Future Trends in Green Synthesis

Suman Chowdhury, Atanu Rakshit, Animesh Acharjee,
and Bidyut Saha

Abstract

Green approach is an advance technique of synthetic chemistry. It opens up a new vista of modified version of known synthetic reactions in a newer way with associated enlarged potentiality accompanied by sustainability. Revolutionary measures against solvent-based reaction have been invited in green routes. Organic solvents have been substituted by non-organic media in organic synthetic reactions to overcome the hazard of volatile organic solvents and to preserve the greenness of the reactions, following green principles, supported by green matrices. This chapter illustrates the successive green revolutionary measures in solvent-based organic chemistry followed by solvent-free synthetic routes and their future trends in a nut shell.

Keywords

Sustainable chemistry • Biocatalysis • Biphasic reaction • Solvent-free synthesis

1 Introduction

The synthetic organic chemistry was generally discovered in 1828 by Wöhler while synthesising urea, a natural product, from ammonium isocyanate (Dunn et al. 2010a). Since then, time to time, many advancements in the synthetic procedures have been attained and in the present times, the welfare of human race is inconceivable without abundant synthetic organic products obtained industrially. Quality of our survival does intensely depend upon various pharmaceutical products, foods and so many other products obtained synthetically. But in most cases, the reagents or their sub-products are detrimental to health and also the processes are not sustainable on the ground of pollution, energy consumption and economy. The environmental protection agency (EPA) of USA reported that more or less 100 billion tons of wastes come out of industries every year. The wastes, cost around US$5 billion, have terrifying environmental effect which affect human health extremely. Ozone layer depletion is a typical example of environmental threat which is caused by chlorofluorocarbons (CFCs) come from volatile hazardous organic solvents (Mikami 2005). Hence, some greener eco-friendly or sustainable procedures were really welcome from past few decades. At the beginning of the 1990s, Environmental Protection Agency formulated the definition of green Chemistry or sustainable chemistry as the "Design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances" (Anastas and Eghbali 2010). Green Chemistry being economically profitable aims to reduce hazards across all the life-cycle stages. Synthetic procedures in association with greener approaches can truly termed as green synthesis. The designing concept is of prime important feature of Green Chemistry. Designing requires novelty, planning and systematic approaches. The twelve Principles of Green Chemistry (Fig. 1), coined by Paul Anastas and John Warner in 1998, are guiding framework to reach the goal of sustainability and to reduce adverse consequences by careful planning of chemical synthesis and molecular design (Anastas and Eghbali 2010). In this chapter, some major and prominent applications so far of green synthesis and associated future trends have been focussed.

2 Green Chemistry Metrics

Scientists were put to a challenge to be deeply concerned about the environmental impact of chemical processes for the evolution of green chemistry. The evolution necessitated

---

S. Chowdhury · A. Rakshit · A. Acharjee · B. Saha (✉)
Homogeneous Catalysis Laboratory, Department of Chemistry,
The University of Burdwan, Burdwan, WB 713104, India
e-mail: bsaha@chem.buruniv.ac.in

A. Acharjee
Department of Chemistry, Hooghly Mohsin College, Chinsurah,
WB, India

Inamuddin et al. (eds.), *Advances in Green Synthesis*, Advances in Science, Technology & Innovation,
https://doi.org/10.1007/978-3-030-67884-5_3

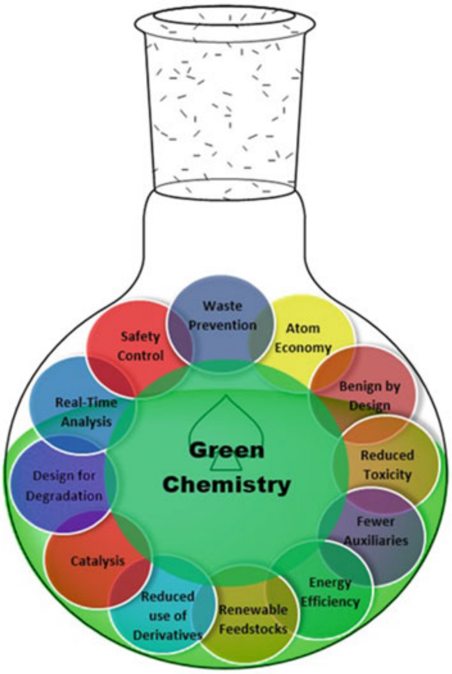


Fig. 1 Principles of green chemistry

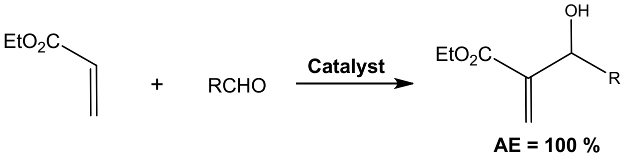
practical changes in industrial and academic processes significantly, and to measure the "greenness" caused by the practical changes, few valid and reliable approaches were essential. Determining greenness does mean not only to measure the waste quantities but also some additional but meaningful factors are to be considered. So, green metrics are that kind of means which can measure how greener a chemical process is. The most common and useful metrics are atom economy (AE), environmental factor (E factor), process mass intensity (PMI) and reaction mass efficiency (RME).

2.1 Atom Economy (AE)

AE, proposed by Trost in 1991, is very widely known measures of efficient chemical processes and is computed from Eq. (1) (Dunn 2012)

$$\text{Atom Economy} = \frac{\text{Molecular mass of desired product}}{\text{Molecular mass of all products}} \times 100\% \tag{1}$$

A higher value of AE clearly indicates more greenness of any process. The atom economy can be easily understood with the help of Baylis–Hillman reaction where the product is impregnated with all the atoms present in the reactant molecules and there is no side product. Hence, this reaction has 100% AE value (Scheme 1).



Scheme 1 Completely atomically economic Baylis–Hillman reaction

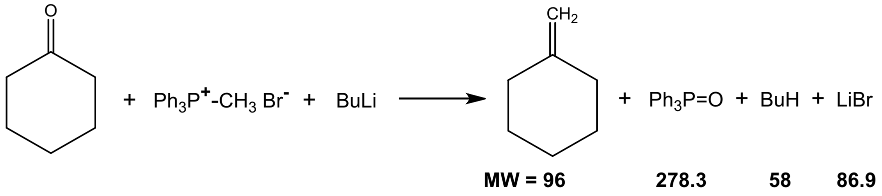
On the other side, for Wittig reaction having three by-products, atom economy is only 18.5% (Scheme 2).

Another elegant example of contrasting AE is production of ibuprofen, a non-steroidal anti-inflammatory drug, in two different routes via the common intermediate, *p*-isobutylacetophenone. The classical route (developed by the Boots Pure Drug Company) with six successive steps has comparatively low AE for sizeable amount inorganic salt formation whereas the other route (developed by the Boots Hoechst- Celanese company) produces it only in three catalytic steps with high AE (Dunn et al. 2010a).

AE is very simple to understand but it possess some demerits. It is calculated only from the reaction scheme, but the yield percentage, even the stoichiometry, is not taken into consideration.

2.2 Environmental Factor (E Factor)

This environmental factor, coined by Sheldon in 1992, is formulated as kilograms of waste per kilogram of product which measures waste products formed in a synthesis of fine chemicals, pharmaceuticals or their intermediates (Table 1) (Dunn 2012). An illustrative example is production of a pharmaceutical intermediate phloroglucinol, a reprographic chemical also, with $Cr_2(SO_4)_3$, NH_4Cl, $FeCl_2$ and $KHSO_4$ as wastes (by-products) from 2,4,6-trinitrotoluene (TNT) in nineteenth century. Calculation shows copious amount of waste is formed in this synthesis with E factor of ca. 20. Ranges of E factor values, differ according to different chemical branches and industries, have been given in tabulated form which are equally applicable for any product, even in the production of laptops or mobiles. A higher E factor indicates more waste with more environmental trace and ideality is attained when the value is zero. This metric includes the chemical yield, reagents, solvent losses, process aids and even fuel. In the computation of E factor in aqueous waste stream, only the inorganic salts and the organic compounds in the water are considered but water is generally removed from consideration. Otherwise, water makes high value of E factor making meaningful comparisons of processes difficult (Dunn et al. 2010a; Dunn 2012) (Scheme 3).



Scheme 2 Wittig reaction with poor AE value

Table 1 E factors in different chemical industry segments (Dunn 2012)

Sector	Volume/tonnes per year	E factor (kg waste per kg product)
Oil refining	10^6–10^8	<0.1
Bulk chemicals	10^4–10^6	<1–5
Fine chemicals	10^2–10^4	5 to >50
Pharmaceutical	10–10^3	25 to >100

2.3 Process Mass Intensity (PMI)

PMI, quite similar to E factor, is computed as the ratio of mass of all the materials in any process and mass of the desired product (Eq. 2). The ideal E factor value, zero, is supposed to be a better reflection of the target of zero waste than the ideal PMI of 1. In this case also water can be included or excluded as per requirements.

$$\text{Process Mass Intensity} = \frac{\text{Mass of all materials used to make the product}}{\text{Mass of product}} = \text{E Factor} + 1 \tag{2}$$

Process chemists choose PMI as the key metric in pharmaceutical industry for the measurement of sustainability of any synthetic process. Besides that, it is very easy to generate, measure, communicate data and can estimate greenness very fast. This mass-based metric focuses on process input rather than output, and targets can be set to measure the process sustainability quantitatively (Monteith et al. 2020).

2.4 Reaction Mass Efficiency (RME)

In 2001, the company GlaxoSmithKline (GSK) invented RME as a practical metric for explaining the greenness of a process. RME is computed as the percentage of mass of product with respect to the sum of the masses of all corresponding reactants in the balanced chemical equation (Eq. 3).

$$\text{Reaction Mass Efficiency} = \frac{\text{Mass of product}}{\text{Mass osf all reactants}} \times 100 \tag{3}$$

Perhaps, RME is one of the most helpful metrics for researchers in knowing the actual greenness of any processes currently because it considers yield, stoichiometry and AE. Solvents, catalysts, acids or bases for the neutralisation of by-products cannot be included in the calculation but, any solvent acting as reactant can be used (only the portion of mass responsible for the product formation) (Dunn et al. 2010b; Dicks and Hent 2015).

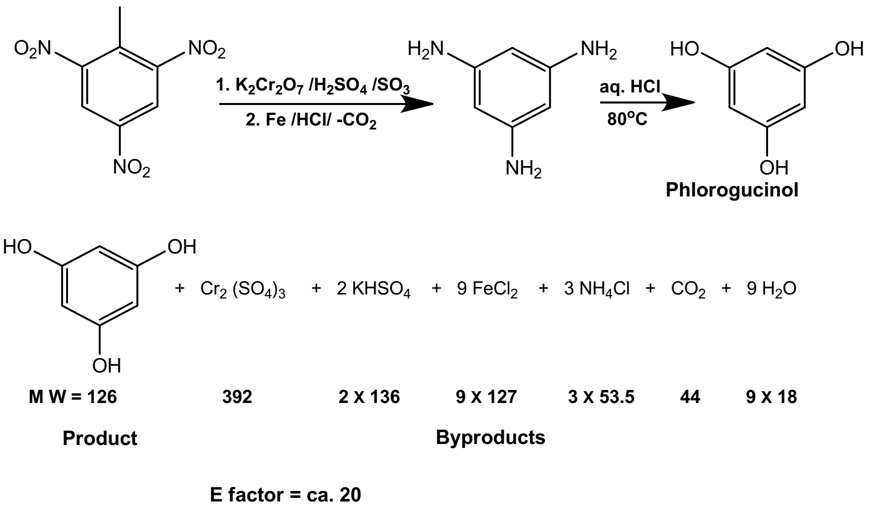
3 Application of Green Concept in Synthesis

Actually, it is more important to apply green concepts in practical purposes to check their viability than only to be written theoretically on pages. There are no scarcity of such practical examples from many past decades where the green principles really have shown their profound positive impacts.

3.1 Solvent-Based Organic Synthesis

It is undeniable that organic synthesis is one of the biggest field wherein the green principles have provided its deepest footprints effectively. It was from the very beginning, organic synthesis was incurred with hazardous organic solvents and the lion's share of the reaction mass is possessed by solvents of which 70% is burnt up for retrieving heat of the reaction. Therefore, solvents are probably the most essential and key portion of green chemistry (Anastas and Eghbali 2010). Waste production, hazardousness, catalysis, inflammability, etc., and many important features of synthetic reactions can be controlled by choosing effective solvent only, even an effective solvent can reduce multistep reactions responsible for their separation, multiple

Scheme 3 Phloroglucinol preparation from TNT



by-products, their costly separation and huge energy consumption also. So, revolutionary measures have been adopted to gain sustainability, conforming to the green matrices, by choosing effective greener solvents replacing the organic solvents.

3.2 Aqueous Medium

There is no doubt that water is the greenest solvent of all time for its abundance, cheap availability, non-inflammability, nontoxicity and non-volatility making it fully eco-friendly. Organic synthesis in aqueous medium sounds weird to hear but, really it has come into existence probably after the work of Breslow in 1980. It was a Diels–Alder (D.A.) reaction (cycloaddition) of butenone with cyclopentadiene undergone in water with 740 folds faster rate than in isooctane and increased selectivity for endo product (Rideout and Breslow 1980). As organic compounds are insoluble in water, it was considered to be a contaminant and was taken as a poor solvent for organic syntheses from the inception. But in particular, polarity, hydrogen bonding, hydrophobic effect and trans-phase interactions arising from the structural uniqueness and associated physicochemical properties of water impart influences in the reaction route profoundly with much reactivity and selectivity. The findings in aqueous solvent are justified by the hydrophobic effect (Fig. 2) (Breslow 1991), as the work of Breslow was also tested in protic solvents like ethanol and methanol which resulted same as obtained in case of hydrocarbons. The hydrophobic effect arises from the repulsion of hydrophobic organic reagents with water molecules. This effect inhibits the surface of hydrophobic aggregation of reagents to come in contact with water molecules. Now, to keep the hydrogen bonding among water molecules unaffected, water molecules wrap around the hydrophobic aggregates increasing the pressure inside the wrapper and this internal pressure enhance the reaction rate to make activation volume negative. Though, some reaction rates may be facilitated also due to interfacial interaction between the organic molecules and free hydroxyl groups of water (Simon and Li 2012).

Cycloaddition-type Diels-Alder (D.A.) reaction, revealed by Engberts et al., of 3-aryl-1-(2-pyridyl)2-propen-1-ones in aqueous solvent is an excellent example of our present discussion. The said reaction showed 287 times greater rate in aqueous medium than in acetonitrile (Scheme 4) (Li 2005). It is worthy to note that the same reaction in presence of water, Lewis acid and micellar catalyst [2.4mM Cu $(OSO_3C_{12}H_{25})_2$] was reported with 1,800,000 fold rate enhancement than in acetonitrile.

Pirrung tested the influence of water in the multicomponent transformations, for example, Ugi and Passerini reactions thinking over the negative activation volumes. According to their report, the reaction of 3-methylbut-2-enoic acid, 3-methylbutanal and 2-isocyano-2-methylpropane in water medium (Scheme 5) resulted in the desired product with 100% yield only within 3.5 h whereas in dichloromethane and dimethylformamide, the yields were 50% after 18 h and 15% after 24 h, respectively. They also reported that no product was found in methanol (Pirrung and Sarma 2003, 2005).

In an industrial-level synthesis of 1-substituted-4-cyano-1,2,3-triazoles from 2-chloroacrylonitrile and organic azides, Novartis took water as solvent (Scheme 6) (Chanda and Fokin 2009). He compared the result of his experiment with the results of the same reaction in organic solvents and he reported that 98% yield was obtained in water which is very high in comparison to the others (46% in n-heptane, 51% in toluene, 78% in dimethylformamide and 40% in ethanol). In water medium, unwanted side reactions were minimised to improve the yield. Generally, hydrogen

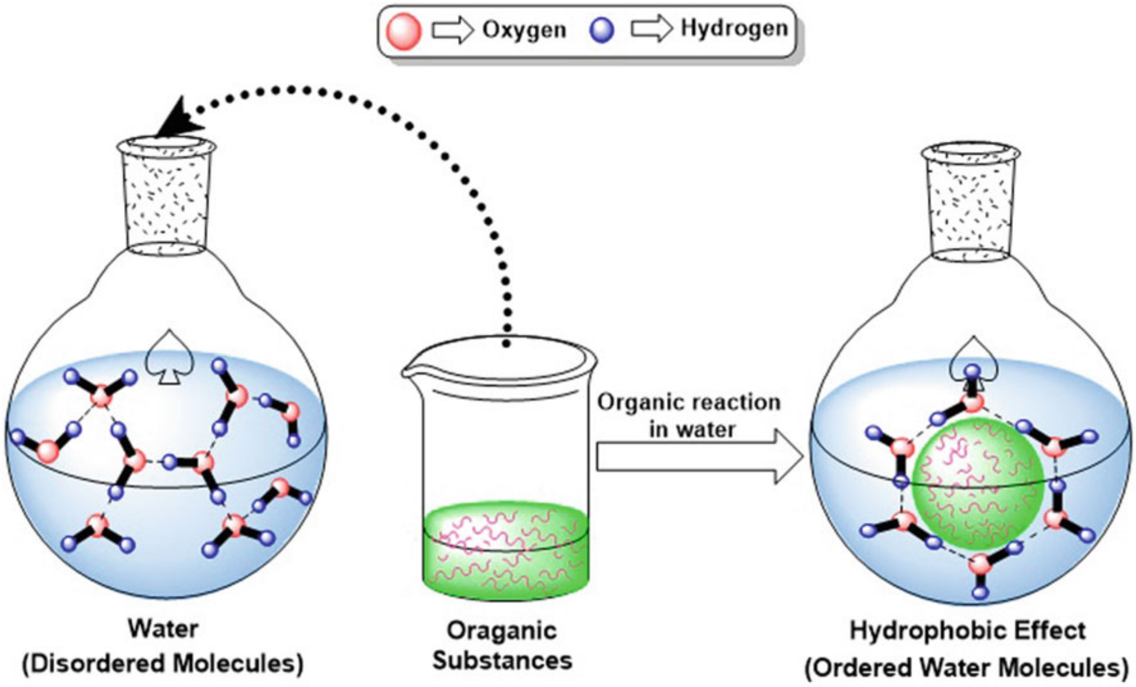
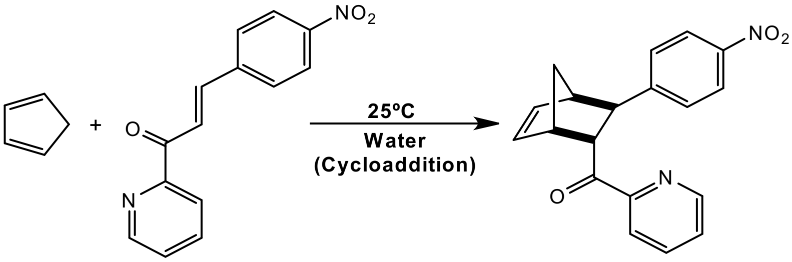
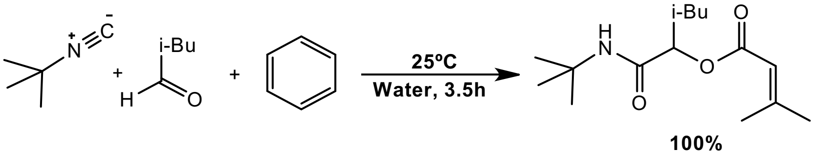


Fig. 2 Hydrophbic effect in water solvent

Scheme 4 D.A. reaction in water solvent



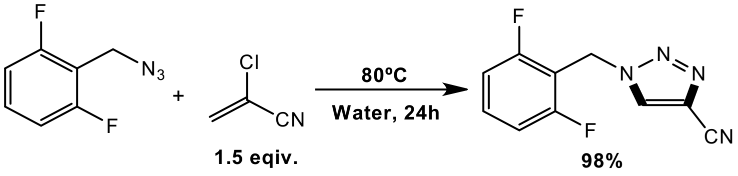


Scheme 5 Passerini reaction in aqueous medium

chloride, a by-product, is produced in the 1,3-dipolar cycloaddition after aromatisation and the medium becomes acidic. Now, 2-chloroacrylonitrile gets polymerised both in acidic and basic media, but in present case, the produced hydrogen chloride goes to aqueous phase and 2-chloroacrylonitrile goes to organic phase and the reaction proceeds easily without any hindrance of olefinic polymerisation yielding high percentage of product.

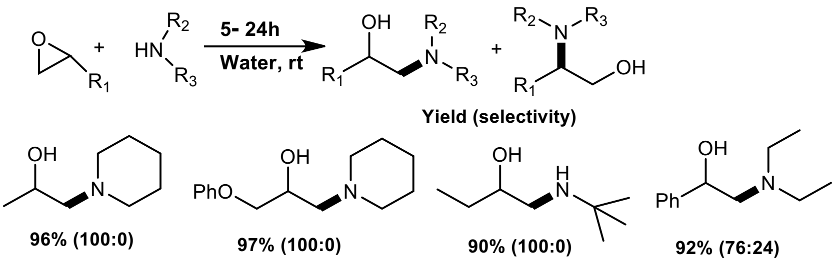
A nice reaction was reported by Aziz et al. where selectivity of water increased the sustainability decreasing environment impact. The reaction was synthesis of β-aminoalcohols at room temperature, with high regio- and stereoselectivity, from the reaction of epoxides and amines in high yields in water (Scheme 7) (Azizi and Saidi 2005). In every cases, the yields percentage in water were >90%, but in ethanol, it was only 50% and in dichloromethane, acetonitrile and di-ethylether, no product was found.

Hayashi et al. reported an asymmetric Mannich reaction of some ketones with dimethoxyacetaldehyde, in an aqueous solution, and p-anisidine in presence of an excellent organocatalyst (Scheme 8) (Hayashi et al. 2007). The organocatalyst was prepared by the Hayashi group using



Scheme 6 Triazole synthesis from azides and acrylonitrile in aqueous medium

Scheme 7 β-aminoalcohols synthesis from epoxides in water



siloxy and tetrazole functional groups in presence of pyrrolidine scaffold. This reaction gave high yield on using only the aqueous solution of dimethoxyacetaldehyde (60% solution in water) and required no additional water to gain the benefit of high yield or selectivity (yields = 78% with 95% ee). Use of aqueous solution of the aldehyde also made the work up process easier and the product extraction from the crude mixture was possible by chromatography through a silica gel column.

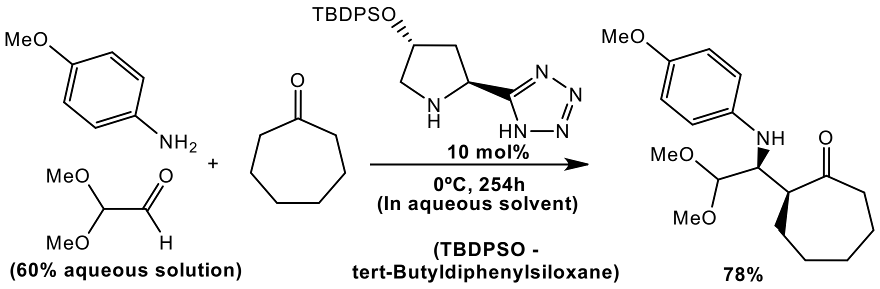
Mizoroki–Heck reaction an important organometallic reaction which was repeated by Firouzabadi et al. in water using insoluble Pd(0)L_2 complex (Scheme 9). The Pd catalyst, synthesised using 2-aminophenyldiphenylphosphinite and palladium acetate, was found to catalyse the reaction of aromatic halides and different alkenes in presence of water and air at two different temperatures 80 and 95 °C (Firouzabadi et al. 2009). After the completion of the reaction, the catalyst can be used again about six more times to get again 79–83% yields on an average.

Lemaire et al. used water soluble ammonium derivative of BINAP analogue for ruthenium-catalysed asymmetric hydrogenation of ethyl acetoacetate (Scheme 10) (Shaughnessy 2009). The reaction was brought about in aqueous phase efficiently giving 100% chemical yield with 97% enantiomeric excess. The most promising fact is that the catalyst can be reused about 9 times more with quite same activity.

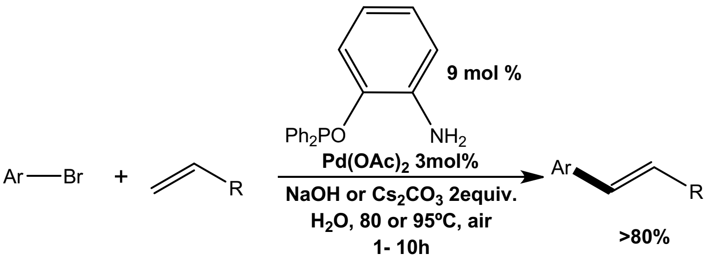
Gruttadauria and groups reported an asymmetric aldol reaction of cycohexanone and *p*-nitrobenzaldehyde in water medium catalysed by a substituted proline derivative at room temperature with excellent selectivity and chemical yields (99%) of the desired product (Scheme 11) (Giacalone et al. 2008). They developed the 4-substituted prolines organocatalyst particularly with n-propylpyrene-1-carboxylate as a substituent which shows high selectivity at very low concentration even in presence of tap water instead of distilled water and the said catalyst can be repeatedly used with same activity. In organic solvents, the reaction was found to give very poor yields.

The versatile function of water in organic syntheses came into knowledge again after the work of Auge´ and groups. They perfomed Claisen rearrangement of 6-b-glycosylallyl vinylethers and concomitant reduction of the produced aldehyde using sodium borohydride in water (Scheme 12) (Xu and Queneau 2014). The reaction was completed with full conversion to the desired product within one hour only at 80 °C and no additional protection or deprotection steps were needed making the reaction away from green

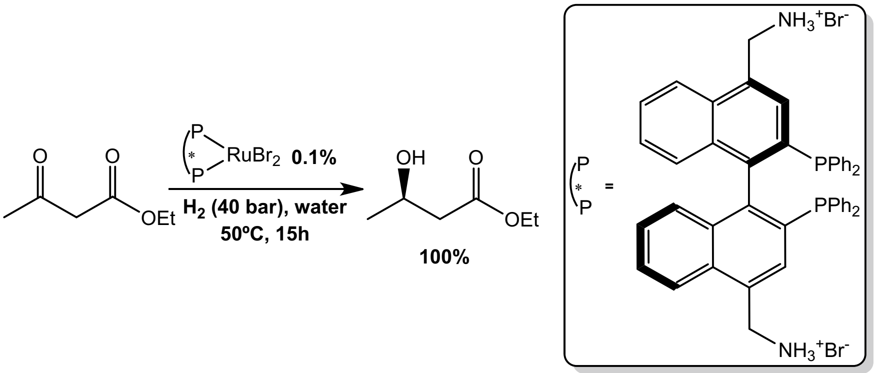
Scheme 8 Organocatalyzed asymmetric Mannich reaction in aqueous medium



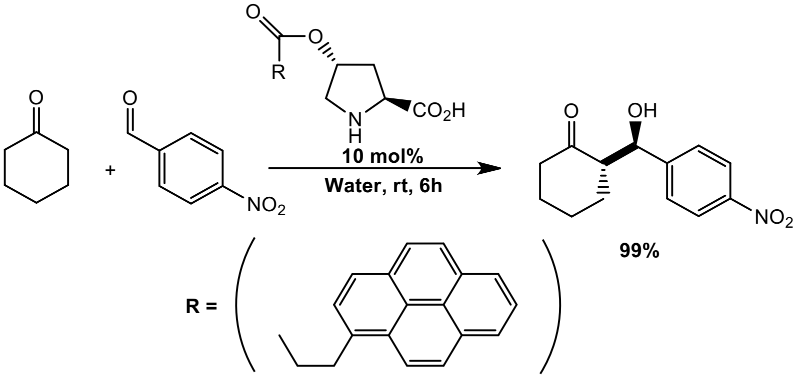
Scheme 9 Mizoroki–Heck reaction in aqueous medium using insoluble Pd–phosphinite complex catalyst



Scheme 10 Keto-ester hydrogenation asymmetrically in aqueous phase



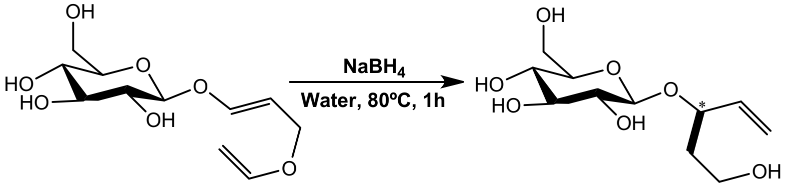
Scheme 11 Proline derivative-catalysed asymmetric aldol reaction in water medium



chemistry. It is relevant to mention here that in toluene, the reaction took 13 days to be completed from the substrate.

Such many reported synthetic reactions in water medium have not been mentioned here, which really opened up new avenues in the field of green synthesis (Vilotijevic and Jamison 2007; Ohnmacht et al. 2008; Rogozinska et al. 2011; Wang et al. 2003; Hu and Manetsch 2010; Mamidyala and Finn 2010).

Biocatalysis was the best way of green synthesis for all time and to start any discussion about this the name “enzyme” must be spelt, in fact enzyme is the prime ingredient that authorises the chemistry as green. History is the witness that searching for suitable enzymes from nature for organic syntheses is in vogue from old ages. Upto 1980s, enzymatic reactions were performed in aqueous medium (Mikami 2005). But, enzymes being organic molecule hardly soluble



Scheme 12 Claisen rearrangement in aqueous medium

in water to be potential to conduct reactions with no limitations. Non-aqueous solvents are more welcome in this purpose. In life processes, also liposomes, the lipid bilayers assist enzymatic reactions to happen in aqueous medium. A smallest extent of water is essential to maintain the active conformation of enzymes, which varies with the enzyme, but proteins have no activity in fully dehydrated condition. Therefore, the presence of water is critical for any kind of biocatalytic reaction. Use of biocatalytic reaction in aqueous medium is very common in food industries (Marques et al. 2012). But, biphasic medium, i.e. aqueous medium coupled with another non-aqueous medium, is promising for biocatalytic reactions. Some discussions in this regard have been provided in the later sections.

3.2.1 Micellar Media

Micelles, the nano-scale assemblies, (Fig. 3a) formed by aggregation of amphiphilic surfactants (cationic, anionic, neutral or Gemini type) are in equilibrium thermodynamically, where monomers of surfactant swiftly exchange among aggregates with an average lifetime of order 10^{-3}–10^{-2} s. One thing should be mentioned here that some liquid polymers are also included in non-ionic or neutral surfactants (Chowdhury et al. 2019a; Dwars et al. 2005). Surfactants, above critical micelle concentration (CMC), exhibit good catalytic activities in aqueous medium (Dwars et al. 2005). Micellar catalysis is one of the simplest methods, even economic, in the field of catalytic reactions. It is also abundantly used in detergency for attaining cleansing property. Therefore, surfactants are termed not only as soapy version of homogeneous catalysis but also as nano-reactors having distinct features. Surfactants are versatile molecules and very useful for many inconceivable purposes with some magical features (Chowdhury et al. 2019a; Dwars et al. 2005; Sar et al. 2019). It being amphiphilic in nature helps solubilising hydrophobic organic substrates in aqueous medium. Moreover, surfactants make sure contacts between substrates of different polarity controlling mutual heat transfer and favouring their interaction that accounts for the final transformation making the whole process environment friendly with less waste production and less greenhouse emissions as well as making E factor close to zero. Micellar assembly encompasses the organic substrates and thus increases the local concentration of the substrate favouring compartmentalisation (Fig. 3b). Now, the concentration of surfactants can be increased in aqueous medium to increase the no of micelles – even to generate micro-emulsions which encompass more substrates. Hydrophobic effect of surfactants stabilises the organic substrates in the micellar cavity making the overall concentration of the substrate in micellar media greater than that in organic solvent and enhance reactivity as well with distinctive chemo-, regio- and stereo-selectivities. Water insoluble-charged metal catalysts are also inherently soluble in oppositely charged micellar media for coulombic interactions and reside on the peripheral surface as the second coordination sphere (Fig. 3b). Thus, they can easily come close to the apolar substrates to catalyse the reaction easily (Sorella et al. 2015). There are so many examples of successful organic syntheses performed in aqueous micellar media (Tomasek and Schatz 2013; Ohara et al. 2014; Lipshutz et al. 2011; Isley et al. 2014a, b; Linstadt et al. 2014).

The synthesis of quinoxalines from 1, 2-diamines (aromatic, hetero-aromatic or aliphatic) and 1,2-dicarbonyl compounds (aromatic or aliphatic) at room temperature, a dehydration reaction, using about fifty different surfactants is a good example of micellar catalytic reaction, reported by Chakraborti and co-workers (Scheme 13) (Kumar et al. 2013a). The micellar reactions produced more yield and were faster than the reaction with no surfactants. The neutral surfactants, for example, tween—40 among the all surfactants displayed better yield production and their catalytic activity follows the sequence: non-ionic surfactants > anionic surfactants > Brønsted acid surfactants > cationic surfactants. The high local concentration of the nonpolar substrates within the micellar cavity facilitates the water expulsion.

Another traditional reaction named Friedel-Craft acylation of aromatic rings which also gave very high yield in aqueous medium in presence of cationic surfactants, for example, cetyltrimethylammonium bromide (CTAB) or cetyltrimethylammonium chloride (CTAC) at room temperature. The reaction was carried out between acetyl chloride and 1-halo-2-methoxynaphthalenes (Scheme 14). Some other substrates, for example, 2-methoxynaphthalene, anisole, 2-methoxypyridine, and 2-methoxypyrimidine were also used under the same condition (Rajendar Reddy et al. 2013). In this process, sluggishness of the reaction, severity of reaction condition, metal triflates, mineral acids and production of wastes can be reduced by this method.

Hydration of alkyne is a very popular C–heteroatom bond forming reaction which needs presence of transition metals as catalyst to increase the electrophilicity of the alkyne. But, in presence of surfactants, the reaction proceeded very nicely in aqueous medium at 140 °C without using any transition metal with effective hydration of aromatic alkynes terminally and internally (Scheme 15). Terminal alkenes were also found to be hydrated in this process (Nairoukh et al. 2013).

Oxidation of alcohols in aqueous acidic medium by Cr (VI) is a very common reaction and it is very slow to move to the product. The rate of oxidation of 2-propanol got higher in presence of trace amount of Ru(III) and also in SDS (sodium dodecyl sulphate) micellar medium separately at 30 °C. But in presence of both Ru(III) and SDS micellar media, the rate became around 8 times higher than that of the uncatalysed propanol oxidation in absence of surfactant at

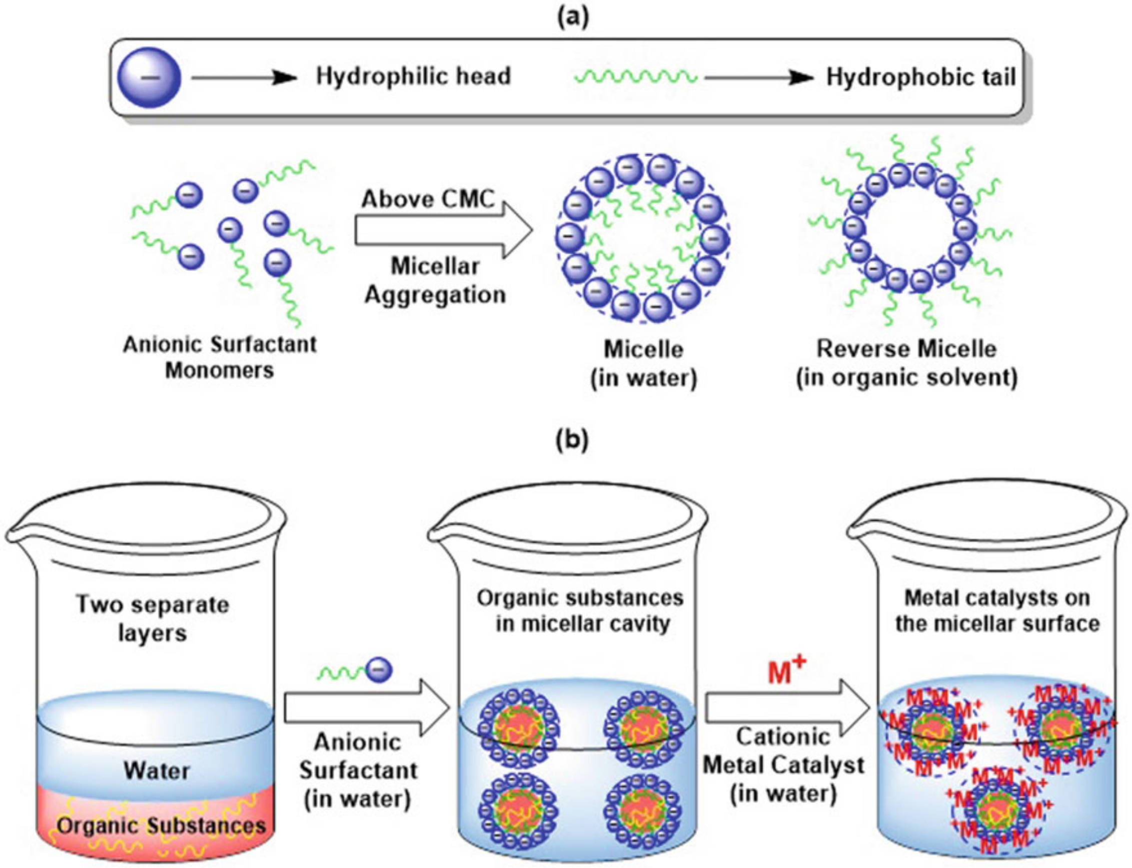
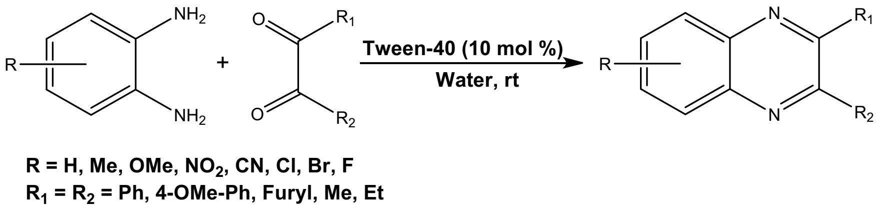
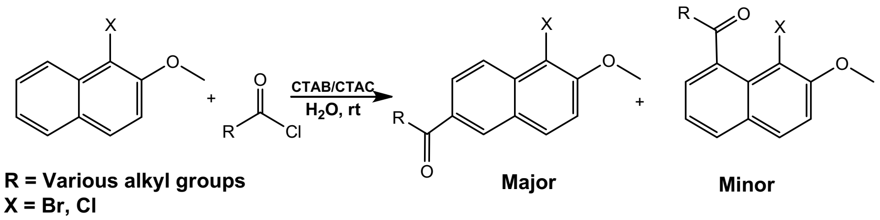


Fig. 3 (a) Micellar aggregation. (b) Compartmentalisation of organic compounds by micellar formation in aqueous medium



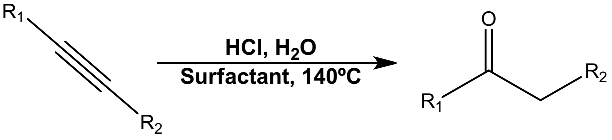
Scheme 13 Neutral surfactant-assisted synthesis of quinoxalines in aqueous medium



Scheme 14 Cationic surfactants assisted Friedel-Craft acylation in aqueous medium

the same temperature (Scheme 16) (Chowdhury et al. 2019b). The micellar reaction is truly an enhancement of the oxidation reaction.

Another oxidation of an alicyclic alcohol in acidic aqueous medium, cyclohexanol, was expedited repeating the reaction in micellar media. In this, oxidation reaction Ce(IV)



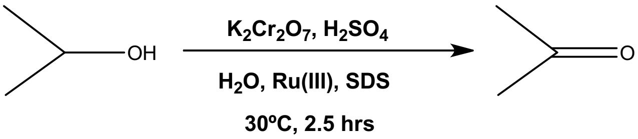
Scheme 15 Surfactant-assisted hydration of alkyne

was used as an oxidant which oxidised cyclohexanol in around 6 h at 28 °C having no catalyst but in presence of small quantity of an anionic surfactant, SDS, the reaction completed within only 21 min though in presence of CPC (*N*-cetylpyridinium chloride), a cationic surfactant, the reaction rate slowed down (Scheme 17) (Chowdhury et al. 2020a).

Oxidation of long-chain fatty aldehydes in aqueous medium is not at all very easier. Octanal, such a long-chain aldehyde was successfully oxidised to corresponding fatty acid, caprylic acid, by Cr(VI) in acidic aqueous medium with the help of surface phenomena in micellar media (Scheme 18) (Chowdhury et al. 2020b). The reaction was reported with good solubilising power and catalytic activity of surfactants. In the reaction, SDS and TX-100 both elevated the rate of the reaction considerably with their increasing concentration and CPC does the opposite. The micellar catalytic reaction was also reported with some rate enhancing effect by some promoters (Phen, PA and Bpy) which are actually hetero-aromatic bases in nature. The micellar-promoted reactions display more enhancement where the combination of SDS and Bpy was reported as the best for such observation.

Micellar media is very useful in Diels-Elder reaction, with a high atom economy, in the preparation of 4-amidyl-2-methyl-1, 2, 3, 4-tetrahydroquinolines, a pharmacologically relevant molecule (Scheme 19) (Merchán Arenas et al. 2013). In this case, using SDS in acidified water a very high yield was produced diastereospecifically and increasing the concentration of SDS above critical micelle concentration the yield percentage was improved more effectively.

Ruthenium-catalysed ring closing metathesis using, for example, first-generation Grubbs, Hoveyda–Grubbs and Zhan catalysts, is a very popular reaction. Such reactions responded the catalytic behaviour of surfactants effectively. In the ring closing reaction of *N*,*N*-diallyl tosylamine Gemini bis-cationic surfactants (various common surfactants linked with a spacer) showed improvement of catalytic efficiency of metal catalysts in aqueous medium (Scheme 20) (Laville et al. 2012). By NMR investigation, it was examined that only the substrate molecule gets dissolved in the medium of reaction, whereas the metal catalysts and the products remained undissolved.

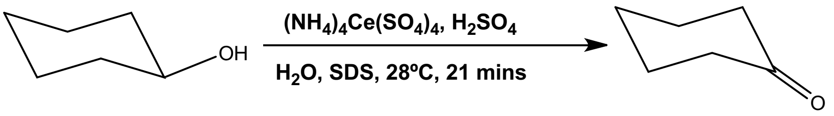


Scheme 16 Ruthenium-catalysed oxidation of alcohols in micellar medium

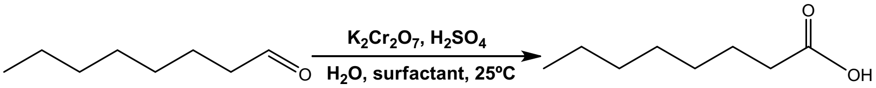
A very impressive contribution of micellar reaction was announced by Ismail and groups in case of nitration of aromatic compounds using nitric acid. The researchers reported that in SDS micellar medium, nitration of aromatic compounds steadily gave only para-isomer with strong regioselectivity and higher atom economy even at room temperature only within 30 min. Not only that, but also the regiolselectivity was equally valid for other aromatic electron rich (like aniline) and electron poor substrates (having nitro, carboxylic acid groups, etc.) as well and no protection required in that case (Scheme 21) (Dey et al. 2013). High yield, less tedious work up, no poly nitration and usages of organic solvent make the process highly sustainable with very small E factor. The substrate molecule gets dissolved in the micellar medium of SDS and the micelles facilitate the approach of substrate to the cationic nitronium ion.

Enantioselective asymmetric hydrogenation of itaconic acid and dimethyl itaconate like important benchmark substrates with chiral Rh(I) catalysts in methanol medium is a very important reaction. The reactions were performed in SDS and TX-100 media successfully with high turnover-numbers (up to 1000) though the selectivity was quite similar to the previous and the rates were rather lesser than that in methanol (Scheme 22) (Schwarze et al. 2011). The micellar media provide suitable membrane for the recycling of the Rh(I) catalyst.

Suzuki coupling of aryl bromides and aryl chlorides is a very well-known coupling reaction in presence of ligand-free Pd catalyst which was repeated by Li and co-workers in guanidinium ionic liquids containing six lipophilic alkyl chains and reported with high yield. Here, the guanidium ionic liquids acted as micellar media was ensured by TEM analysis. Actually, the micelles of those ionic liquids catalyse the reaction by stabilising the generation of elemental Pd-nanoparticles (~5.1 nm). The length of the lipophilic chain of the guanidium molecule has strong impact upon the reaction efficiency. In presence of hexaethylguanidinium bromide, the reaction between 4-bromoanisole and phenylboronic acid produced 30% more product than the usual and in presence of hexa-dodecyl-guanidinium bromide, almost 100% product was obtained (Scheme 23) (Lin et al. 2011). Here also, the micellar media provided an additional benefit of recycling the elemental Pd catalyst without losing its significant activity.

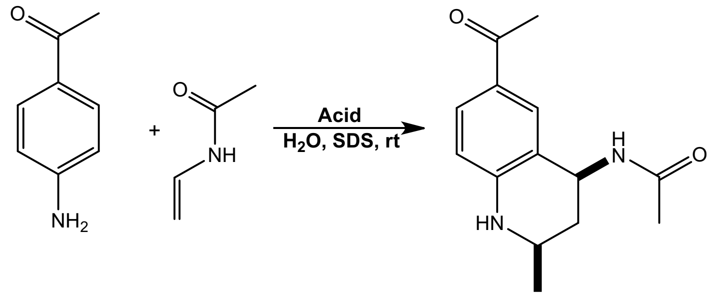


Scheme 17 Micellar-promoted oxidation of alicyclic alcohols in water

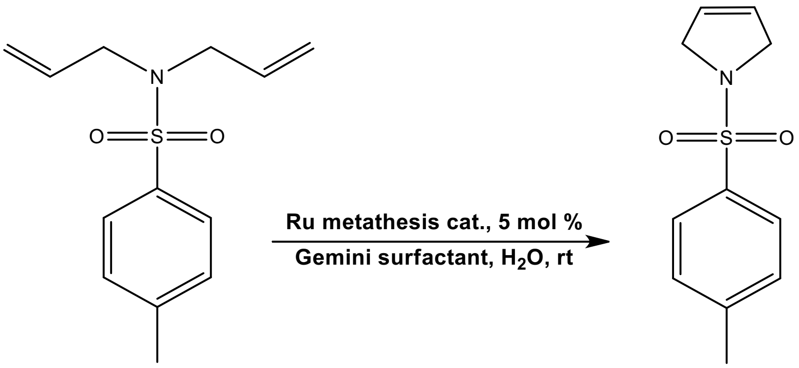


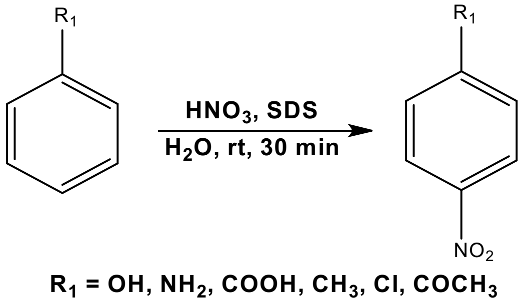
Scheme 18 Micellar-assisted oxidation of long-chain fatty aldehydes in aqueous medium

Scheme 19 Diels-Elder reaction in micellar medium



Scheme 20 Ruthenium metathesis in presence of Gemini surfactants

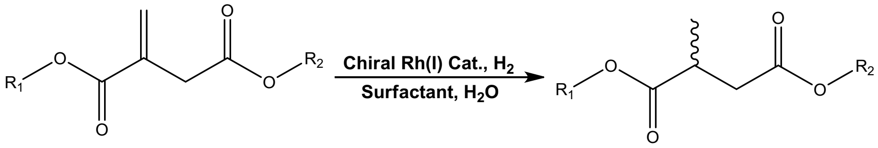




Scheme 21 Nitration of aromatic compounds in SDS micellar medium

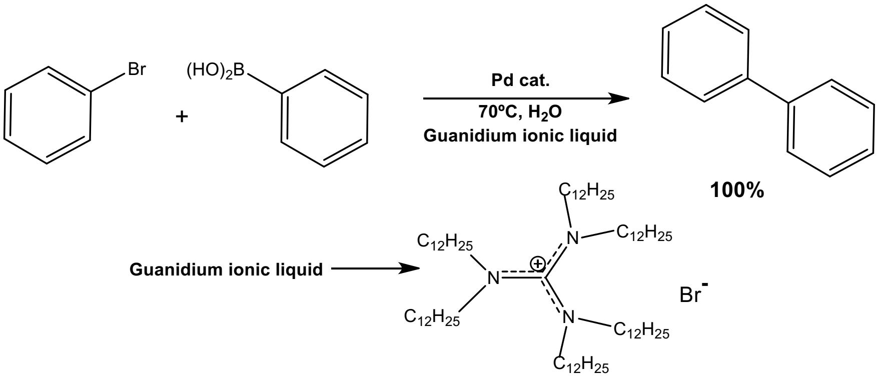
Multicomponent reactions (MCRs) are good expansion of chemist's toolbox of sustainable organic synthesis. In this type of reactions, at least three reactants combine in a single pot to make a product having most of the atoms (preferably all) of the reactants. High atom economy, mild reaction condition, efficiency, great convergence and concerted steps economy have made this methodology a transcendence. Some very well-known examples of MCRs are Strecker, Biginelli, Mannich, Passerini, Ugi, Groebke–Blackburn–Bienaymé, Orru, etc., synthetic reactions (Cioc et al. 2014). In all cases, the minimum atom economy is 80% and waste production is also very minimal. But, use of benign solvents was not in vogue beforehand. It comes into play comprehensively in this century (Touré and Hall 2009). Use of micellar medium as solvent has really provided good consequences.

In three-component one-pot synthesis of spirooxindole derivatives, very important for the synthesis of pharmaceuticals and natural products, weakly basic sodium stearate was proved to be very efficient as micellar medium. The micellar aggregations of weakly basic sodium stearates



Scheme 22 Enantioselective asymmetric hydrogenation in presence of surfactants

Scheme 23 Influence of guanidinium ionic liquids in Suzuki coupling



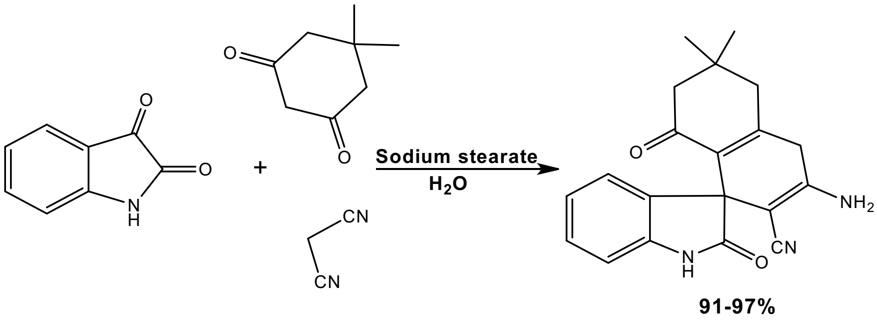
dissolved the substrate molecule forming colloidal dispersion and then stimulated the deprotonation of malononitrile which reacted with isatin and next with a 1,3-dicarbonyl compound to give 91–97% yield of the product (Scheme 24) (Wang et al. 2010). It is very relevant to mention here that use of SDS, SDBS (sodium dodecylbenzenesulfonate) or any other weak bases, for example, acetate gave different amount of yields in each cases.

Another example of multicomponent reaction is one-pot synthesis of 3-amino alkylated indoles in aqueous micellar medium via a Mannich-type reaction of secondary amines, aldehydes and indoles. In presence of any Bronsted or Lewis acid, the reaction produced mostly bis-indole derivative whereas in micellar medium of SDS, it produced 3-amino alkylated indoles in a smooth way with high selectivity and very high yields (Scheme 25) (Kumar et al. 2013b). The hydrophobic moiety of the anionic surfactant primarily promotes the dehydration and cationic iminium formation and the cationic additive reacts with indole for product formation. In this procedure, about 25 different products were synthesised easily within only 2–14 h with high yields (78–94%).

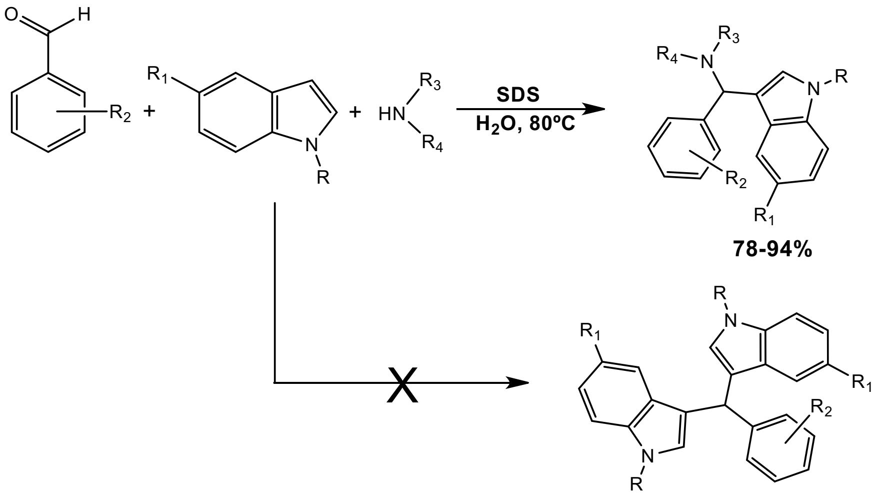
Cu(I)-mediated Sonogashira-cyclisation of three-components, i.e. *o*-halo-*N*-phenylbenzamides (I and Br), phenylacetylene and indoles in one-pot is a very interesting regioselective reaction which were tested using different micellar media (Scheme 26) (Sarkar et al. 2013). Neutral surfactants, PTS (polyoxyethanyl-α-tocopheryl sebacate) in particular, and a base, triethylamine, gave the best result with 76% at 80 °C. The ligand, 2,20-(1E,10E)-(1R,2R)-cyclohexane-1,2-diylbis(azan1-yl-1-lidene)bis(methan-1-yl-1-ylidene)diphenol has a vital role in this reaction for the activation of Cu(I) metal centre.

Micellar enzymology is a very important physicochemical line of research in biocatalysis. Enzymes can be of two types: (1) hydrophilic or lyophobic and (2) hydrophobic or lyophilic. The hydrophilic and hydrophobic moieties impregnated surfactants can solubilise enzymes above CMC forming supramolecular assemblies named micelles or vesicles or o/w micro-emulsions, in aqueous medium, and

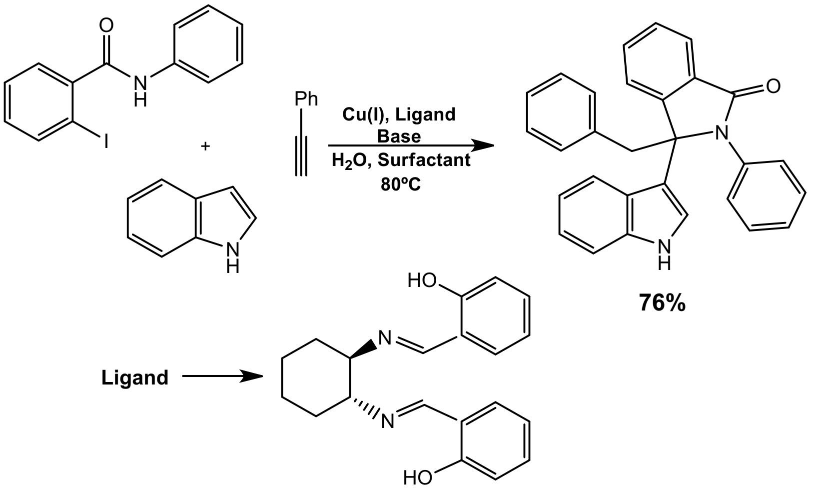
Scheme 24 Three-component one-pot synthesis in sodium stearate micellar medium



Scheme 25 Multicomponent reaction in aqueous micellar medium

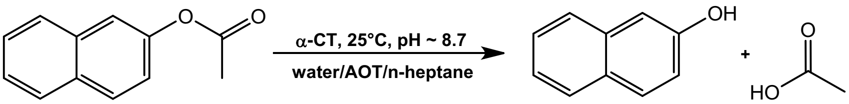


Scheme 26 Sonogashira-cyclisation of three-components in micellar media



reverse micelles or reverse vesicles or w/o micro-emulsions, in organic solvents. In most cases, enzymes were found to be more active in micellar medium (normal micelle or reverse micelle) than in any pure solvent (water or organic solvent) (Biasutti et al. 2008; Adlercreutz 2013). Stability of enzymes under non-aqueous conditions is very crucial, which depends upon (1) the character of the enzymes, (2) their state of mobility, (3) the presence or absence of additives, for example, sugars, (4) on the water content, and (5) sort of non-aqueous solvent (Adlercreutz 2013; Cao and Matsuda 2016). In micellar media, all the factors are maintained very carefully as per requirements. So, for in vitro biocatalytic reaction, micellar enzymology has worldwide applications (Biasutti et al. 2008; Adlercreutz 2013).

In 2004, Falcone and groups studied spectrophotometrically the kinetics of a successful enzymatic hydrolysis of 2-naphthyl acetate by α-chymotrypsin (α-CT), a hydrophilic and globular enzyme, in reverse micelles constructed by sodium bis(2-ethylhexyl)sulfosuccinate (AOT), water and n-heptane [water/AOT/n-heptane] (Scheme 27) (Darío Falcone et al. 2004). In this reverse micellar reaction mixture, addition of glycerine (GY) [water and a GY-water (38% v/v) mixture], a non-aqueous polar solvent, exhibited significant rate enhancement at pH ≈8.7 at about 25 °C. The half-life of the enzymatic reaction in reverse micellar medium was obtained 0.5 min, which is much larger than that of homogeneous non-enzymatic reaction (about 420 min). In both, the reverse micellar hydrolysis quantitative yields of the product were obtained. The rate enhancement, on addition of water soluble GY to the reverse micellar medium, is attributed to the increased order of micellar matrix structure causing decrease of the mobile nature of the enzyme molecule and, hence, increase of its stability. In 2006, a biomimetic route was reported where haemoglobin was used in polymerisation of aniline in SDS, CTAB and TX-100 micellar media. Good yields were obtained at pH = 2.0 (Hu et al. 2006). Shome et al. presented a very relevant aspect of micellar enzymology. They upheld that non-ionic surfactants



Scheme 27 Hydrolysis of 2-naphthyl acetate in presence of enzyme in reverse micelles

can enhance the catalytic efficiency of surface-active enzymes, for example, lipase, in cationic reverse micellar media (Shome et al. 2007). They used CTAB as cationic surfactant and displayed up to 200% rate enhancement in presence of non-ionic surfactants, for example, Brij-30, Brij-92, Tween-20, and Tween80. The rate enhancement was mainly ascribed to the attenuated positive charge density at the interface of cationic W/O microemulsions in presence of the non-ionic surfactants. Similar trend of rate acceleration was also inspected in case of peroxidase activity (Shome et al. 2007).

3.2.2 Different Non-Aqueous Media

Some different non-aqueous media are also in good books of modern researchers to replace hazardous organic solvents in organic syntheses. Ionic liquids, fluorous media and supercritical fluids are those promising non-aqueous solvents which have been used extensively in this regard.

Ionic Liquids

Ionic liquids [ILs] are a kind of salts which are basically liquid unlike solid salts and form by the ionic interaction of mismatched cations and anions. Some structures of common ILs have been produced for convenience (Fig. 4) (Mikami 2005). Amphiphilic nature of ILs has been revealed by many investigations and ILs with long-chain imidazolium- and pyridinium moieties behave like cationic surfactants in aqueous solutions (Pei et al. 2018). ILs have some very good qualities to be chosen as a green solvent. Firstly, the liquids are salts; they cannot vapourise to pollute atmosphere and a simple distillation is enough for product separation. Secondly, different organic, organometallic, inorganic and polymeric compounds are highly soluble in the media including catalysts, so organic syntheses can be carried out in high concentration of the reagents. Even, it can dissolve gaseous compound better than organic solvents. Thirdly, ionic liquids are stable over a wide range of temperatures (−96 to 300 °C) and kinetics can be controlled in these media better than in water and organic solvents. Fourthly, many organic solvents are immiscible with ionic liquids for which they can be used in biphasic catalytic reactions and product can be extracted easily from the catalyst. At the fifth, though ionic liquids are of high price, large number derivatives of the ionic liquids can be synthesised easily at low cost and they are very tunable solvent (Mikami 2005; Pârvulescu and Hardacre 2007; Hallett and Welton 2011).

In ionic liquid epoxidation of enones was done efficiently in a basic aqueous solution of hydrogen peroxide requiring no metal catalyst. In this case, hydrophobic [bmim][PF_6] and hydrophilic [bmim][BF_4](bmim$^+$=1-butyl-3-methylimidazolium cation) both were used as the medium producing quantitative yields of the desired epoxide in a very short time (Scheme 28). The same strategy was used for the epoxidation of chromones and flavonoids also (Bortolini et al. 2002; Bernini et al. 2004).

The Suzuki–Miyaura coupling with good yield was reported in a mixture of water and ammonium salt or pyrrolidinium salt of BF_4^- with ligand-free palladium catalyst (Scheme 29) (Calò et al. 2005). The salts are of high melting point (above 120 °C) but in water, they melt easily and form a biphasic mixture at lower temperature (~50 °C and 80 °C, respectively). In this reaction, the salts were separated and purified though the recycling was not so good.

After few years, an interesting example of Swern oxidation of a secondary alcohol in sulphide containing ionic liquids was reported. Here, non-volatile sulphur-containing compounds were grafted to the scaffold of imidazolium ionic liquids (n = 2, 3 and 6) and oxidised to corresponding sulfoxides by periodic acid. These sulfoxides actually oxidised the secondary alcohol to ketones and the sulphur-containing compound was regenerated easily in the process (Scheme 30) (He and Chan 2006). The advantage over normal Swern oxidation is that the sulphides or sulphur-containing compounds used or generated in this whole process were non-volatile and odourless, so this process is quite eco-friendly. There are many more reactions as such in the same field.

Microwave (MW)-assisted heterocyclic compounds synthesis of ionic liquids is an advancement in the field of green chemistry. MW acts as high-frequency electric field and it can heat charged material (cations or anions) to synthesise ionic liquids very fast reducing the reaction time to great extent. There are many examples of MW-assisted reactions reported so far. A couple of important examples of them have been given below. (Pathak et al. 2016; Palou 2010).

A nice example of MW-assisted pyrazole derivatives synthesis at room temperature was reported by Raghuvanshi et al. The reaction of phthalhydrazide, aromatic aldehydes and malononitrile was carried out in [bmim][OH] medium at 45 °C under the irradiation of high-frequency electric field to synthesise 1H-pyrazolo[1,2-b]phthalazine-5,10-dione as sole product (Scheme 31) (Singh et al. 2011).

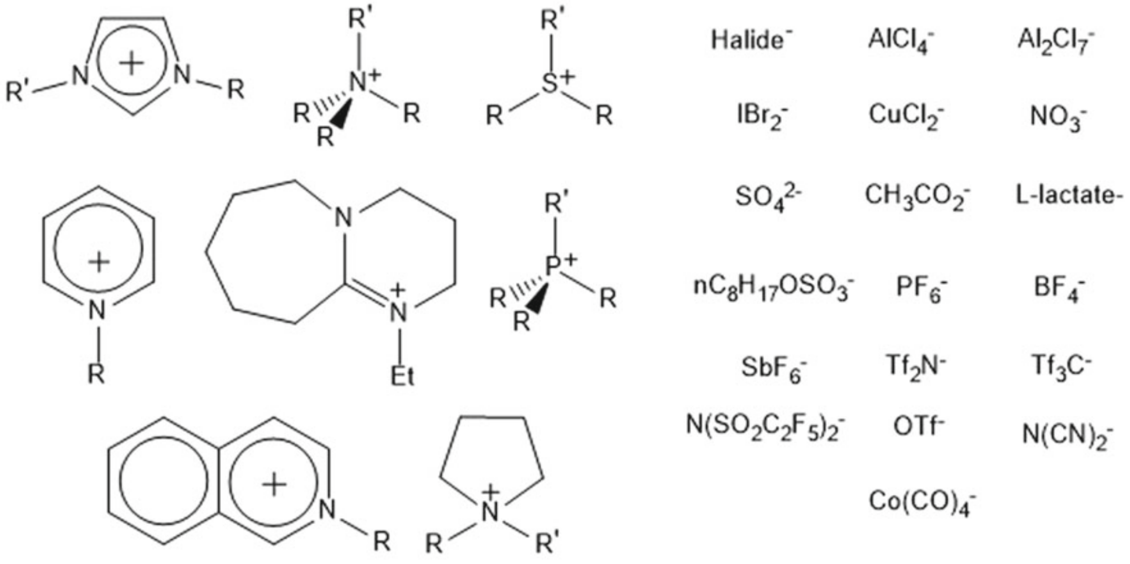
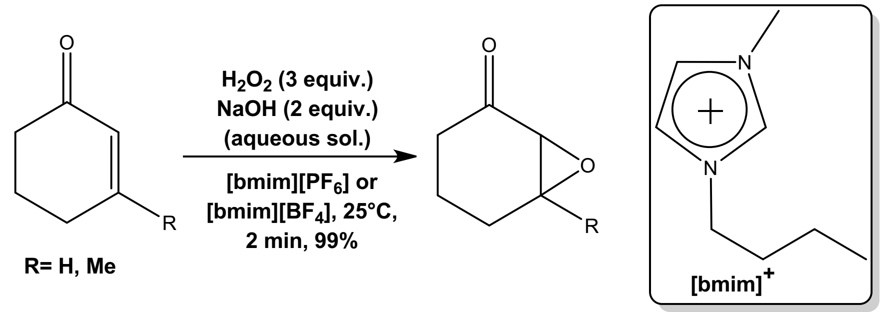
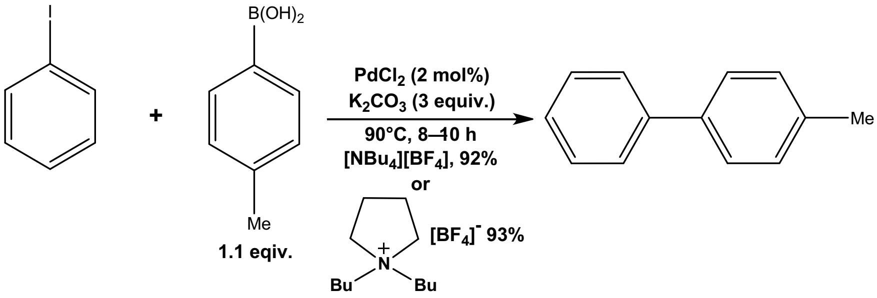


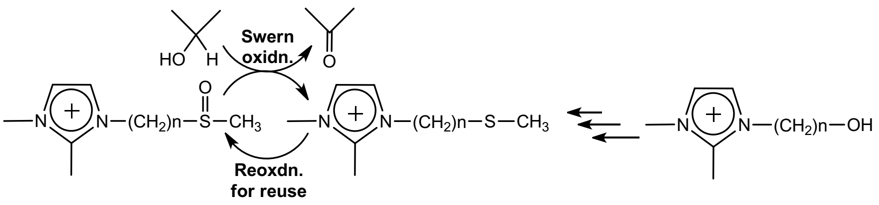
Fig. 4 Cationic and anionic entities of some common ionic liquids



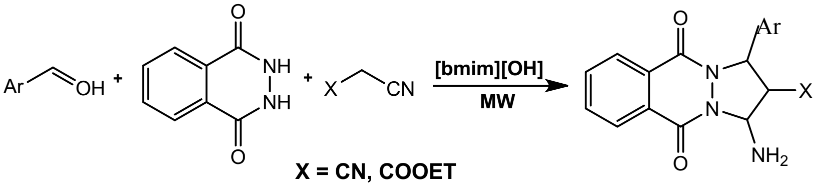
Scheme 28 Epoxidation of enones in IL medium



Scheme 29 Suzuki–Miyaura coupling in IL/water biphasic mixture



Scheme 30 Swern oxidation of a secondary alcohol in sulphide containing IL



Scheme 31 MW-assisted pyrazole derivatives synthesis in IL medium

Few years ago, a derivative of xanthene [1,8-dioxo-octahydroxanthene] was synthesised very efficiently from 5,5-dimethyl-1,3cyclohexanedione (dimedone) and benzaldehyde in [cmmim][BF_4](cmmim$^+$=1-carboxylmethyl-3-methylimidazolium cation) IL medium by Dadhania and co-workers, which was irradiated by MW (Scheme 32) (Singh and Savoy 2020). The reaction procedure provided reusability of catalyst, quantitative yields in a very little time and work up was also very easier.

Biocatalysis in ionic liquids is a very relevant and ardent topic of green chemistry which cannot be omitted in ILs by any chance. Enzymes being an organic molecule have poor solubility in aqueous medium. So, some non-aqueous media were solicited and ionic liquids are really that kind of media. Beside that the charged functional groups of enzymes may interact with the counter ions of ionic liquids which may enhance catalytic behaviour of enzymes (Sheldon et al. 2002; Sheldon and Pereira 2017).

Lipases (hydrolases) are the most extensively used biocatalytic enzymes because it can catalyse almost all kind of organic synthetic reactions. There are many updated instances of lipase-mediated synthesis of biodiesel using ILs as reaction media (Scheme 33) (Itoh 2017). It is really an interesting method of production of energy, one of the most important needs in the world, by a sustainable way and so, we accepted this example among the numerous. Moreover, organic solvent-free separation of hydrophobic diesel from the reaction medium has been perceived. There are many such recent lipase-catalysed reactions in ionic liquids media. Not only lipase but also many such enzymes like proteases, cellulase, epoxide hydrolase, horseradish peroxidase (HRP), alcohol dehydrogenase, cytochrome C, lyase, etc., have profound positive impact in organic syntheses in a very eco-friendly process (Li et al. 2015; Abe et al. 2012; Ou et al. 2016; Mohammadyazdani et al. 2016; Dong et al. 2016; Daneshjoo et al. 2011; Rodrigues et al. 2014). But we have no opportunity to discuss them here in detail.

Fluorous Media

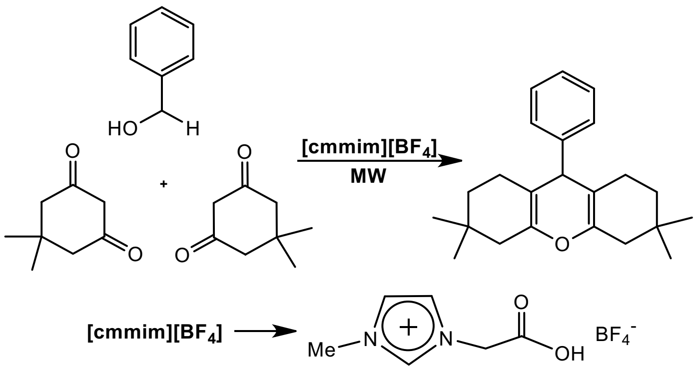
Perfluorocarbons (PFCs) (Fig. 5) (Mikami 2005), the fluorinated hydrocarbon analogues, can dissolve gases (due to low surface tension) and they can be separated easily from organic hydrocarbon solvents. Only for these qualities, they were considered to give trial as solvent in biphasic organic synthetic reactions of fluids (gas and liquid) and sometimes for purification of products and catalysts. They were first used by Zhu in 1993 as solvent in organic reaction. Time to time, many more interesting features of PFCs were revealed, which assists them to be greener solvent (Mikami 2005). In fact, fluorous biphasic systems (FBS), first interpreted by Horváth and Rábai, are widely exploited in many reactions (Sheldon 2005). The characteristic features of fluorous solvents (Mikami 2005; Sheldon 2005; Hobbs and Thomas 2007) are

1. At room temperature, the fluorous and organic phases are not miscible. But, on increasing temperature, miscibility and homogeneity of the two phases are achieved (Fig. 6). On lowering temperature, the phases separate again. So, the catalyst (organometallic catalyst) can be separated from the product only by temperature variation, which provides a basis for performing biphasic catalysis reaction using fluorous solvents.
2. In catalytic reactions, fluorous catalyst can be extracted as well as recycled directly from the reaction mixture and organic product can be extracted using organic solvent.
3. Fluorous solvents are very inactive towards oxidant, radicals, nucleophiles and electrophiles almost unlike the common organic solvents.
4. They are less polar, non-protic solvents and not strongly Lewis acidic or basic.
5. They are not too viscous to inhibit the movement of reagents.
6. They are very friendly to environment for being less volatile, non-toxic and having zero potential to deplete ozone layer. Their greenhouse potential is also very low.

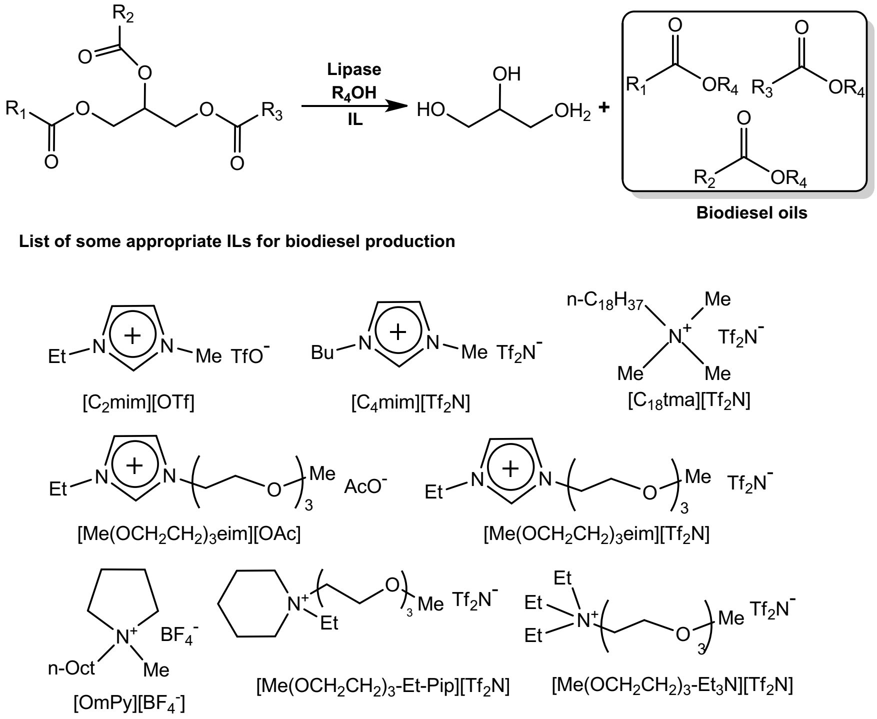
There are numerous examples of organic synthetic reactions, where fluorous media have been discovered as a great solvent and catalyst as well (Goto et al. 2005; Akiyama and Mori 2015; Yan et al. 2010; Brittain et al. 2005; Trindade et al. 2009; Zhang 2009).

Acetalisation of benzaldehyde with 1,3-propanediol and Mukaiyama aldol reaction of an enol silyl ether with benzaldehyde in neat organic medium in presence of fluorous super Brønsted acid catalyst are interesting examples of biphasic organic reaction (Scheme 34) (Akiyama 2007). In this process, the recovery of the fluorous catalyst was very

Scheme 32 MW-irradiated MCR in IL for the synthesis of xanthene derivative



Scheme 33 Lipase-mediated synthesis of biodiesel in ILs Media



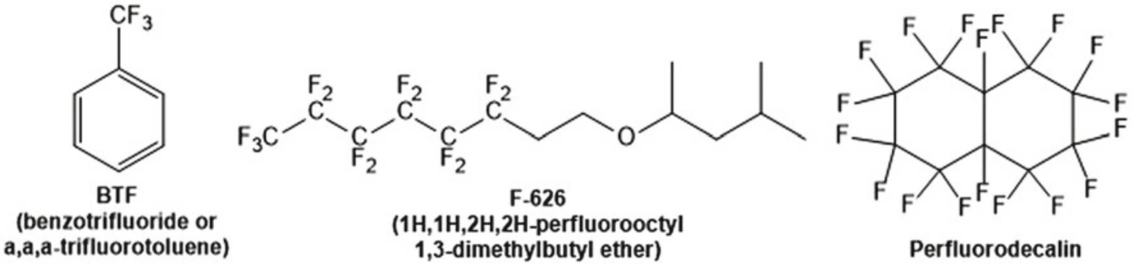


Fig. 5 Common perfluorocarbons (PFCs)

easier, it only needed precipitation by decreasing the temperature of the reaction mixture to ambient temperature.

Mizoroki–Heck arylation reaction of acrylic acid in fluorous medium was reported with both catalytic as well as good solvent behaviour of fluorous medium. A fluorous Pd catalyst was used as catalyst and F-626 was adopted as reaction medium (Scheme 35) (Molnár 2011). The catalyst was synthesised in situ using a fluorous IL and palladium acetate. The products precipitated in the reaction as the solubility of arylated carboxylic acids is very low in F-626.

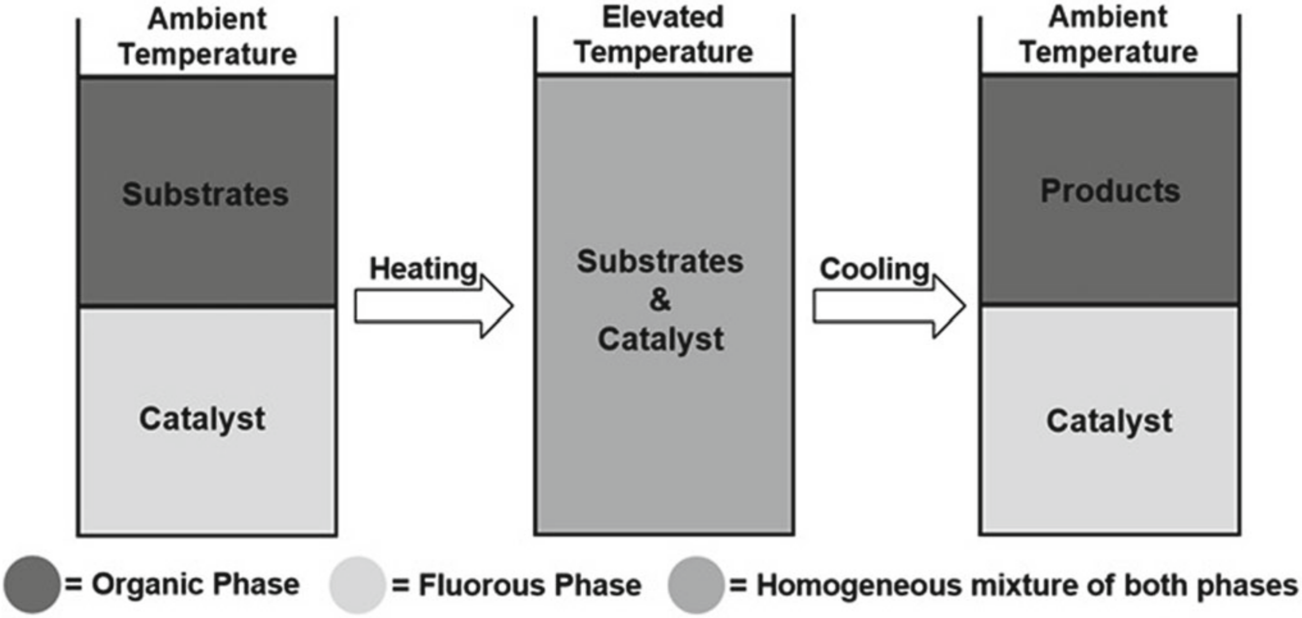
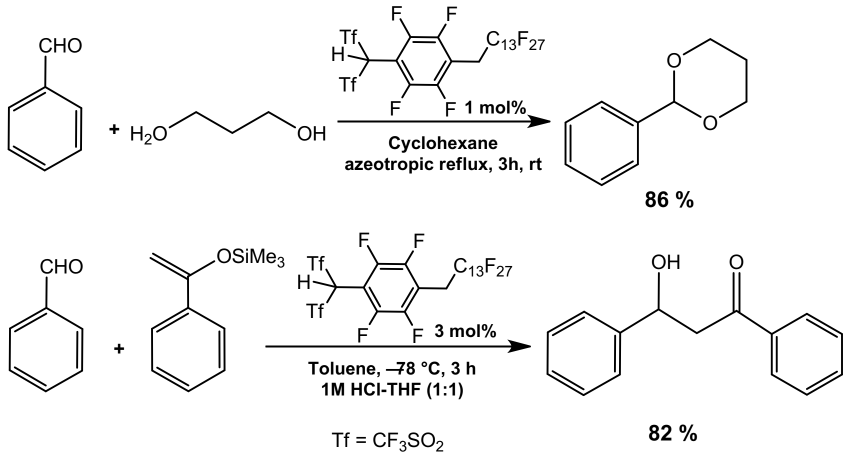


Fig. 6 Miscibility of fluorous media with temperature variation

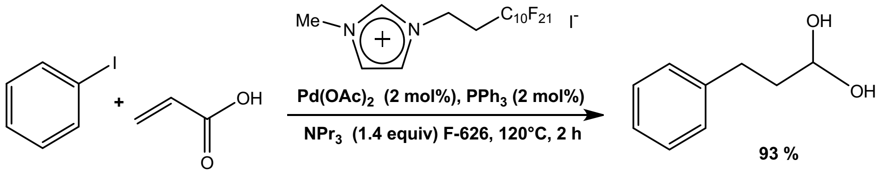


Scheme 34 Acetalisation reaction and Mukaiyama aldol reaction of benzaldehyde in organic/fluorous biphasic media

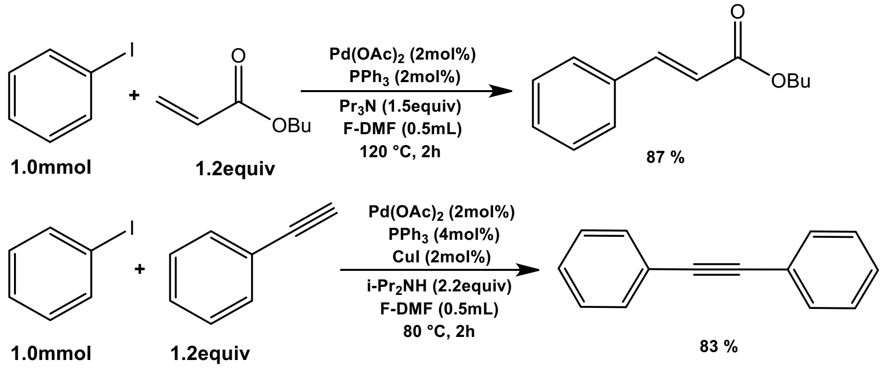
After the filtration of product and amine salts, recycling of the fluorous Pd catalyst was possible for some more times.

The cross-coupling reactions, Mizoroki–Heck and the Sonogashira reactions, also gave good response in organic/fluorous biphasic medium (Scheme 36) (Matsubara et al. 2014). These reactions moved forward steadily producing good yields of the desired product. The Pd catalyst was recyclable and reusable in presence of the F-DMF in the reaction medium.

A novel benzylation reagent, 2-benzyloxy-1methylpyridinium triflate, was reported by Dudley et al. in BTF solvent with higher yields (>95%) than in organic solvents like toluene and 1,2-dichloroethane (Scheme 37) (Sowmiah et al. 2018). Later, some studies of the reaction



Scheme 35 Fuorous Pd-catalysed Mizoroki–Heck arylation reaction in fluorous medium



Scheme 36 Mizoroki–Heck and the Sonogashira reactions in organic/fluorous biphasic medium

confirmed the observations. Apart from this, the benzylation also was successful by preparation of Dudley's reagent in situ (Scheme 38) (Yang and Dudley 2010).

Isomeric mixtures of methyl perfluorobutyl ether ($C_4F_9OCH_3$) are organic hybrid ether solvents, commercially known as Novec 7100. In a report, Novec-7100 was successfully discovered as a co-solvent with quite good yields, where *N*-fluoro-2,4,6-trimethylpyridinium tetrafluoroborate was used for electrophilic fluorination of aryl Grignard reagents (Scheme 39) (Petrone et al. 2016).

Fluorous solvent-based biocatalytic reaction is quite a recent topic in research area. But not much work has been reported yet thereof, for partial insolubility of enzymes in fluorous solvents. But, "like dissolves like" so highly fluorinated enzymes are soluble in fluorous solvents and catalysts can be fluorinated by incorporating fluorous ponytails therein (Hobbs and Thomas 2007; Sheldon and Woodley 2018). This strategy allows fluorous solvents are excellent to be used in multiphasic (biphasic or triphasic) biocatalytic reactions coupled with organic solvent. Highly fluorinated enzymes are readily soluble in fluorous media and organic substrate is soluble in organic solvent. The immiscible fluorous solution and organic solution can be made miscible by raising temperature and after successful reaction, the products can be obtained in the organic medium only by cooling the reaction mixture. Even the enzyme, in the fluorous medium, can be recycled and reused without losing its activity (Lozano 2010; Zhang and Cai 2008).

Enantioselective esterification of rac-2-methylpentanoic acid with a fluorinated alcohol catalysed by candida rugosa lipase (CRL) is a good example of heterogeneous-type biocatalytic reaction in FBS (perfluorohexane and hexane), reported by Beier and O'Hagan (Scheme 40) (Beier and O'Hagan 2002). The acidic substrate is soluble in hexane, the alcohol and product (S-fluorinated ester) are soluble in fluorous solvent. The reaction is termed as heterogeneous due to insolubility of the CRL in either solvents. In the reaction, only the (S)-2-methylpentanoic acid was selectively converted to corresponding (S)-fluorinated ester and unreacted (R)-2-methylpentanoic acid was obtained in hexane. The catalyst was separated by filtration after the reaction is over. A real homogeneous FBS reaction, where the enzyme is soluble in flourous solvent, is very rare because of trouble and difficulty in separation of enzyme from products within the same fluorous solvent. If the substrates get into organic solvent and only fluorinated enzyme gets into fluorous solvent, the case will be more facilitating. But, more research is expected in this field.

Supercritical Fluid

Any substance above its critical point is termed as supercritical fluid (SCF). The critical point indicates the maximum temperature (critical temperature, T_c) and pressure (critical pressure, P_c) at which both phases (vapour and liquid) of the substance exist in equilibrium (Fig. 7). Carbon dioxide has the critical pressure 73.8 bar and temperature 31.1 °C. Water is also a supercritical fluid for reaction chemistry (T_c = 374.0 °C, P_c = 220.6 bar) but its high critical point values limits its application appreciably as a solvent. SCFs are essential because of its dramatic changes in physical properties at small changes in pressure and temperature, especially around critical points (Mikami 2005; Boyère et al. 2014).

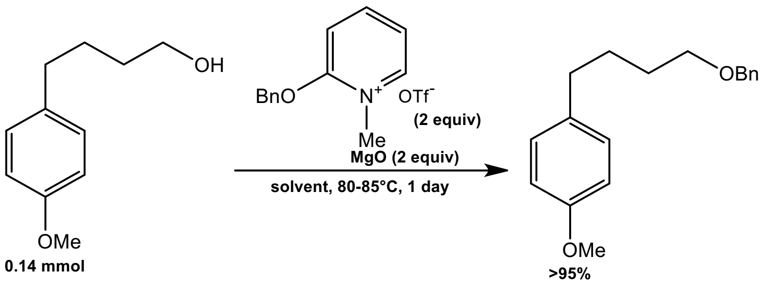
At critical point, the density of gas phase intersects and equals to the density of the liquid phase of any substance. So, there is no discrimination between the two phases at that point (Fig, 8), which leads to an end of the boiling curve (Fig. 7). The density of SCF is 100 times higher than that of the gas and lower than the half density of the traditional liquid (Mikami 2005; Hobbs and Thomas 2007).

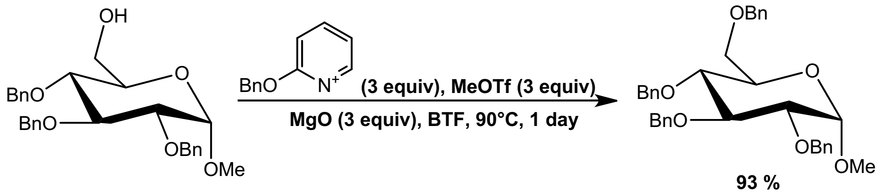
The viscosity and diffusivity both depend upon temperature and pressure. SCF has ten-fold lower viscosity and higher diffusion rate in comparison to the liquid, which is very helpful to make a reaction faster.

Most of the SCFs exert increase in dielectric constants and thermal conductivities steeply with increase in pressure near critical points.

SCFs having no surface tension, like gases, can spread rapidly in the whole reaction volume and left no option other than being miscible with gas compound.

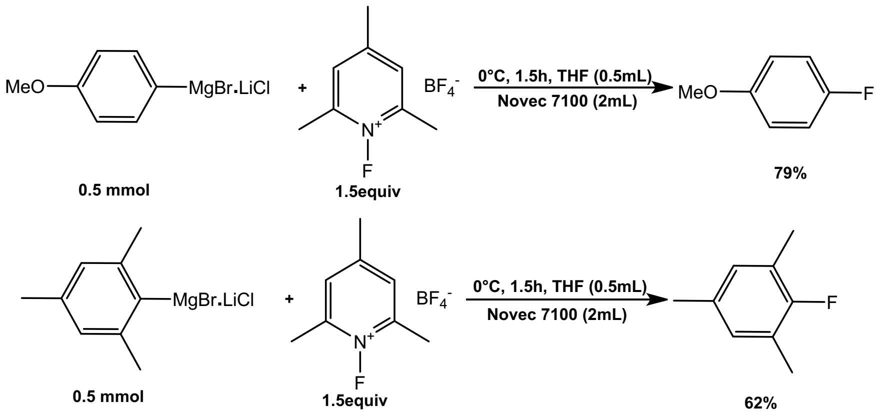
Scheme 37 Benzylation in BTF solvent

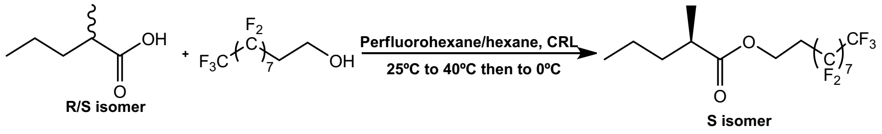




Scheme 38 Benzylation in BTF solvent by synthesis of reagents in situ

Scheme 39 Electrophilic fluorinations of aryl Grignard reagents in Novec-7100





Scheme 40 CRL-catalysed enantioselective esterification of rac-2-methylpentanoic acid in FBS

SCFs can dissolve liquid and solid compounds also in its highly pressurised and liquid-like dense condition. So, the solubility of the compounds can be changed by varying pressure and products can also be separated by precipitation according to our intention. So, SCFs are very powerful solvent in organic synthesis and exceedingly important to the bulk chemical industry. An extra benefit of using SCFs as reaction medium is that, by changing the pressure of the reaction medium, the phase number (single phase to bi-phase or vice versa) of reaction can be controlled easily (Hobbs and Thomas 2007).

For these salient features, SCFs are immensely useful as catalysts and solvents in homogeneous or heterogeneous organic reactions for many times (Machida et al. 2011; Firin et al. 2013; Pavlovič et al. 2013; Onwudili and Williams 2006; Housaindokht and Monhemi 2013; Eckert et al. 1996). Among the SCFs, supercritical carbon dioxide (scCO$_2$) is a very widely used ideal green reaction medium for its unique, well understood physical and chemical properties as well as its nontoxicity to the nature and to human beings. It is an asphyxiant at high concentrations, but precautions can be taken suitably to minimise the risk. It produces no hazardous

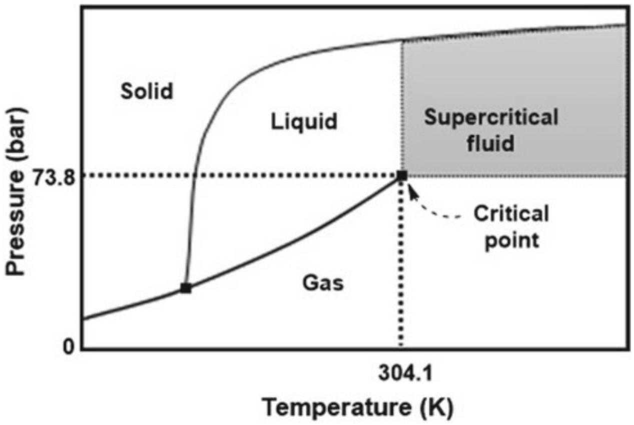


Fig. 7 Phase diagram for a SCF

waste or effluent like other organic solvents, because at atmospheric pressure, CO_2 is in gaseous state and easily can escape from reaction medium without any severe treatment. Non-polar solutes are more soluble in CO_2 than polar solutes, but with larger molecular quadrupole, the case is quite opposite for $scCO_2$. However, the solubility in $scCO_2$ can be tuned by change in density, addition of co-solvent and modification of solutes (Hobbs and Thomas 2007). These unique features of $scCO_2$ have smoothen many uneven circumstances of organic synthesis intensely and we have mentioned here some interesting examples.

Metal catalysts are necessary for hydrogenation and nanoparticles of the metal catalysts are far more active in this purpose. Such a case was reported where colloidal Pd-nanoparticles supported with polymers were discovered very efficient in catalysis of hydrogenation of 4-methoxycinnamic acid to 4-methoxyhydrocinnamic acid in $scCO_2$ at a 10 bar hydrogen-pressure at 56 °C (Scheme 41) (Astruc 2007). More than 99% of the reactant was successfully converted to the product in 20 s in this process with high turnover frequency. The nanoparticles of Pd were stabilised in the micro-emulsion of water-$scCO_2$ medium and uniform dispersion of the nanoparticles there caused fast movement of the reaction to the product. Similar examples are also there, efficient hydrogenation of naphthalene and benzene using nanoparticles of Rhodium catalyst in $scCO_2$ (Ohde et al. 2004).

Many coupling reactions have been processed in $scCO_2$ so far. Stille coupling is one of the remarkable and exemplary of them using $Pd_2(dba)_3$ (dba—dibenzalacetone) and $P[3,5\text{-}(CF_3)_2C_6H_3]_3$. In this reaction, the product, vinyl-coupled-phenyl, was obtained quantitatively (>99%) using iodobenzene and vinyl(tributyl)tin as reagent in the supercritical solvent which is much higher than that obtained in conventional method using triphenylphosphine as ligand (Scheme 42) (Morita et al. 1998). The responsibility of this achievement has been attributed to the greater solubility of Pd complex in $scCO_2$, which was also supported by another Pd-catalysed popular coupling reaction, Heck reaction, using $PPh(C_6F_5)_2$—another fluorinated ligand (Fujita et al. 2002).

Base (DABCO—1,4-diazabicyclo[2.2.2]octane)-catalysed Morita–Baylis–Hillman reaction of *p*-nitrobenzaldehyde with an electrophilic alkene in $scCO_2$ was found with higher rate than in organic solvents. The pressure required in the experiment was as low as 80–100 bar and integrated dehydration of the product led to symmetrical ether (Scheme 43) (Rose et al. 2002). Unsymmetrical ethers was also generated using other alcohol at the etherification step.

In the field of polymer synthesis, the contribution of $scCO_2$ is just indispensable. For high mass transfer, diffusivity, low viscosity and tunable solvation property, $scCO_2$ has captured a unique possession in this field. In this medium, polymers can be synthesised smoothly via both step-growth and chain-growth polymerisation. It is very

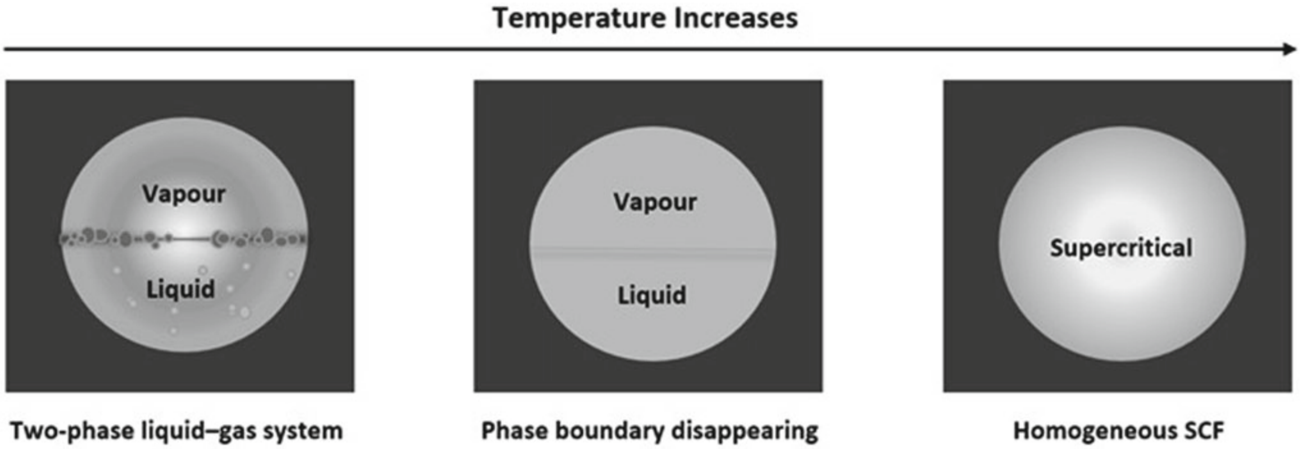
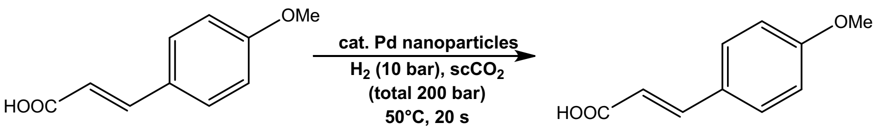
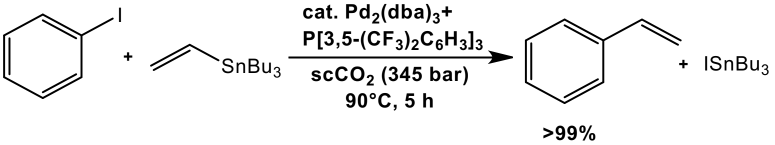


Fig. 8 Change in physical state of biphasic system towards supercritical temperature

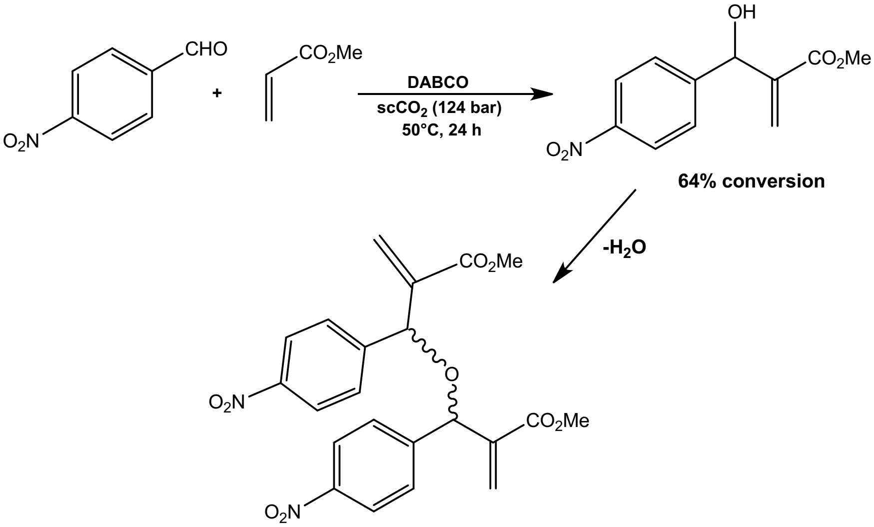


Scheme 41 Nano-Pd-catalysed hydrogenation of 4-methoxycinnamic acid in $scCO_2$



Scheme 42 Efficient Stille coupling in $scCO_2$

Scheme 43 DABCO-catalysed Morita–Baylis–Hillman reaction in $scCO_2$



notable that after the synthesis, the solid product can be obtained only by simple depressurisation (Boyère et al. 2014).

The offering of $scCO_2$ in polymerisation reaction was realised towards the end of the last century. Till now, many reactions have been processed in the medium including RAFT (Reversible addition fragmentation chain transfer) polymerisation (Birkin et al. 2011, 2013; Zong et al. 2008). Many polyesters, polycarbonates, polyamides (nylons), polyurethanes, polyureas, poly(ether carbonate)s and poly (ether ester)s were easily synthesised in the supercritical fluid medium (Fig. 9) (Boyère et al. 2014). An important achievement by using this non-aqueous solvent, $scCO_2$, is the first homogeneous and heterogeneous synthesis of polymeric fluorinated polymers (e.g. polymerisation of 1,1-dihydrofluorooctyl acrylate) (Scheme 44) (Du et al. 2009). With the help of biotechnology, a novel strategy of bio-fuel production has been revealed on treatment of cellulosic materials, the most abundant renewable biopolymer, in this unique $scCO_2$ medium (Medina-Gonzalez et al. 2012). This is really a fascinating and unprecedented fact in the field of green chemistry. Metal-catalysed polymeric syntheses are also not an exception of improvement in same reaction medium (Islam et al. 2014a, b; Akbarinezhad 2014; Guironnet et al. 2009).

In the mid-1980s, the enzymatic activities were developed in $scCO_2$ and there are some merits of enzymatic reactions in this medium unlike water. The biocatalytic substances are insoluble in this medium, so easily separable from it after the reaction is over. As the medium possesses high diffusivity, the $scCO_2$/solid reaction will be more beneficial than in other liquid solvents. Moreover, the separation of the product is also easier than in aqueous solvent. Apart from these, the tunable physical properties of this solvent should not be forgotten ever in any adverse situation. One relevant thing is to be mentioned here that, a minimum volume of water is always present in the medium to prepare buffer solution (Mikami 2005; Matsuda 2013).

In this purpose, lipases have been used widely as biocatalytic substance (Dias et al. 2018). Recently, in a

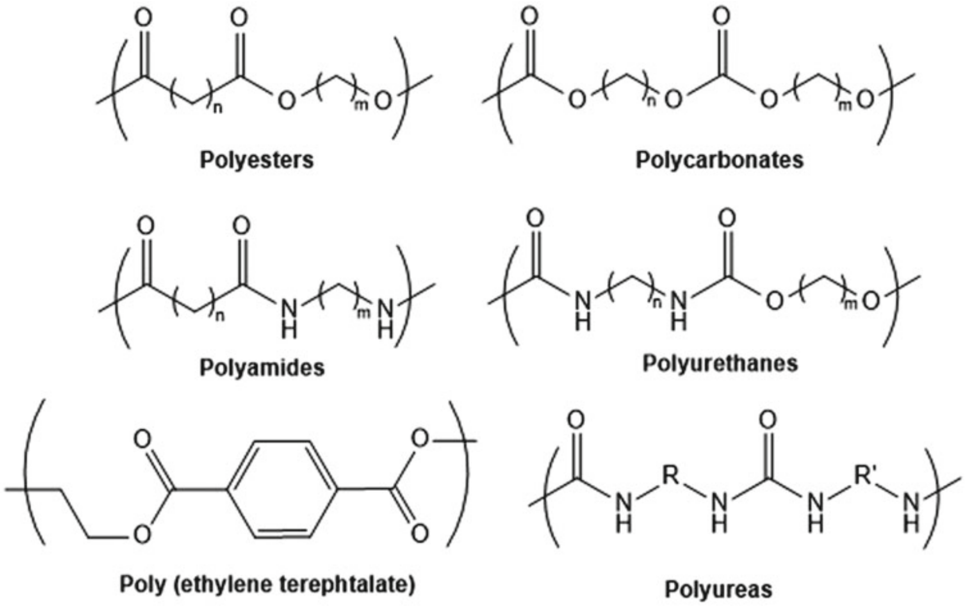
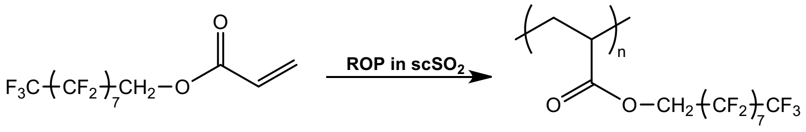


Fig. 9 Some polymers synthesized in the supercritical fluid medium



Scheme 44 Synthesis of polymeric fluorinated polymers by ROP in $scCO_2$

synthesis of a biodegradable star polycaprolactone by ring opening polymerisation (ROP), Novozym 435 (Lipase B from Candida Antarctica fixed on a solid support) was utilised as biocatalyst in $scCO_2$ effectively. In this reaction, monomeric ε-caprolactone (ε-CL) and D-sorbitol were used to synthesise the polymer star polycaprolactone. In presence of $scCO_2$, the conversion to the product was found very fast (96% conversion in 7 h) at 60 °C. The same reaction was also carried out in presence of conventional metal catalyst, tin(II) 2-ethylhexanoate [$Sn(Oct)_2$], and 96% conversion took place in that case too but after 56 h at 95 °C (Scheme 45) (Baheti et al. 2018).

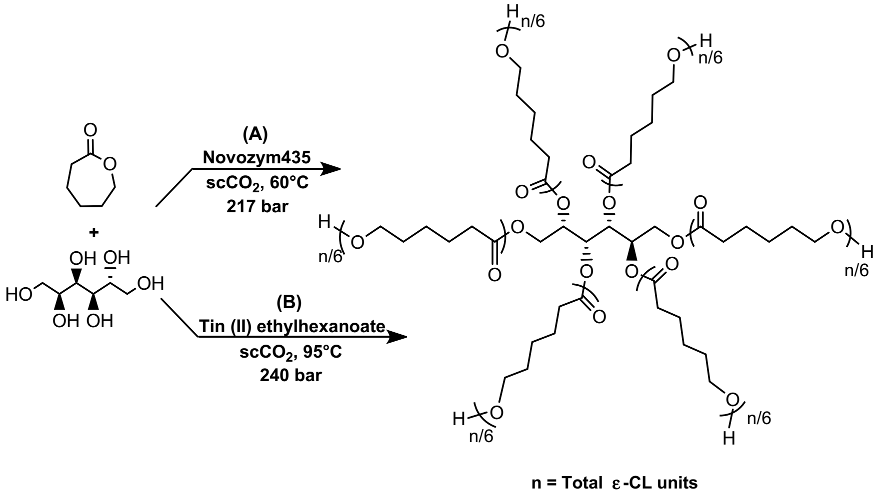
Mixture of $scCO_2$ and IL is a highly admiring biphasic system for effective organic synthesis. ILs and $scCO_2$ both have tunable physical properties. ILs, polar solvent of no vapour pressure, can solubilise organic, inorganic and organometallic compounds. It can be miscible with $scCO_2$ at high temperature and so ILs are more compatible with $scCO_2$ in a two-phase system than any other solvents. Isolation of products from ILs can also be undergone by using $scCO_2$ smoothly without requiring any organic solvent. Metal-catalysed reactions get additional benefit of getting metal complexes dissolved in ILs to enhance the reaction rate (Pârvulescu and Hardacre 2007; Hallett and Welton 2011; Horng et al. 2016; Jessop et al. 2003).

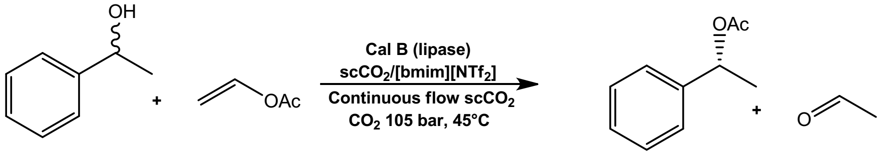
There are striking evidences of effective biocatalytic organic synthesis also in the biphasic system (Mikami 2005; Sheldon and Pereira 2017). A fine instance is transesterification of racemic secondary alcohols in presence of lipase in $scCO_2$/[bmim][NTf_2] biphasic medium (Scheme 46) (Reetz et al. 2002; Sheldon 2008). The benefits of this reaction unlike the traditional methods were associated with easy product/enzyme, product/solvent separations and effortless recycling of the biocatalyst with no considerable loss of activity at 40 °C. A similar transesterification reaction was reported in the same year in presence of same enzyme in $scCO_2$/[bmim][NTf_2] and $scCO_2$/[bmim][PF_6] medium with equal benefits (Scheme 47) (Laszlo and Compton 2002).

Solvent-Free Synthesis

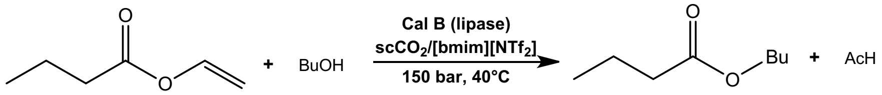
In chemistry, solvent is an essential part whenever any reaction is supposed to carry out. It makes reaction medium and takes care of transporting heat throughout the medium to cause the reaction happen effectively. It takes care of the solubilisation of solutes and rates and equilibrium status of reactions considerably. But, the solvent, the largest chemical species in any reaction, is also responsible for eco-unfriendliness of organic reactions in many ways. In following the guidelines of green chemistry, few hazardless and benign solvents have been discussed so far. But, it was

Scheme 45 Synthesis of star polycaprolactone by ROP in $scCO_2$ catalysed by (A) Novozym 435 (B) $Sn(Oct)_2$





Scheme 46 Lipase-catalysed transesterification of racemic secondary alcohols in $scCO_2$/[bmim][NTf$_2$]



Scheme 47 Lipase-catalysed transesterification of butanol in $scCO_2$/[bmim][NTf$_2$]

said that "the best solvent is no solvent" to overcome the maximum unsustainability caused by solvents. So, solvent-free synthesis is supposed to be the best possible choice hitherto. It sounds weird to hear a reaction without solvent but it happened in many common and important reactions, for example, condensation of carbonyl compounds, cycloadditions, alkylations, aromatic substitutions, additions of amines, water, and alcohols, cyclisations, eliminations, rearrangements, C–C coupling, cascade reactions and catalysed reactions (Toda and Tanaka 2000).

There are many positive outcomes of solvent-free syntheses over the solvent-based reactions: (1) there is no question of any collection, purification, and recycling from reaction medium; (2) high yields are obtained (3) products are pure enough and sometimes no chromatographic purification, even recrystallisations, is necessary; (4) reactions are sometimes extraordinarily faster than conventional organic solvent-based reactions; (5) often no modern instrument and their setting up is required; (6) mostly energy requirement is also not too high; (7) preformed salts and metal-metalloid complexes are not in use often; (8) there is no need of protection-deprotection of functional groups; (i) batch experiments at low cost is possible more eco-friendly than conventional solvent-based methods. In association with these advantages some disadvantages, for example, formation of "hot spots" and the possibility of runaway reactions, are also present, which can be overcome technically (Cave et al. 2001; Dunk and Jachuck 2000).

The understanding of molecular movements and contacts between reactants of solvent-free synthetic reactions where reagents are solids at reaction temperature, unlike the miscible combinations of solid–liquid or liquid–liquid reagents, were quite complex. But, later, it was comprehended and demonstrated (Martins et al. 2009; Tanaka 2009). Actually, in case of solid–solid combination, minimum requirements are to be hosted to process the reaction. In solvent-free solid–solid reaction, four mechanisms are employed for activation (Fig. 10)—(1) mechanochemistry (grinding); (2) microwave irradiation (MW); (3) ultrasound irradiation (US); and (4) conventional thermal heating. In mechanochemistry, the solid solute substances are grinded physically by using mortar and pestle or by ball milling. In MW irradiation, microwave is employed to the solutes and the solutes absorb the waves to convert into thermal energy, which propagates through reaction mixture by dielectrical heating. MW irradiation is the most effective solvent-free solid–solid reaction process and in this internal heating process reaction rate increases, yield percentage increases significantly in comparison to the traditional heating method. In US technique, powerful ultrasound is used to irradiate the reagents till the product raising the reaction temperature of range 4900–5200 K by cavitation (Hobbs and Thomas 2007; Martins et al. 2009; Tanaka 2009). In the conventional thermal heating method, the reaction mixture is heated using magnetic stirring and oil bath. In this connection, it is worthy to mention that this conventional thermal heating is quite inefficient and sometimes unable to produce any yield (Martins et al. 2009; Tanaka 2009).

In last few decades, numerous reactions have been performed in solvent-free conditions (Chandna et al. 2013; Hernández and Juaristi 2010; Kanagaraj and Pitchumani 2010; Hasaninejed et al. 2012; Kumar and Sharma 2017; Li et al. 2012; Panja and Saha 2013; Singh and Chowdhury 2012; Wen et al. 2012; Zhanga and Wang 2012). Atom economy of these reactions are very high. Many organic molecules can very easily be synthesised by this method with less trouble.

Michael addition is an atom economic reaction. In 2011, a simple catalyst-free as well as solvent-free synthesis of nitroamines and nitrosulfides by following Michael addition were reported by Choudhary et al. In the effective experiment, high yields (>99%) were produced simply by grinding the mixtures of amines and thiols individually with nitroolefins (Scheme 48) (Choudhary and Peddinti 2011). The process is so effective that it ended within few minutes only at room temperature and requiring no purification of product.

In the same year, another solvent-free synthesis of poly-substituted quinolines under microwave irradiation was reported, in which a polyethylene glycol supported catalyst (PEG-6000) was used effectively. The speciality of the polymeric catalyst is its bio-degradability and modified by sulphuric acid, presenting as PEG-OSO$_3$H. In this Friedländer-type synthesis, poly-substituted quinolines and 4-aminoquinolines were synthesised under the said condition swiftly by condensing 2-aminoarylketones or anthranilonitrile with carbonyl compounds, unlike the conventional method (Scheme 49) (Hasaninejad et al. 2011). The

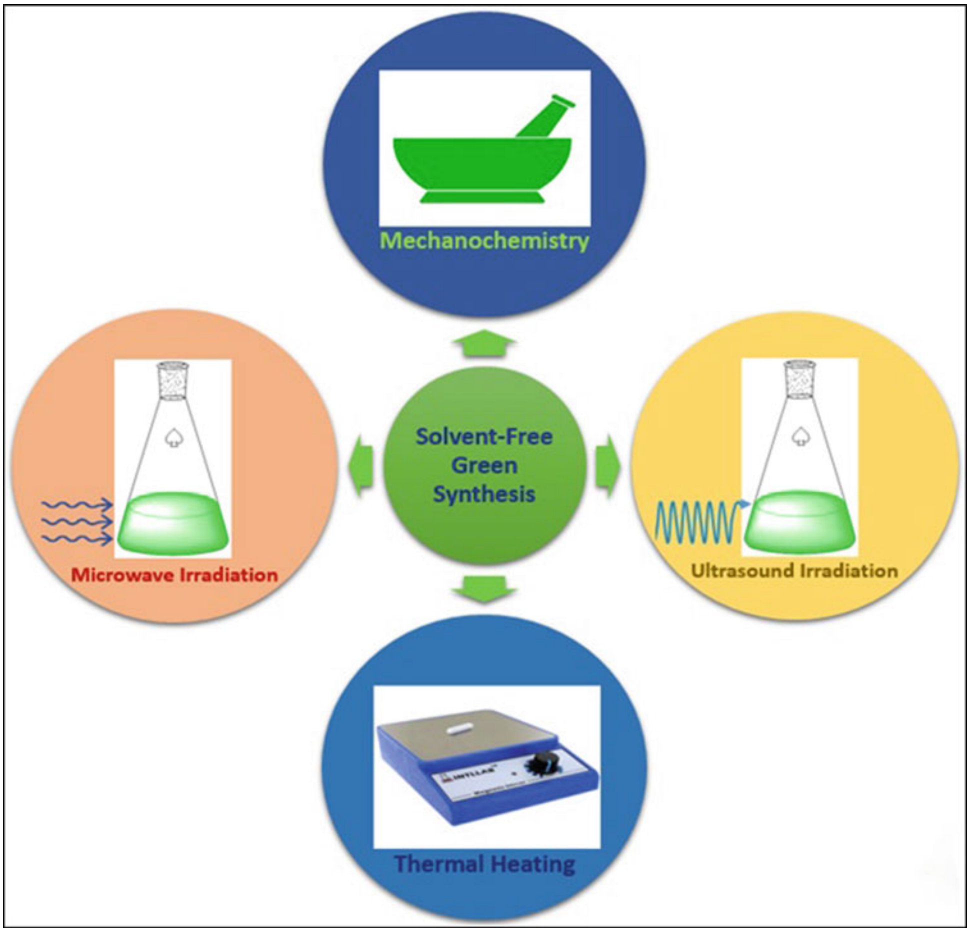
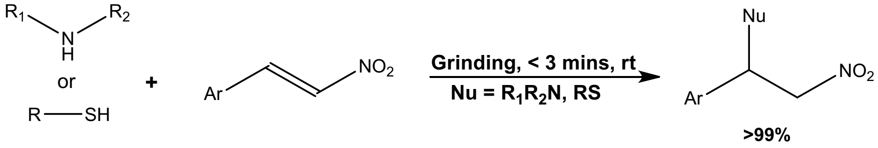


Fig. 10 Mechanisms of solid-solid solvent synthesis reactions

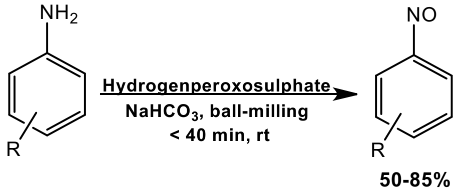


Scheme 48 Mechanochemical Michael addition of nitroamines and nitrosulfides in solvent-free pathway

maximum yields (80–95%) were obtained within 12 min, when 3 mol% of PEG-OSO_3H and 600 W of microwave irradiation was used at 130 °C in solvent-free condition. After the reaction was over, the catalyst could be recycled adding water in the medium followed by evaporation and the water-insoluble product was separated and recrystallised using ethanol. The recycled catalyst can be reused ten times without undergoing any loss of activation.

In 2012, Huskić et al. reported appealing mechanochemical solvent-free synthesis of nitrosobenzenes by oxidation of different para derivatives of aniline using potassium hydrogenperoxosulphate, also known as Oxone®, ($K_2SO_5.K_2SO_4.KHSO_4$) and featuring solvent-free purification of the product only by sublimation under reduced pressure ($\sim$0.1 mbar) (Scheme 50) (Huskić et al. 2012). From good to excellent yields (50–85%) were gained in the study based upon the para substituent of anilines. The para-iodoaniline yielded maximum. The yield % was found to be enhanced while adding equimolar extent of basic $NaHCO_3$ to the reaction vessel.

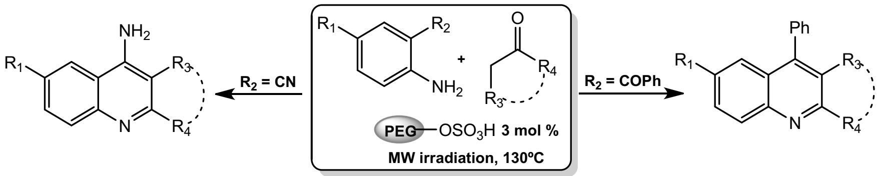
In 2013, another outstanding nano-S-catalysed solvent-free MCR was performed by Das and co-workers to synthesise 1 Amidoalkyl-2naphthols using mortar and pestle. In the preparation reaction, aldehyde derivatives, naphthol and amides were grinded in mortar using the synthesised S_8 nanoparticles and quantitative yields were produced in a while at 50 °C, unlike the solvent-based method using the conventional catalysts (Scheme 51) (Das et al. 2013). The nano-sized S_8 catalyst could be used another five times with no loss of its substantial activity. The determined green metrics supported the intensive greenness of this process.



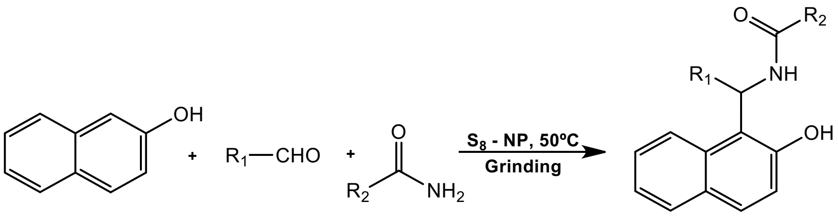
Scheme 50 Solvent-free synthesis of nitrosobenzenes by ball-milling process

Another efficient example of solvent-free heterocyclic compounds synthesis in room temperature catalysed by recyclable, in situ prepared, ZnO-NPs by ball-milling strategy was reported by Sharma and co-workers. Different derivatives of benzothiazole, benzimidazole and benzoxazole were synthesised with quantitative yields (> 85%) in 30 min in this experiment which are environment friendly with low E-factor. Various aldehydes were considered to react with 2-aminothiophenol, *o*-Phenylenediamine and 2-aminophenol to obtain benzothiazole, benzimidazole and benzoxazole, respectively (Scheme 52) (Sharma et al. 2014). But the substituents in aldehydes were not found to show any significant effect on the percentage of yields. It is noteworthy that turnover number (TON), turnover frequency (TOF) increased linearly with the amount of NPs but upto up to 0.5 mol%. Maximum yields were obtained at rpm 600 of ball-mill.

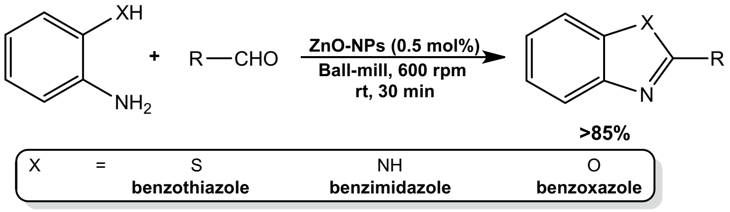
Solvent-free organic synthesis of heterocyclic compounds using renewable chemicals is a very exciting fact and demanding also nowadays. Such an interesting example of solvent-free and metal-free short time (15–40 min) synthesis of 1,4-dihydropyridines in presence of slight amount chitosan nanoparticles (NPs) was reported few years ago. The reaction was got going with Hantzsch synthesis using aldehyde, ethylacetoacetate, ammonium acetate and chitosan NPs in a round bottom flask fitted with a magnetic stirrer at 80 °C (Scheme 53) (Safari et al. 2015). The chitosan NPs were prepared by gelation of chitosan using heptamolybdate anions and then it was made suitable to use by drying with dry CO_2 for 30 min. In this solvent-free synthesis, the rate



Scheme 49 MW-irradiated solvent-free synthesis of poly-substituted quinolines



Scheme 51 Mechanochemical solvent-free MCR catalysed by nano-S



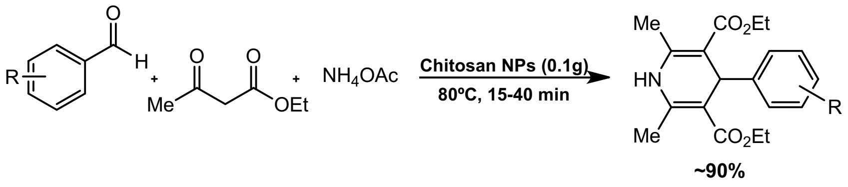
Scheme 52 ZnO-NPs catalysed solvent-free synthesis of heterocyclic compounds by ball milling

and yields (~ 90%) both were higher than that of solvent-based synthesis.

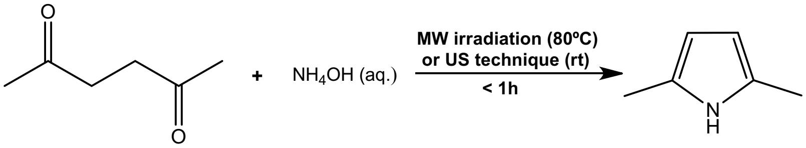
Paal-Knorr synthesis is a very popular organic reaction for heterocyclic compounds synthesis. Cho and co-workers reported this reaction for synthesising underivatised pyrroles by reaction of hexan-2,5-diones with aqueous NH_4OH in catalyst and solvent-free condition assisted by MW irradiation (80 °C) and US technique (room temperature) (Scheme 54) (Cho et al. 2015). In conventional method, about 120 h is required to get quantitative product but in this present method, the same was obtained in less than 1 h. MW irradiation was discovered more effective than US strategy in this process. Similarly, efficient solvent-free synthesis of N-substituted pyrroles was also reported using hexan-2,5-diones and amines by the same group with more yields, even faster than the previous, but without using MW irradiation or US strategy.

There are significant drawbacks of mechanochemistry—lack of temperature control and scalability—for which twin screw extrusion (TSE) was introduced. The melting temperatures of reactants are very crucial in reactions especially in solvent-free synthesis. TSE involves moving of the substances through a narrow restricted area by the rotation of a pair of intermeshing, modular screws to get the desired condition. Already, it has extensive use in food, polymer and pharmaceutical industries, including reactive extrusion of polymers (Crawford et al. 2017). In 2017, Crawford and co-workers studied solvent-free Knoevenagel condensation, a benchmark reaction, of barbituric acid with aldehydes (vanillin, veratraldehyde and 5-bromovanillin) by TSE (Scheme 55). In conventional solvent-based method, these reactions take around 50 days to reach equilibrium. But, in this ball-milling process, the reaction-completion times were not more than 90 min at 25 Hz. TSE takes care of the reaction temperature, and in these reactions, maximum yields were produced at 160 °C at 55 rpm screw speed. The same group also reported efficient solvent-free Aldol condensation and Michael addition using same apparatus (Crawford et al. 2017).

Use of no solvent is the best way in the green synthesis. In case of sustainable biocatalytic reactions also, an extra benefit can be achieved under solvent-free condition. If one or more of the reagents in biocatalytic reactions is a liquid then mixing of substrate and enzyme is as simple as reactions in non-aqueous solvents. But, for solid substrates and solid catalysts, then, the reaction will not be accessed smoothly. The lack of miscibility of substrate and enzyme will limit the rate and yield of the reaction. There are two approaches in this solvent-free biocatalytic reactions —"heterogeneous eutectic" and "solid-to-solid" reactions.

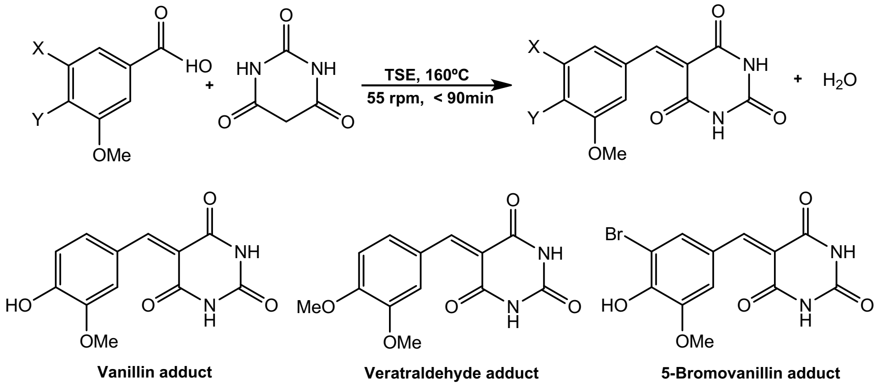


Scheme 53 Solvent-free Hantzsch synthesis by thermal heating catalysed by chitosan-NPs



Scheme 54 Solvent-free Paal-Knorr synthesis by MW irradiation or US technique

Scheme 55 Solvent-free Knoevenagel condensation using TSE technique



A minimum extent liquid phase is essential in both the approaches, so that enzyme can conduct the reaction. In heterogeneous eutectic approach, enzyme gets compatible with the low melting (in general, <60 °C) eutectic mixture of substrates (or in combination with very little adjuvant, for example, water or organic compound). In the solid-to-solid reaction, as the reactants are mostly in the solid state, an added liquid phase is required for the reaction to occur. Both the approaches are used extensively in organic synthesis (Hobbs and Thomas 2007). To provide enzymes enough resistance to influential conditions, for example, pH or temperature enzyme immobilisation is very effective, especially for commercial uses. Enzyme immobilisation involves modification of enzyme by binding to a solid support (carrier), entrapment and cross-linking (Sheldon and Pereira 2017). Though, immobilisation of enzymes are not fully free of disadvantages. Enzymes have already been used in many synthesis reactions in immobilised condition (Hobbs and Thomas 2007).

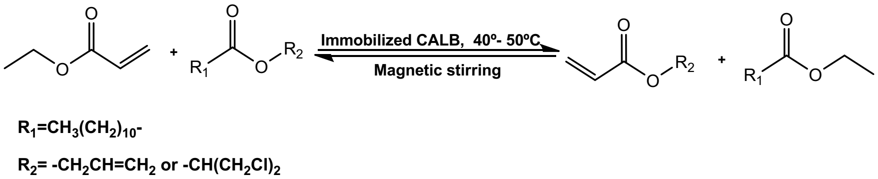
In 2012, a solvent-free interesterification of acrylate derivatives was catalysed by a lipase enzyme in a synthetic process. Actually, allyl and dichloropropyl acrylates were synthesised in the process from allyl and dichloropropyl dodecanoates using whole cells (fungal resting cells) supported lipase-based commercial biocatalysts (e.g. CALB—Candida antarctica lipase B) at temperature below 50 °C under solvent-free condition (Scheme 56) (Varón et al. 2012). Quantitative yields of chlorohydrin acrylates were produced in this green process which was a maiden achievement and more advantageous than conventional methods. There are examples where lipases have been also used towards feasible and scalable solvent-free enzymatic polycondensations (Pellisa et al. 2015).

Few years ago, Liu et al. proposed solvent-free enantioselective aldol reactions of isatin derivatives with cyclic ketones catalysed by Nuclease P1 extracting from Penicillium citrinum (Scheme 57). The effective reaction was discovered to be enantioselective in association with high yielding (up to 95%) at mild condition. In conventional solvent-based methods, poor yields were produced under same reaction conditions. Harnessing Nuclease in this biocatalytic organic synthesis widens its applicability in pharmaceutical industry also (Liu et al. 2014).

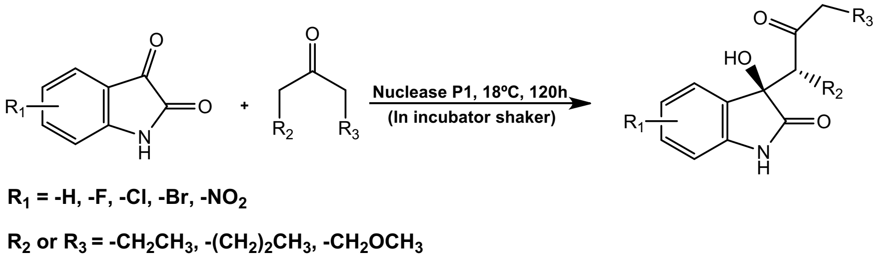
4 Future Trends

According to the Nobel Laureate Professor Ryoji Noyori "Green Chemistry is not just a mere catch phrase; it is the key to the survival of mankind." (Noyori 2010) In addition, the long discussion about organic synthesis with greener approaches, the dependency of chemical reaction upon solvent is understood in essence. Therefore, discovering more appropriate solvent or solvent mixture from the hidden treasure of chemistry is a prime task to climb the summit of transcendence of green chemistry in the forthcoming future.

The hydrophobic effect and trans-phase activity of water ameliorated organic synthetic path with a new version. It provided mild reaction condition, good reactivity, selectivity, easy separation and recycling of catalysts. But, uncommon reactivity and reverse selectivity of water unlike organic solvents limited its further use in synthesis. Even, its



Scheme 56 Lypase-catalysed solvent-free interesterification of acrylate derivatives by thermal by magnetic stirring



Scheme 57 Nuclease P1-catalysed solvent-free enantioselective aldol reactions of isatin derivatives

nontoxicity could not make it completely green solvent. On the contrary, the supramolecular aspects of micellar aggregation have drawn a great attention in the field of green synthesis (Acharjee et al. 2019a, b, 2020; Rakshit et al. 2020). Contribution of surfactants to almost all classes of chemical transformations, as medium as well as catalyst of reaction, is just undeniable. Sophisticate optimisation of chemical nature, concentration and molar ratio of surfactants can greatly influence the desired outcome of reaction. Unique combination of catalyst, substrate and surfactant can result some incredible happenings. Recently, preparation of molecular capsule by new surfactants and their photoactive encapsulation property has gained potential applications in many technological fields, in catalysis and drug delivery (Moscoso and Ballester 2017; Beaudoin et al. 2016). In future, further research is necessary for some more multiple applications, understanding and development of photocontrolled molecular capsules. In heterogeneous catalysis, stabilisation of nanoparticles with controlled shape and its fate in micellar media is attracting researchers for more research in near future (Yin et al. 2015; Xi et al. 2018). Another very important research is to discover suitable reversible bio-surfactants for upgraded biocatalytic organic synthesis to mimic green metabolic reactions in aqueous medium in living organisms.

ILs are getting more attention, as non-aqueous media, than fluorous media. The tunable property of ILs by selecting appropriate ion-pairs has made them so unique. Enzymes are very stable in some ILs for which they are suitable for enzymatic reactions. Many organic compounds are immiscible in ILs unlike fluorous solvents. Therefore, ILs are very satisfactorily acceptable in biphasic reaction. Whereas, in case of FBS, volatile organic solvents are to be consumed for organic product separation. Hence, ILs are supposed to be getting wider appreciation in near future in green synthesis including industrial purpose than fluorous media. The high price of fluorous solvent is also a limitation of using it. The coupling of $scCO_2$ with ILs is a great combination in harnessing green synthesis. Some liquid polymers, for example, poly(ethyleneglycol) (PEG), poly (propyleneglycol) (PPG) or poly(tetrahydrofuran) (PTHF), being biodegradable and widely tunable may be alternative to slightly biodegradable ILs (Lozano 2010). CO_2 in its supercritical state with tunable solvent property and nontoxicity has occupied a remarkable position as a green solvent. But, in enzymatic reaction, the carbamate formation and pH reduction due to carbonic acid formation have created problems (Lozano 2010). So, some scope of research is there to find way-out to overcome the problems. Synthesis of solid nanocomposites, assembly of metal-organic framework and amphiphiles may solve many challenging problems hereafter in $scCO_2$/IL biphasic medium (Zhang et al. 2014, 2016; Ivanova et al. 2015).

In the wake of this, one thing should not be forgotten that solvent-free synthesis is more successful than solvent-based system. In biocatalytic reactions also no exception happened. But, in following solvent-based biocatalysis in living organisms, finding some better green solvents is of utmost importance and more exquisite research is necessary to unfold this fact.

References

Abe Y, Yagi Y, Hayase S, Kawatsura M, Itoh T (2012) Ionic liquid engineering for lipase-mediated optical resolution of secondary alcohols: design of ionic liquids applicable to ionic liquid coated-lipase catalyzed reaction. Ind Eng Chem Res 51:9952–9958

Acharjee A, Rakshit A, Chowdhury S, Malik S, Barman MK, Ali MA, Saha B (2019a) Micellar catalysed and heteroaromatic base promoted rate enhancement of oxidation of an alicyclic alcohol in aqueous medium. J. Mol. Liq. 277:360–371. https://doi.org/10.1016/j.molliq.2018.12.082

Acharjee A, Rakshit A, Chowdhury S, Datta I, Barman MK, Ali MA, Saha B (2019b) Micellar catalysed oxidation of hydrophobic fatty alcohol in aqueous medium. J Mol Liq 293:111475. https://doi.org/10.1016/j.molliq.2019.111475

Acharjee A, Rakshit A, Chowdhury S, Ali MA, Singh B, Saha B (2020) Mixed anionic-nonionic micelle catalysed oxidation of aliphatic alcohol in aqueous medium. J Mol Liq 303:112655. https://doi.org/10.1016/j.molliq.2020.112655

Adlercreutz P (2013) Immobilisation and application of lipases in organic media. Chem Soc Rev 42:6406–6436. https://doi.org/10.1039/C3CS35446F

Akbarinezhad E (2014) Synthesis of conductive polyaniline–graphite nanocomposite in supercritical CO_2 and its application in zinc-rich epoxy primer. J Supercrit Fluids 94:8–16. https://doi.org/10.1016/j.supflu.2014.06.018

Akiyama T (2007) Stronger Brønsted acids. Chem Rev 107(12):5744–5758. https://doi.org/10.1021/cr068374j

Akiyama T, Mori K (2015) Stronger Brønsted acids: recent progress. Chem Rev 115(17):9277–9306. https://doi.org/10.1021/acs.chemrev.5b00041

Anastas P, Eghbali N (2010) Green chemistry: principles and practice. Chem Soc Rev 39:301–312. https://doi.org/10.1039/b918763b

Astruc D (2007) Palladium nanoparticles as efficient green homogeneous and heterogeneous carbon−carbon coupling precatalysts: a unifying view. Inorg Chem 46(6):1884–1894. https://doi.org/10.1021/ic062183h

Azizi N, Saidi MR (2005) Highly chemoselective addition of amines to epoxides in water. Org Lett 7:3649

Baheti P, Gimello O, Bouilhac C, Desmazes PL, Howdle SM (2018) Sustainable synthesis and precise characterisation of bio-based star polycaprolactone synthesised with a metal catalyst and with lipase. Polym Chem 9:5594. https://doi.org/10.1039/c8py01266k

Beaudoin D, Rominger F, Mastalerz M (2016) Chirality-assisted synthesis of a very large octameric hydrogenbonded capsule. Angew Chem Int Ed 55:1–6. https://doi.org/10.1002/anie.201609073

Beier P, O'Hagan D (2002) Enantiomeric partitioning using fluorous biphase methodology for lipase-mediated (trans)esterifications. Chem Commun 1680–1681

Bernini R, Mincione E, Coratti A, Fabrizi G, Battistuzzi G (2004) Epoxidation of chromones and flavonoids in ionic liquids. Tetrahedron 60:967.

Biasutti MA, Abuin EB, Silber JJ, Correa NM, Lissi EA (2008) Kinetics of reactions catalyzed by enzymes in solutions of surfactants. Adv Colloid Interface Sci 136:1–24. https://doi.org/10.1016/j.cis.2007.07.001

Birkin NA, Arrowsmith NJ, Park EJ, Richez AP, Howdle SM (2011) Synthesis and application of new CO_2-soluble vinyl pivalate hydrocarbon stabilisers via RAFT polymerisation. Polym Chem 2:1293. https://doi.org/10.1039/C1PY00062D

Birkin NA, Wildig OJ, Howdle SM (2013) Effects of poly(vinyl pivalate)-based stabiliser architecture on CO_2-solubility and stabilising ability in dispersion polymerisation of N-vinyl pyrrolidone. Polym Chem 4:3791. https://doi.org/10.1039/c3py00275f

Bortolini O, Conte V, Chiappe C, Fantin G, Fogagnolo M, Maietti S (2002) Epoxidation of electrophilic alkenes in ionic liquids. Green Chem 4:94

Boyère C, Jérôme C, Debuigne A (2014) Input of supercritical carbon dioxide to polymer synthesis: an overview. Eur Polym J 61:45–63. https://doi.org/10.1016/j.eurpolymj.2014.07.019

Breslow R (1991) Hydrophobic effects on simple organic reactions in water. Acc Chem Res 24:159

Brittain SM, Ficarro SB, Brock A, Peters EC (2005) Enrichment and analysis of peptide subsets using fluorous affinity tags and mass spectrometry. Nat Biotechnol 23:463–468. https://doi.org/10.1038/nbt1076

Calò V, Nacci A, Monopoli A, Montingelli F (2005) Pd Nanoparticles as efficient catalysts for suzuki and stille coupling reactions of aryl halides in ionic liquids. J Org Chem 70(15):6040–6044. https://doi.org/10.1021/jo050801q

Cao C, Matsuda T (2016) Chapter 3—Biocatalysis in organic solvents, supercritical fluids and ionic liquids, organic synthesis using biocatalysis, pp 67–97. https://doi.org/10.1016/B978-0-12-411518-7.00003-2

Cave GWV, Raston CL, Scott JL (2001) Recent advances in solventless organic reactions: towards benign synthesis with remarkable versatility. Chem Commun 21:2159

Chanda A, Fokin VV (2009) Organic synthesis "On Water." Chem Rev 109:725–748. https://doi.org/10.1021/cr800448q

Chandna N, Chandak N, Kumar P, Kapoor JK, Sharma PK (2013) Metal- and solvent-free synthesis of N-sulfonylformamidines. Green Chem 15:2294. https://doi.org/10.1039/c3gc40797g

Cho H, Madden R, Nisanci B, Török B (2015) The Paal-Knorr reaction revisited a catalyst and solvent-free synthesis of underivatized and N-substituted pyrroles. Green Chem 17:1088–1099. https://doi.org/10.1039/C4GC01523A

Choudhary G, Peddinti RK (2011) An expeditious, highly efficient, catalyst-free and solvent-free synthesis of nitroamines and nitrosulfides by Michael addition. Green Chem 13:276. https://doi.org/10.1039/c0gc00830c

Chowdhury S, Rakshit A, Acharjee A, Saha B (2019a) Novel amphiphiles and their applications for different purposes with special emphasis on polymeric surfactants. Chem Sel 4:1–19. https://doi.org/10.1002/slct.201901160

Chowdhury S, Rakshit A, Acharjee A, Ghosh A, Mahali K, Saha B (2019b) Ru(III) catalysed oxidation of 2-propanol by Cr(VI) in micellar media. J Mol Liq 290:111247. https://doi.org/10.1016/j.molliq.2019.111247

Chowdhury S, Rakshit A, Acharjee A, Mahali K, Saha B (2020b) Surface phenomenon in micellar media: an excellent controlling factor for oxidation of fatty aldehyde in aqueous medium. J Mol Liq 310:113224. https://doi.org/10.1016/j.molliq.2020.113224

Chowdhury S, Rakshit A, Acharjee A, Ghosh A, Mahali K, Saha B (2020a) Trivalent ruthenium and iridium salt: excellent homogeneous catalysts for alicyclic alcohol oxidation in micellar media. Tenside Surfactant 57:298–309

Cioc RC, Ruijter E, Orru RVA (2014) Multicomponent reactions: advanced tools for sustainable organic synthesis. Green Chem 16:2958. https://doi.org/10.1039/c4gc00013g

Crawford DE, Miskimmin CKG, Albadarin AB, Walker G, James SL (2017) Organic synthesis by Twin Screw Extrusion (TSE): continuous, scalable and solvent-free. Green Chem 19:1507–1518. https://doi.org/10.1039/C6GC03413F

Daneshjoo S, Akbari N, Sepahi AA, Ranjbar B, Khavarinejad R-A, Khajeh K (2011) Imidazolium chloride-based ionic liquid-assisted improvement of lipase activity in organic solvents. Eng Life Sci 11:259–263

Darío Falcone R, Alicia Biasutti M, Mariano Correa N, Silber JJ, Lissi E, Abuin E (2004) Effect of the addition of a nonaqueous polar solvent (glycerol) on enzymatic catalysis in reverse micelles.

Hydrolysis of 2-naphthyl acetate by r-chymotrypsin. Langmuir 20:5732–5737. https://doi.org/10.1021/la036243x

Das VK, Borah M, Thakur AJ (2013) Piper-betle-shaped nano-S-catalyzed synthesis of 1-amidoalkyl-2naphthols under solvent-free reaction condition: a greener, “Nanoparticle-Catalyzed Organic Synthesis Enhancement” approach. J Org Chem 78 (7):3361–3366. https://doi.org/10.1021/jo302682k

Dey J, Saha M, Kumar Pal A, Ismail K (2013) Regioselective nitration of aromatic compounds in an aqueous sodium dodecylsulfate and nitric acid medium. RSC Adv (2013) 3:18609

Dias ALB, Santos PD, Martínez J (2018) Supercritical CO_2 technology applied to the production of flavor ester compounds through lipase-catalyzed reaction: a review. J. CO_2 Util 23:159–178. https://doi.org/10.1016/j.jcou.2017.11.011

Dicks AP, Hent A (2015) Atom economy and reaction mass efficiency. In: Green chemistry metrics, springer briefs in molecular science. Springer, Cham, pp 17–44. https://doi.org/10.1007/978-3-319-10500-0_2

Dong X, Fan Y, Zhang H, Zhong Y, Yang Y, Miao J, Hua S (2016) Inhibitory Effects of ionic liquids on the lactic dehydrogenase activity. Int J Biol Macromol 86:155–161

Du L, Kelly JY, Roberts GW, De Simone JM (2009) Fluoropolymer synthesis in supercritical carbon dioxide. J Supercrit Fluids 47 (3):447–457

Dunk B, Jachuck R (2000) A novel reactor for UV irradiated reactions. Green Chem 2:G13. https://doi.org/10.1039/B000158I

Dunn PJ, Wells AS, Williams MT (2010a) Introduction to green chemistry, organic synthesis and pharmaceuticals. In: Green chemistry in the pharmaceutical industry, Wiley, pp 1–18

Dunn PJ, Wells AS, Williams MT (2010b) Green chemistry metrics, in green chemistry in the pharmaceutical industry. Wiley, 21–46

Dunn (2012) The importance of green chemistry in process research and development. Chem Soc Rev 41:1452–1461. https://doi.org/10.1039/c1cs15041c

Dwars T, Paetzold E, Oehme G (2005) Reactions in micellar systems. Angew. Chem Int Ed 44:7174–7199. https://doi.org/10.1002/anie.200501365

Eckert CA, Knutson BL, Debenedetti PG (1996) Supercritical fluids as solvents for chemical and materials processing. Nature 383:313–318

Firin ŸZ, Demirkol O, Akbaflar D, Giray ES (2013) Clean and efficient synthesis of flavanone in sub-critical water. J Supercrit Fluids 217–220. https://doi.org/10.1016/j.supflu.2013.05.014

Firouzabadi H, Iranpoor N, Gholinejad M (2009) 2-Aminophenyl diphenylphosphinite as a new ligand for heterogeneous palladium-catalyzed Heck–Mizoroki reactions in water in the absence of any organic co-solvent. Tetrahedron 65:7079

Fujita S, Yuzawa K, Bhanage BM, Ikushima Y, Arai MJ (2002) Palladium-catalyzed heck coupling reactions using different fluorinated phosphine ligands in compressed carbon dioxide and conventional organic solvents. Mol Catal A 180:35

Giacalone F, Gruttadauria M, Meo PL, Riela S, Noto R (2008) New simple hydrophobic proline derivatives as highly active and stereoselective catalysts for the direct asymmetric aldol reaction in aqueous medium. Adv Synth Catal 350:2747

Goto K, Miura T, Mizuno M (2005) Synthesis of peptides and oligosaccharides by using a recyclable fluorous tag. Tetrahedron Lett 46:8293–8297. https://doi.org/10.1016/j.tetlet.2005.09.160

Guironnet D, Friedberger T, Mecking S (2009) Ethylene polymerization in supercritical carbon dioxide with binuclear nickel(II) catalysts. Dalton Trans 8929–893. https://doi.org/10.1039/b912883b

Hallett JP, Welton T (2011) Room-temperature ionic liquids: solvents for synthesis and catalysis. 2. Chem Rev 111:3508–3576. https://doi.org/10.1021/cr1003248

Hasaninejad A, Zare A, Shekouhya M, Rada JA (2011) Sulfuric acid-modified PEG-6000 (PEG-OSO_3H): an efficient, biodegradableandreusablepolymericcatalystforthesolvent-freesynthesis of poly-substituted quinolines under microwave irradiation. Green Chem 13:958. https://doi.org/10.1039/c0gc00953a

Hasaninejed A, Kazerooni MR, Zare A (2012) Solvent-free, one-pot, four-component synthesis of 2H-indazolo[2,1-b]phthalazine-triones using sulfuric acid-modified PEG-6000 as a green recyclable and biodegradable polymeric catalyst. Catal Today 196:148–155. https://doi.org/10.1016/j.cattod.2012.05.026

Hayashi Y, Urushima T, Aratake S, Okano T, Obi K (2007) Organic solvent-free, enantio- and diastereoselective, direct mannich reaction in the presence of water. Org Lett 10:21

He X, Chan TH (2006) New non-volatile and odorless organosulfur compounds anchored on ionic liquids. Recyclable reagents for swern oxidation. Tetrahedron 62:3389–3394

Hernández JG, Juaristi E (2010) Green synthesis of r, β- and β, β-dipeptides under solvent-free conditions. J Org Chem 75:7107–7111. https://doi.org/10.1021/jo101159a

Hobbs HR, Thomas NR (2007) Biocatalysis in supercritical fluids, in fluorous solvents, and under solvent-free conditions. Chem Rev 107:2786–2820. https://doi.org/10.1021/cr0683820

Horng RS, Lee SK, Hsu WT, Wu TA (2016) Pressure influences on CO_2 reaction with cyclohexylamine using ionic liquid as reaction medium and catalyst. J Chin Inst Eng 39(7):876–881. https://doi.org/10.1080/02533839.2016.1203734

Housaindokht MR, Monhemi H (2013) The open lid conformation of the lipase is explored in the compressed gas: new insights from molecular dynamic simulation. J Mol Catal B Enzym 87:135–138

Hu X, Manetsch R (2010) Kinetic target-guided synthesis. Chem Soc Rev 39:1316

Hu X, Shu XS, Li XW, Liu S-G, Zhang Y-Y, Zou G-L (2006) Hemoglobin-biocatalyzed synthesis of conducting polyaniline in micellar solutions. Enzyme Microb Technol 38:675–682. https://doi.org/10.1016/j.enzmictec.2005.08.006

Huskić I, Halasz I, Friščić T, Vančik H (2012) Mechanosynthesis of nitrosobenzenes: a proof-of-principle study in combining solvent-free synthesis with solvent-free separations. Green Chem 14:1597. https://doi.org/10.1039/c2gc35410a

Islam MT, Haldorai Y, Nguyen VH, Islam MN, Ra CS, Shim JJ (2014) Controlled radical polymerization of vinyl acetate in supercritical CO_2 catalyzed by CuBr/terpyridine. Korean J Chem Eng 31 (6):1088–1094. https://doi.org/10.1007/s11814-014-0031-5

Islam MN, Haldorai Y, Nguyen VH, Shim JJ (2014) Synthesis of poly (vinyl pivalate) by atom transfer radical polymerization in supercritical carbon dioxide. Eur Polym J 61:93–104. https://doi.org/10.1016/j.eurpolymj.2014.09.003

Isley NA, Linstadt RTH, Slack ED, Lipshutz BH (2014) Copper-catalyzed hydrophosphinations of styrenes in water at room temperature. Dalton Trans 43:13196

Isley NA, Dobarco S, Lipshutz BH (2014) Installation of protected ammonia equivalents onto aromatic & heteroaromatic rings in water enabled by micellar catalysis. Green Chem 16:1480

Itoh T (2017) Ionic liquids as tool to improve enzymatic organic synthesis. Chem Rev 117:10567–10607. https://doi.org/10.1021/acs.chemrev.7b00158

Ivanova M, Kareth S, Spielberg ET, Mudring AV, Petermann M (2015) Silica ionogels synthesized with imidazolium based ionic liquids in presence of supercritical CO_2. J Supercrit Fluids 105:60–65. https://doi.org/10.1016/j.supflu.2015.01.014

Jessop PG, Stanley RR, Brown RA, Eckert CA, Liotta CL, Ngo TT, Pollet P (2003) Neoteric solvents for asymmetric hydrogenation: supercritical fluids, ionic liquids, and expanded ionic liquids. Green Chem 5:123–128. https://doi.org/10.1039/b211894g

Kanagaraj K, Pitchumani K (2010) Solvent-free multicomponent synthesis of pyranopyrazoles: per-6-amino-β-cyclodextrin as a remarkable catalyst and host. Tetrahedron Lett 51:3312–3316. https://doi.org/10.1016/j.tetlet.2010.04.087

Kumar A, Sharma S (2017) A grinding-induced catalyst- and solvent-free synthesis of highly functionalized 1,4-dihydropyridines via a domino multicomponent reaction. Green Chem 2011:13. https://doi.org/10.1039/c1gc15223h

Kumar D, Seth K, Kommi DN, Bhagat S, Chakraborti AK (2013) Surfactant micelles as microreactors for the synthesis of quinoxalines in water: scope and limitations of surfactant catalysis. RSC Adv 3:15157

Kumar A, Kumar Gupta M, Kumar M, Saxena D (2013) Micelle promoted multicomponent synthesis of 3-amino alkylated indoles via a Mannich-type reaction in water. RSC Adv 3:1673

Laszlo JA, Compton DL (2002) Adv Chem Ser 818:387

Laville L, Charnay C, Lamaty F, Martinez J, Colacino E (2012) Chem Eur J 18:760

Li CJ (2005) Organic reactions in aqueous media with a focus on carbon−carbon bond formations: a decade update. Chem Rev 105:3095–3166. https://doi.org/10.1021/cr030009u

Li M, Cao H, Wang Y, Lv XL, Wen LR (2012) One-pot multicomponent cascade reaction of N,S-ketene acetal: solvent-free synthesis of imidazo[1,2-a]thiochromeno[3,2-e]pyridines. Org Lett 14(13). https://doi.org/10.1021/ol301441v

Li X, Zhang C, Li S, Huang H, Hu Y (2015) Improving catalytic performance of candida rugosa lipase by chemical modification with polyethylene glycol functional ionic liquids. Ind Eng Chem Res 54:8072−8079

Lin L, Li Y, Zhang S, Li S (2011) Enhancing activity of suzuki reactions in water by using guanidinium ionic liquid stabilized palladium micelle catalyst. Synlett 1779

Linstadt RTH, Peterson CA, Lippincott DJ, Jette CI, Lipshutz BH (2014) Stereoselective silylcupration of conjugated alkynes in water at room temperature. Angew Chem Int Ed 53:4159

Lipshutz BH, Ghorai S, Wen W, Leong T, Taft BR (2011) Manipulating micellar environments for enhancing transition metal-catalyzed cross-couplings in water at room temperature. J Org Chem 76:5061.

Liu ZQ, Xiang ZW, Shen Z, Wu Q, Lin XF (2014) Enzymatic enantioselective aldol reactions of isatin derivatives with cyclic ketones under solvent-free conditions. Biochimie 101:156–160. https://doi.org/10.1016/j.biochi.2014.01.006

Lozano P (2010) Enzymes in neoteric solvents: from one-phase to multiphase systems. Green Chem 12:555–569. https://doi.org/10.1039/b919088k

Machida H, Takesue M, Smith RL Jr (2011) Green chemical processes with supercritical fluids: properties, materials, separations and energy. J Supercrit Fluids 60:2–15. https://doi.org/10.1016/j.supflu.2011.04.016

Mamidyala SK, Finn MG (2010) In situ click chemistry: probing the binding landscapes of biological molecules. Chem Soc Rev 39:1252

Marques MPC, Lourenço NMT, Fernandes P, de Carvalho CCCR (2012) Green solvents for biocatalysis. In: Mohammad A, Inamuddin (eds) Green solvents I. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1712-1_3

Martins MAP, Frizzo CP, Moreira DN, Buriol L, Machado P (2009) Solvent-free heterocyclic synthesis. Chem. Rev. 109:4140–4182. https://doi.org/10.1021/cr9001098

Matsubara H, Maegawa T, Kita Y, Yokoji T, Nomoto A (2014) Synthesis and properties of fluorous benzoquinones and their application in deprotection of silyl ethers. Org Biomol Chem 12:5442–5447. https://doi.org/10.1039/C4OB00783B

Matsuda T (2013) Recent progress in biocatalysis using supercritical carbon dioxide. J Biosci Bioeng 115:233–241. https://doi.org/10.1016/j.jbiosc.2012.10.002

Medina-Gonzalez Y, Camy S, Condoret J-S (2012) Cellulosic materials as biopolymers and supercritical CO_2 as a green process: chemistry and applications. Int J Sust Eng 5:47–65. https://doi.org/10.1080/19397038.2011.613488

Merchán Arenas DR, Martínez Bonilla CA, Kouznetsov VV (2013) Org Biomol Chem 11:3655.

Mikami K (2005) Green reaction media in organic synthesis. Blackwell Publishing, Oxford, UK

Mohammadyazdani N, Reza Bozorgmehr M, MomenHeravi M (2016) Conformation changes and diffusion of a-amylase in 1hexyl-3-methylimidazolium chloride ionic liquid: a molecular dynamics simulation perspective. J Mol Liq 221:463–468

Molnár Á (2011) Efficient, selective, and recyclable palladium catalysts in carbon−carbon coupling reactions. Chem Rev 111(3):2251–2320. https://doi.org/10.1021/cr100355b

Monteith ER, Mampuys P, Summerton L, Clark JH, Maes BUW, Robert McElroy C (2020) Why we might be misusing process mass intensity (PMI) and a methodology to apply it effectively as a discovery level metric. Green Chem 22:123. https://doi.org/10.1039/c9gc01537j

Morita, DK, Pesiri DR, David SA, Glaze WH, Tumas W (1998) Palladium-catalyzed cross-coupling reactions in supercritical carbon dioxide. Chem Commun 1397

Moscoso AD, Ballester P (2017) Light-responsive molecular containers. Chem Commun 53:4635. https://doi.org/10.1039/c7cc01568b

Nairoukh Z, Avnir D, Blum J (2013) Acid-catalyzed hydration of alkynes in aqueous microemulsions. Chemsuschem 6:430–432

Noyori R (2010) Insight: Green chemistry: the key to our future. Tetrahedron 66:1028

Ohara M, Hara Y, Ohnuki T, Nakamura S (2014) Direct enantioselective three-component synthesis of optically active propargylamines in water. Chem Eur J 20:8848–8851.

Ohde H, Ohde M, Wai CM (2004) Swelled plastics in supercritical CO_2 as media for stabilization of metal nanoparticles and for catalytic hydrogenation. Chem Commun 930–931. https://doi.org/10.1039/B311522D

Ohnmacht SA, Mamone P, Culshaw AJ Greaney MF (2008) Direct arylations on water: synthesis of 2,5-disubstituted oxazoles balsoxin and texaline. Chem Commun 1241

Onwudili JA, Williams PT (2006) Flameless supercritical water incineration of polycyclic aromatic hydrocarbons. Int J Renew Energy Res 30:523–533

Ou G, He B, Halling P (2016) Ionization basis for activation of enzymes soluble in ionic liquids. Biochim Biophys Acta Gen Subjects 1860:1404–1408

Palou RM (2010) Microwave-assisted synthesis using ionic liquids. Mol Divers 14:3–25. https://doi.org/10.1007/s11030-009-9159-3

Panja SK, Saha S (2013) Recyclable, magnetic ionic liquid bmim [FeCl4]catalyzed, multicomponent, solvent-free, green synthesis of quinazolines. RSC Adv 3:14495–14500. https://doi.org/10.1039/c3ra42039f

Pârvulescu VI, Hardacre C (2007) Catalysis in ionic liquids. Chem Rev 107:2615–2665. https://doi.org/10.1021/cr050948h

Pathak AK, Ameta C, Ameta R, Punjabi PB (2016) Microwave-assisted organic synthesis in ionic liquids. J Heterocycl Chem 53:1697–1705. https://doi.org/10.1002/jhet.2515

Pavlovič I, Knez Ž, Škerget M (2013) Hydrothermal reactions of agricultural and food processing wastes in sub- and supercritical water: a review of fundamentals, mechanisms, and state of research. J Agric Food Chem 61:8003–8025

Pei Y, Hao L, Ru J, Zhao Y, Wang H, Bai G, Wang J (2018) The self-assembly of ionic liquids surfactants in ethanolammonium nitrate ionic liquid. J Mol Liq 254:130–136. https://doi.org/10.1016/j.molliq.2018.01.095

Pellisa A, Corici L, Sinigoia L, D'Amelioc N, Fattor D, Ferrario V, Ebert C, Gardossi L (2015) Towards feasible and scalable solvent-free enzymatic polycondensations: integrating robust biocatalysts with thin film reactions. Green Chem 17:1756–1766. https://doi.org/10.1039/C4GC02289K

Petrone DA, Ye J, Lautens M (2016) Modern transition-metal-catalyzed carbon-halogen bond formation. Chem Rev 116(14):8003–8104. https://doi.org/10.1021/acs.chemrev.6b00089

Pirrung MC, Sarma KD (2003) Multicomponent reactions are accelerated in water. J Am Chem Soc 126:444

Pirrung MC, Sarma KD (2005) Aqueous medium effects on multi-component reactions. Tetrahedron 61:11456

Rajendar Reddy K, Rajanna KC, Uppalaiah U (2013) Environmentally benign contemporary Friedel–Crafts acylation of 1-halo-2-methoxynaphthalenes and its related compounds under conventional and nonconventional conditions. Tetrahedron Lett 54:3431

Rakshit A, Chowdhury S, Acharjee A, Datta I, Dome K, Biswas S, Bhattacharyya SS, Saha B (2020) Hetero-aromatic N-base-promoted oxidation of 4-chlorobenzyl alcohol by Cr(VI) in micellar media. Res Chem Intermediate 46:2559–2578. https://doi.org/10.1007/s11164-020-04106-x

Reetz MT, Wiesenhöfer W, Franciò G, Leitner W (2002) Biocatalysis in ionic liquids: batchwise and continuous flow processes using supercritical carbon dioxide as the mobile phase. Chem Commun 992–993. https://doi.org/10.1039/B202322A

Rideout DC, Breslow R (1980) Hydrophobic acceleration of Diels-Alder reactions. J Am Chem Soc 102:7816

Rodrigues JV, Ruivo D, Rodríguez A, Deive FJ, Esperanca JMSS, Marrucho IM, Gomes CM, Rebelo LPN (2014) Structural−functional evaluation of ionic liquid libraries for the design of co-solvents in lipase-catalysed reactions. Green Chem 16:4520–4523

Rogozinska M, Adamkiewicz A, Mlynarski J (2011) Efficient "on water" organocatalytic protocol for the synthesis of optically pure warfarinanticoagulant. Green Chem 13:1155

Rose PM, Clifford AA, Rayner CM (2002) The Baylis–Hillman reaction in supercritical carbon dioxide: enhanced reaction rates, unprecedented ether formation, and a novel phase-dependent 3-component coupling. Chem Commun 968–969. https://doi.org/10.1039/B111347J

Safari J, Azizi F, Sadeghi M (2015) Chitosan nanoparticles as a green and renewable catalyst in the synthesis of 1,4-dihydropyridine under solvent-free conditions. NewJ Chem 39:1905. https://doi.org/10.1039/c4nj01730g

Sar P, Ghosh A, Scarso A et al (2019) Surfactant for better tomorrow: applied aspect of surfactant aggregates from laboratory to industry. Res Chem Intermed 45:6021–6041. https://doi.org/10.1007/s11164-019-04017-6

Sarkar S, Pal R, Kumar Sen A (2013) Efficient synthesis of 3-benzyl-3-(indol-3-yl)-2-phenyl-2,3-dihydroisoindolinone derivatives via a simple and convenient MCR in aqueous micellar system. Tetrahedron Lett 54:4273

Schwarze M, Milano-Brusco JS, Strempel V, Hamerla T, Wille S, Fischer C, Baumann W, Arlt W, Schomäcker R (2011) RSC Adv 1:474

Sharma H, Singh N, Jang DO (2014) A ball-milling strategy for the synthesis of benzothiazole, benzimidazole and benzoxazole derivatives under solvent-free conditions. Green Chem 16:4922–4930. https://doi.org/10.1039/C4GC01142B

Shaughnessy KH (2009) Hydrophilic ligands and their application in aqueous-phase metal-catalyzed reactions. Chem Rev 109:643–710. https://doi.org/10.1021/cr800403r

Sheldon RA (2005) Green solvents for sustainable organic synthesis: state of the art. Green Chem 7:267–278. https://doi.org/10.1039/b418069k

Sheldon RA (2008) E factors, green chemistry and catalysis: an odyssey. Chem Commun 3352–3365. https://doi.org/10.1039/B803584A

Sheldon RA, Pereira PC (2017) Biocatalysis engineering: the big picture. Chem Soc Rev 46:2678–2691. https://doi.org/10.1039/C6CS00854B

Sheldon RA, Woodley JM (2018) Role of biocatalysis in sustainable chemistry. Chem Rev 118(2):801–838. https://doi.org/10.1021/acs.chemrev.7b00203

Sheldon RA, Lau RM, Sorgedrager MJ, Rantwijk FV, Seddon KR (2002) Biocatalysis in ionic liquids. Green Chem 4:147–151. https://doi.org/10.1039/B110008B

Shome A, Roy S, Das PK (2007) Nonionic surfactants: a key to enhance the enzyme activity at cationic reverse micellar interface. Langmuir 23:4130–4136. https://doi.org/10.1021/la062804j

Simon MO, Li CJ (2012) Green chemistry oriented organic synthesis in water. Chem Soc Rev 41:1415–1427. https://doi.org/10.1039/c1cs15222j

Singh MS, Chowdhury S (2012) Recent developments in solvent-free multicomponent reactions: a perfect synergy for eco-compatible organic synthesis. RSC Adv 2:4547–4592. https://doi.org/10.1039/c2ra01056a

Singh SK, Savoy AW (2020) Ionic liquids synthesis and applications: an overview. J Mol Liq 297:112038. https://doi.org/10.1016/j.molliq.2019.112038

Singh D, Krishna R, Singh N (2011) A highly efficient green synthesis of 1H-pyrazolo[1,2-b]phthalazine-5,10-dione derivatives and their photophysical studies. Tetrahed Lett 52:5702–5705. https://doi.org/10.1016/j.tetlet.2011.08.111

Sorella GL, Strukul G, Scarso A (2015) Recent advances in catalysis in micellar media. Green Chem 17:644–683

Sowmiah S, Esperança JMSS, Rebelo LPN, Afonso CAM (2018) Pyridinium salts: from synthesis to reactivity and applications. Org Chem Front 5:453–493. https://doi.org/10.1039/C7QO00836H

Tanaka K (2009) Solvent free organic synthesis. Wiley, Weinheim, Germany

Toda F, Tanaka K (2000) Solvent-free organic synthesis. Chem Rev 100:1025

Tomasek J, Schatz J (2013) Olefin metathesis in aqueous media. Green Chem 15:2317

Touré BB, Hall DG (2009) Natural product synthesis using multicomponent reaction strategies. Chem Rev 109(9):4439–4486. https://doi.org/10.1021/cr800296p

Trindade AF, Gois PMP, Afonso CAM (2009) Recyclable stereoselective catalysts. Chem Rev 109(2):418–514. https://doi.org/10.1021/cr800200t

Varón EY, Joli JE, Torres M, Sala N, Villorbina G, Méndez JJ, Garayoa RC (2012) Solvent-free biocatalytic interesterification of acrylate derivatives. Catal Today 196:86–90. https://doi.org/10.1016/j.cattod.2012.02.055

Vilotijevic I, Jamison TF (2007) Epoxide-opening cascades promoted by water. Science 317:1189

Wang Q, Chan TR, Hilgraf R, Fokin VV, Sharpless KB, Finn MG (2003) Bioconjugation by copper(I)-catalyzed azide-alkyne [3 + 2] cycloaddition. J Am Chem Soc 125:3192

Wang LM, Jiao N, Qiu J, Yu J-J, Liu J-Q, Guo F-L, Liu Y (2010) Sodium stearate-catalyzed multicomponent reactions for efficient synthesis of spirooxindoles in aqueous micellar media. Tetrahedron 66:339

Wen LR, Li ZR, Li M, Cao H (2012) Solvent-free and efficient synthesis of imidazo[1,2-a]pyridine derivatives via a one-pot three-component reaction. Green Chem 14:707. https://doi.org/10.1039/c2gc16388h

Xi W, Phan HT, Haes AJ (2018) How to accurately predict solution-phase gold nanostar stability. Anal Bioanal Chem 410:6113–6123. https://doi.org/10.1007/s00216-018-1115-6

Xu R, Queneau Y (2014) How the polarity of carbohydrates can be used in chemistry. In: Rauter AR, Queneau YQ, Lindhorst TK (eds) Carbohydrate, chemical, royal society of chemistry, vol 40, pp 31–50. https://doi.org/10.1039/9781849739986-00031

Yan N, Xiao C, Kou Y (2010) Transition metal nanoparticle catalysis in green solvents. Coord Chem Rev 254:1179–1218. https://doi.org/10.1016/j.ccr.2010.02.015

Yang J, Dudley GB (2010) Pyridine-directed organolithium addition to an enol ether. Adv Syn Cat 352:3438–3442. https://doi.org/10.1002/adsc.201000495

Yin Y, Yu S, Shen M, Liu J, Jiang G (2015) Fate and transport of silver nanoparticles in the environment. In: Liu J, Jiang G (eds) Silver nanoparticles in the environment. Springer, Berlin, Heidelberg

Zhang W (2009) Fluorous linker-facilitated chemical synthesis. Chem Rev 109(2):749–795. https://doi.org/10.1021/cr800412s

Zhang W, Cai C (2008) New chemical and biological applications of fluorous technologies. Chem Commun 5686–5694. https://doi.org/10.1039/B812433G

Zhang J, Peng L, Han B (2014) Amphiphile self-assemblies in supercritical CO_2 and ionic liquids. Soft Matter 10:5861–5868. https://doi.org/10.1039/C4SM00890A

Zhang B, Zhang J, Han B (2016) Assembling metal–organic frameworks in ionic liquids and supercritical CO_2. 11:2610–2619. https://doi.org/10.1002/asia.201600323

Zhanga X, Wang L (2012) TBHP/I_2-promoted oxidative coupling of acetophenones with amines at room temperature under metal-free and solvent-free conditions for the synthesis of α-ketoamides. https://doi.org/10.1039/c2gc35489f

Zong M, Thurecht KJ, Howdle SM (2008) Dispersion polymerisation in supercritical CO_2 using macro-RAFT agents. Chem Commun 5942–5944. https://doi.org/10.1039/b812827h