



MINI REVIEW

Supercritical Carbon Dioxide as Greener Solvent of 21st Century

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Received: 23 November 2017;

Accepted: 3 December 2017;

Published online: 28 February 2018;

AJC-18771

“Green” or “Sustainable” chemistry is mainly concerned with development of “greener” solvents that have comparatively less negative impact on human health and environment. Many of the commonly used solvents in chemical and pharmaceutical industries are flammable, toxic and emit out volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) which cause serious environmental, health and safety concerns. Now-a-days supercritical carbon dioxide (Sc-CO₂) is receiving more and more attention as reaction media in scientific and industrial fraternity due to versatile possibilities of it as an eco-friendly, efficient, alternate and attractive solvent for today and tomorrow chemical processes. Supercritical carbon dioxide has liquid-like densities and solvent strength, which can be “tuned” by altering the pressure in reactor. So the present review article focuses on the applications and advantages of Sc-CO₂. Applications of it range from extraction, particle formation, chemical reactions, polymerization and soil treatment to dyeing.

Keywords: Supercritical carbon dioxide, Green solvents, Environment friendly technology.

INTRODUCTION

Today, green chemistry is considered synonymous with sustainable chemistry. One of the twelve principles of green chemistry states that, “the use of auxiliary substances (*e.g.* solvents, separation agents, *etc.*) should be made unnecessary wherever possible and innocuous when used” [1]. Solvents are commonly used as heat transfer, mass transfer and reaction media in chemical processes. In other words, solvents are main raw material of pharmaceutical, manufacturing and processing industries and to fulfill this rising need million tones of organic and halogenated solvents are produced annually. Many of the commonly used solvents such as benzene, toluene, halogenated solvents are known carcinogens and many others pose hazardous threats to the human health and environment. New regulations under U.S. Pollution Prevention Act, 1990 forced the industries to reduce their emissions into the environment and to investigate ways to recycle solvent waste. The health and environmental impact of solvent waste emphasize the current need to find “greener” and more sustainable alternative of current harmful solvents. Supercritical carbon dioxide (Sc-CO₂) is one of the many green solvent that has gained considerable importance in the various fields of extraction, polymerization, chemical and enzymatic reactions, soils treatment, nanoparticles formation, *etc.* Supercritical carbon dioxide has negligible environmental

impacts and is abundant, non-toxic, non-flammable and cost effective, making it a potential green and alternative solvent to the systems already in place. This review article seeks to present some of the applications of Sc-CO₂ in order to assess its efficiency in replacement of conventional solvents.

Supercritical carbon dioxide (Sc-CO₂): Sc-CO₂ is fluid state of CO₂ at or above its critical temperature (304.1 K) & critical pressure (73.8 bar) as shown in Fig. 1. It has liquid-like densities and solvent strength, which can be “tuned” by altering the pressure in reactor. It allows the control of the solu-

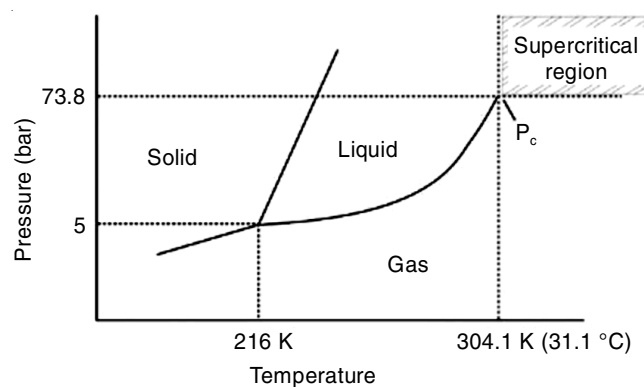


Fig. 1. Phase diagram of pure CO₂

bility of the reactants along with density-dependent properties such as viscosity and diffusivity.

Properties of Sc-CO₂ making it suitable & green solvent

- It is an attractive medium for chemical reactions due to its unique properties. In supercritical phase it has advantages of gas phase reactions including low viscosity, high miscibility with other gases, high diffusivity, thereby providing enhanced heat transfer and potential for fast reactions. Diffusion controlled reactions can be selectively carried out in Sc-CO₂.

- Products and catalysts of a chemical reaction can be separated by altering the solubility property of Sc-CO₂.

- For organic compounds such as triglycerides, esters and sterols its dissolving power is similar to hexane and for high molecular weight polymers having low vapour pressure its dissolving power is analogous to chlorofluorocarbons.

- Due to 'benign by design' nature of Sc-CO₂ solvent removal steps can be avoided after completion of reaction.

- CO₂, as a final product of deep oxidations, behave fully inert under oxidizing conditions, making this reaction medium especially attractive for aerobic oxidations.

- High specific-heat capacity of CO₂ ensures efficient heat transfer in highly exothermic oxidation reactions.

- CO₂ is cost effective, abundant & non-flammable, non-toxic reagent.

- "Tunable" dielectric constant of Sc-CO₂ can be used for changing the rate of reactions.

- Solvent properties can be further modified by employing co-solvents.

- It can be employed in homogeneous catalytic processes because of high miscibility of light gases, some catalysts and substrates into Sc-CO₂ that make the reaction medium homogeneous

Application of Sc-CO₂

In chemical reactions: Sc-CO₂ has been studied in various chemical reactions either as reaction medium or as a substrate actively participating in chemical reactions. Due to its versatile nature its certain properties such as dielectric constant, viscosity can be altered which contribute significantly in increased reaction rate, yield and selectivity [2]. Polymerization reactions occurring in heterogeneous media have lower reaction rate than in homogeneous media in Sc-CO₂.

Velocity of hydrogenation reactions is function of solubility of hydrogen in solution as well as the diffusivity of hydrogen once dissolved. But hydrogen is immiscible in organic solvents [3]. Because of high miscibility of hydrogen gas in Sc-CO₂, reaction rate can be increased by increasing concentration of hydrogen in solution. Sc-CO₂ can further speed up the reaction due to increased diffusivity of hydrogen into it. Catalytic hydrogenation of vegetable oils to fat offers great scope of Sc-CO₂ as reaction media due to its less toxic, non-flammable and eco-friendly nature. Catalytic hydrogenation of anthracene in Sc-CO₂ over Ni supported on H β -zeolite catalyst yielded 100 % conversion to reduced product (Fig. 2) due to increased solubility of hydrogen and anthracene in Sc-CO₂ [4].

The epoxidation of propylene to propylene oxide *via* H₂O₂ was carried out in Sc-CO₂ by employing Pd/titanium silicate (Fig. 3) [5]. The use of Sc-CO₂ as reaction media significantly

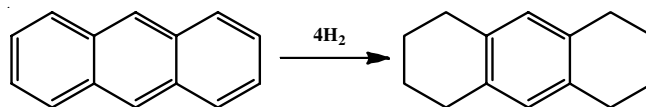


Fig. 2. Selective hydrogenation of anthracene in Sc-CO₂

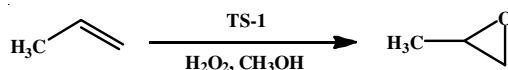


Fig. 3. Epoxidation of propylene to propylene oxide in Sc-CO₂

improved the product yield due to increased mass transfer and diffusion performance of it and increased solubility of propylene into it.

Due to high miscibility of Sc-CO₂ with hydrogen, oxygen and syngas (CO/H₂) it is useful reaction media for hydrogenation, oxidation and hydroformylation reactions respectively, leading to high selectivity and efficiency. It can be repeatedly employed as green solvent in chemical reactions due to easy separation of products and catalysts from it by depressurization and easy recapture.

Sako *et al.* [6] reported the production of furfural from xylose with increased selectivity in Sc-CO₂. Conventional methods have low selectivity due to high reactivity of furfural so the appearance of side reactions such as decomposition and polymerization. Oxidation of cumene was carried with increased selectivity in homogeneous phase by employing Sc-CO₂ as reaction media with elimination of side reactions [7]. In Diels-Alder reaction of isoprene with maleic anhydride in Sc-CO₂ product precipitated out as a solid from reaction medium even at very low concentration of reactants [8]. Cellulose molecules present in fabricated paper undergo oxidation and hydrolysis resulting into the formation of acid substances. Sc-CO₂ has many advantages over organic solvents used for the neutralization and strengthening of old papers from economic and environmental point of view [9]. Oxidation of primary and secondary alcohols to aldehydes and ketones, respectively, was carried out in biphasic catalytic system in which PEG-stabilized palladium nanoparticles in Sc-CO₂ were employed. This oxidation process in Sc-CO₂ ensured high selectivity, activity and stability of catalytic system.

In polymerization reactions: Researchers in 1980s found that Sc-CO₂ is equally and in some cases more efficient solvent than chlorofluorocarbons for chemical reactions. This discovery revolutionized the polymer industry. Release of large amount of VOCs, CFCs and catalysts used in industrial production of plastics and resins can be avoided by use of eco-compatible Sc-CO₂ during their processing and manufacturing. Furthermore, polymerization reactions in carbon dioxide do not have to undergo costly drying or solvent removal procedures. Patent for free radical polymerization of styrene, methyl methacrylate, acrylonitrile, vinyl chloride was filed by Sumimoto Chemical. Sc-CO₂ is reported as promising medium for free radical, cationic and condensation polymerization. Due to low viscosity of Sc-CO₂ free radical initiator AIBN have higher efficiency in it than benzene. Formation of Teflon from its monomer TFE (highly explosive) in Sc-CO₂ is highly advantageous because its monomer can form pseudo-azeotrope with CO₂ [10,11]. Dispersion polymerizations are preferably carried out in Sc-CO₂ because of less solubility of product formed and more solubility of vinyl

monomers and free radical initiators involved [12]. Recent advances in condensation polymerizations in Sc-CO₂ have focused on poly (bisphenol A carbonate). Environmentally unfriendly methylene chloride and toxic phosgene were used for industrial synthesis of polycarbonate prior to Sc-CO₂. Other method of industrial preparation of polycarbonate was melt-phase polymerization in the absence of solvent. The success of later method for synthesis of polycarbonate suffered a serious drawback that high temperature was required for polymerization in the absence of solvent and at high temperature viscosity of molten polymers raised. In melt polymerization Sc-CO₂ plasticizes the polymer and reduces the viscosity so high molecular weight polymer can be obtained.

Analytical applications: Sc-CO₂ has been investigated for potential application of it in two analytical techniques- supercritical fluid chromatography (SFC) and supercritical fluid extraction (SFE).

As chromatography is based on partitioning of the desired analyte between stationary phase and mobile phase (Sc-CO₂), capability of Sc-CO₂ for separation of different analytes can be altered by changing its solvating properties with change in temperature and pressure. Due to its low critical temperature it is able to separate thermally labile compounds [13]. At low pressure polar analytes are less soluble in Sc-CO₂. This can be overcome by adding a small amount of modifier (such as methanol) to the sample that can increase the polarity of Sc-CO₂. So it is best suitable for separation of substances having low polarity, but its solvency power can be modified by addition of other substances so it can also be used for polar substances. The mild operating conditions used in supercritical fluid chromatography in which Sc-CO₂ is used as the mobile phase, allows it to be adapted to liquid chromatography (LC) and gas chromatography (GC) [14]. Applications of Sc-CO₂ has been reported in separation of highly polar antibiotics, natural products such as sterols, terpenes, fatty acids and is even used in chiral separations of enantiomeric compounds [15]. Chromatography employing Sc-CO₂ is superior to conventional chromatographic techniques due to its ability to separate mixtures at lower temperature than GC and in shorter time LC [14]. Extraction in Sc-CO₂ has certain advantages over conventional solvents such as:

- Due to negligible surface tension of Sc-CO₂, its molecules can easily penetrate into the pores of heterogeneous matrices and can enhance extraction efficiencies.
- Desired compounds can be extracted selectively in Sc-CO₂ without leaving hazardous residues in the extract.
- Selectivity during extraction can be ensured by alteration in temperature and pressure conditions. Even the desired compounds can be extracted in good yield by adding co-solvent of different polarity.
- Thermal degradation of compounds during extraction in Sc-CO₂ is avoided due to its low operating temperature.
- Sc-CO₂ can be recycled and reused so enhancing the economic viability and ecological sustainability of extraction process in it.

Alkaloids such as caffeine, morphine, emetine, pilocarpine *etc.* are present in many medicinal plants and show therapeutic effect when applied in prescribed dosage. These compounds

are active components of various stimulants and medicinal products and their recovery from medicinal plants is of great economic value to the food, pharmaceutical and cosmetic industries. Sc-CO₂ is reported to be an effective solvent for extraction of caffeine from coffee beans and tea leaves. Recent investigations carried out on potential solvent and anti-solvent properties of Sc-CO₂ have shown that it is very efficient and “greener” solvent for recovery of alkaloids such as theophylline, theobromine and pilocarpine among others [16]. Cholesterol from dairy products and meat can be removed by using Sc-CO₂. Sc-CO₂ and propane mixtures can be used for selective removal of cholesterol from food that compromise the higher cost of propane and its better cholesterol efficiency. Cholesterol removal efficiency can further be improved by its coupling with adsorption process which operated at the same extraction conditions. For example, 97 % of cholesterol from original butter oil was removed by employing alumina as an adsorbent and Sc-CO₂ as solvent. The operation also resulted in generation of butter oil fractions that were distinctly different from those of original oil [17]. High quality essential oils and its derivative having commercial more satisfactory compositions (lower monoterpenes) can be obtained by selective extraction and separation of essential oils in Sc-CO₂. The quality of essential oils obtained in Sc-CO₂ was superior to that obtained by hydro-distillation method.

During extraction of VOCs from urban air particulates in Sc-CO₂, alkanes were extracted at 75 atm while polyaromatic hydrocarbons (PAHs) remained in sample matrix until the pressure was raised to 300 atm. [18]. Adjustable solvating properties in Sc-CO₂ allow it to dissolve less polar analytes at low pressure and more polar & high molecular weight analytes at high pressure [19]. Therefore, in contrast to conventional extractions in which multiple solvents are used for extraction of all desired products, Sc-CO₂ presents a convenient way to remove multiple products without changing the solvent but by altering the physical conditions.

Sc-CO₂ can be employed for extraction and fractionation of waxes from wheat straw due to its control over the selectivity of wax products dissolved into it. For example, selective extraction of alkanes and fatty alcohols is possible by carrying out the experiment at low pressure (60 bar) and high pressure (300 bar) of Sc-CO₂ respectively [20].

Recovery of uranium and plutonium from radioactive waste by Sc-CO₂: Sc-CO₂ is benign solvent for recovery of plutonium and uranium from spent fuel of nuclear reactor. It facilitates faster, efficient and cleaner recovery of these radioactive nuclides from spent fuel matrices without generation of secondary liquid waste. It cannot be used for direct extraction of metal ions due to poor interaction of Sc-CO₂ solvent and charge neutralization requirements [21]. Properties of Sc-CO₂ can be modified with the help of suitable extractant or chelating ligands. Sc-CO₂ modified with β -diketones was used for extraction of various lanthanides and actinides [22]. Supercritical carbon dioxide modified with tri-*n*-butyl phosphate (TBP) was used for extraction of uranium and plutonium from nitric acid medium [23]. Neptunium, plutonium and americium dioxides were extracted and recovered from various matrices by using Sc-CO₂ modified with TBP/nitric acid [24]. So supercritical

fluid extraction having Sc-CO₂ can be used for protection of environment from radioactive waste products by their suitable extraction and recovery.

In pharmaceutical industry: Sc-CO₂ can be used in pharmaceutical research for separation of wide variety of compounds including enantiomers and for better resolution of chiral compounds [15]. It can also be used for synthesis of certain drugs by solution enhanced dispersion by supercritical fluids (SEDS) and rapid expansion of supercritical solutions (RESS). In former method supercritical fluid act as an anti-solvent and help in precipitation of the material, while in latter method supercritical fluid expands rapidly due to pressure difference which causes the dissolved material to precipitate out of the solution in the form of fine particles. These ultrafine particles are used to increase the bioavailability of drugs due to increased surface area to size ratio [25-28].

In enzymatic reactions: Enzymatic reactions in non-aqueous solvents have enhanced solubility, high reactivity and selectivity which have raised the interest of scientific community in studying the biochemical reactions in Sc-CO₂. It is reported as an attractive medium for biocatalysis reactions such as esterification, hydrolysis and oxidation. Enzymes have high stability and activity in Sc-CO₂ and stereoselectivity of enzymatic reactions in Sc-CO₂ may be changed by adjusting pressure & temperature. Enzymatic esterification of triglycerides, vinyl butyrate and esters in Sc-CO₂ has been investigated along with its application for sterilization, recovery of intracellular proteins and selective inactivation of enzymes. Protein purification was performed in Sc-CO₂ by fractional precipitation of protein alkaline phosphatase, insulin, lysozyme, ribonuclease, trypsin and their mixtures from dimethylsulphoxide [29]. Instead of large numbers of advantages like low critical temperature and non-toxic behaviour, the use of Sc-CO₂ in enzymatic reactions suffer serious drawback such as formation of carbonic acid in aqueous layer of enzymes which result into decrease in pH.

Other applications: Sc-CO₂ is helpful for environmental remediation by its application in extraction of PCBs and other pesticides from soil and water. Sc-CO₂ inhibits bacterial growth by penetrating into their cell walls so it is a novel method for sterilization [30]. Sc-CO₂ can be used for dyeing of fabrics [31], metal cleaning, textile processing and dry cleaning purposes. It has replaced the conventional organic solvents and water in microelectronic industry to spin-coat photoresists and to clean integrated circuits and flat-panel displays during manufacturing. Recent investigations indicate the possibility of Sc-CO₂ in carbon quantum dots synthesis in eco-benign manner.

Limitations of Sc-CO₂ as solvent

- Poor solubility of many substrates in supercritical carbon dioxide.
- Modifiers (organic solvents) can be added to regulate solubility, but this move the process away from being green.
- Carbon dioxide-philic surfactants are being developed which are expensive and have to be separated from products.
- High pressure conditions in operating instruments may increase the cost of operation.
- Due to its electrophilic nature it can behave as a substrate instead of solvent and can lead to formation of undesirable products.

- Some reactions may not occur in it or may lead to formation of totally different products.

- Rate of reactions may be decreased leading to possibility of more energy input so may make the chemical process energy intensive.

Conclusion

Solvents are necessary evils in chemical reactions exploited in chemical processing and pharmaceutical industries. Use of solvents has hazardous impacts on environment. So making of chemical processes sustainable and green requires replacement of conventional solvents by more “greener” solvent. Applications of Sc-CO₂ in various fields revealed the possible replacement and reduction of conventional solvents by it. Due to its tunable properties, it is a versatile and eco-compatible solvent offering great opportunity in greening of chemical processes [32]. It can act as eco-friendly solvent in transition period during which a greener and more viable solvent can be sought.

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