rising of green chemistry raises the awareness of atom economic and environmentally friendly method development.¹⁴⁰ In this context, a large number of highly efficient and selective reaction systems have been developed, in which C–H activation catalysed by transition metals is undoubtedly one of the fastest growing areas.^{141–143} In view of both synthetic efficiency and future chemical sustainability, the development of the organometallic reactions in water *via* C–H bond activation, generating a transient C–M based intermediate that quickly reacts with electrophiles rather than water in absence of stoichiometric organometallic reagents, becomes attractive.¹⁴⁴

In the past two decades, there have been great advances in aqueous C–H bond activation catalysed by transition metals. Since C(sp)–H bonds are the most acidic, hence the easiest to activate in water. In 2002, Li and co-workers reported that a bimetallic Ru–In catalytic system could catalyse alkylation of aldehydes in water (Scheme 37).¹⁴⁵

Then, by using Cu/Ru or Cu/pyridine-oxazoline catalyst, they succeeded the addition and asymmetric addition of arylacetylenes to imines to form propargylamines in excellent yields and enantioselectivity in water (Scheme 38).^{146,147} Furthermore a series of transition-metal-catalysed C(sp)–H bond activation reactions in water were reported by his group.^{148,149}

For the less acidic C(sp²)–H bonds, one strategy to facilitate their reaction in water is *via* chelation. In 2010, Dixneuf and co-workers reported a Ru-catalysed and pyridine-directed C(sp²)–H bond activation in water for efficient *ortho*-phenylation (Scheme 39).¹⁵⁰ The selectivity of mono-phenylation and bis-phenylations was found to be better in water than in organic solvent.

In 2012, Ackermann and co-workers developed the Ru-catalysed tandem cyclization of aniline derivative and alkyne



Scheme 37 Ru/In co-catalysed alkylation of aldehydes in water.



Scheme 38 Cu/pyridine-oxazoline catalysed asymmetric addition of phenylacetylene to imine in water *via* C(sp)–H activation.





Scheme 39 Ru-catalysed *ortho*-phenylation in water via C(sp²)-H bond activation.

for efficient indole synthesis via C(sp²)-H bond activation in water (Scheme 40).¹⁵¹

In 2014, Loh and co-workers presented the Rh-catalysed and pyrimidine-directed 2-phenylation of indole derivatives via C(sp²)-H bond activation in water using trimethoxyphenylsilane as phenylation reagent (Scheme 41).¹⁵² In 2015, Li and co-workers reported the Rh-catalysed homo-coupling of aryl carboxylic acid in water via two-fold C(sp²)-H bond activation using MnO₂ as terminal oxidant (Scheme 42).¹⁵³

Such a chelation strategy can also be applied towards the least acidic C(sp³)-H bonds. For example, in 2014, Chen and co-workers reported a Pd-catalysed *N*-quinolylcarboxamide directed β-arylation of alanine at room temperature via C(sp³)-H bond activation, in which water is used as a co-solvent (Scheme 43).¹⁵⁴ This method provided a convenient approach for the synthesis of both natural and unnatural aromatic α-amino acids.

In 2015, Rao and coworkers reported the Pd-catalysed β-C(sp³)-H bond oxidation of amides using 8-aminoquinoline as directing group in water (Scheme 44).¹⁵⁵ Interestingly, the isotope labelling experiment indicates that the oxygen originates from water.

An alternative strategy for the C(sp³)-H bonds activation is via radical process. In 2008, Li and co-workers reported a direct addition of cycloalkanes to imines mediated by peroxide and



Scheme 40 Ru-catalysed tandem cyclization of aniline derivative and alkyne for indole synthesis in water via C(sp²)-H bond activation.



Scheme 41 Rh-catalysed 2-phenylation of indole derivatives in water via C(sp²)-H bond activation.



Scheme 42 Rh-catalysed homo-coupling of aryl carboxylic acid in water via two-fold C(sp²)-H bond activation.



Scheme 43 Pd-catalysed *N*-quinolylcarboxamide directed β-arylation of alanine at room temperature via C(sp³)-H bond activation using water as a co-solvent.



Scheme 44 Pd-catalysed β-C(sp³)-H bond oxidation of amides using 8-aminoquinoline as directing group in water.

the reaction tolerates a wide range of functionalities as well as aqueous conditions (Scheme 45).¹⁵⁶

Via hydrazone umpolung. Umpolung is a phenomenon in which the polarity of a functional group is reversed.^{157,158} This opens up reactions on a functional group which is otherwise not possible. In nature, numerous enzymes such as acetohydroxy acid pseudoephedrine synthase (AHAS) catalyse both nucleophilic acylation and benzoin condensation reactions in aqueous media via umpolung strategy, in which a cofactor thiamine pyrophosphate (TPP) facilitates the catalytic function of these enzymes (Scheme 46).^{159–161} Inspired by the biocatalytic methods that use enzymes as catalysts for various C-C bond forming reactions, chemists have successfully developed numerous C-C forming reactions based on umpolung with carbonyls as acyl anion equivalents. Most of those reactions were catalysed by either *N*-heterocyclic carbene (NHC) or cyanide ion.^{162,163} Related to organometallic reactions, one attractive approach is the metal-catalysed umpolung chemistry



Scheme 45 The peroxide-mediated direct addition of cycloalkanes to imines.



Scheme 46 AHAS catalysed acylin condensation and the synthesis of ephedrine.



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