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Supercritical Carbon Dioxide as an Impregnation Medium for Producing Functional Materials in Textile Finishing

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Abstract

Supercritical carbon dioxide (scCO2) is an environmentally friendly technology and has properties such as high diffusivity, low surface tension, and simple solvent removal at the end of the process. It is used to overcome environmental pollution resulting from textile industries such as dyeing and finishing and adds a functional property to the material by using dyes that have functional properties or metal oxides from which we obtain treated fabrics such as antimicrobial, water and oil resistance, UV protection and flame-resistant fabrics. This paper discusses current research on the use of scCO2 as an impregnation medium in the production of various functional materials in order to stimulate further research on the use of scCO2 in textile finishing.

Keywords: Eco friendly, super critical CO2, organic solvents, dying, Functionalisation, Textile finishing

Introduction

Increasing environmental awareness and interest in the rapid depletion of resources is the driving force for environmentally friendly and sustainable technology in the development of the textile industry. [1-9] This led to a reconsideration of the production methods used in our time and a focus on developing how to use resources. The textile industry contributes significantly to environmental pollution, and this is considered an important traditional industry in using limited resources in processes such as dyeing, printing and finishing. Traditional dyeing consumes extensive amounts of water and generates toxic and partly hazardous liquid waste. Textile finishing processes also involve the use of hazardous chemicals and the consumption of large amounts of water and energy. In addition to more and more restrictions and regulations, especially in developed countries, for wastewater and industrial (polluted) air where emissions arise, it has become the driving force for the implementation of environmentally friendly technologies.[5, 10-14]

The technology supporting such developments is supercritical fluid. This technology provides the advantage of low resource consumption. And waste generation. As well as overcoming the obstacles of high investment costs

Supercritical fluid technology is important when it comes to dyeing textiles, as this method has many advantages compared to the traditional water-based method. This is due to the unique properties of carbon dioxide in its supercritical state, which exhibits solvent properties suitable for non-polar substances. This technology allows for a very even distribution of the solutes throughout the entire fiber matrix. This results in improved performance and can therefore be used in water-free finishing operations. It should be noted that carbon dioxide is non-toxic, non-flammable and recyclable, energy can be saved because the substrate drying process is uncomplicated, and the dyeing time is short compared to traditional methods so great efforts have been made to develop and research environmentally friendly technologies for textile applications which are still ongoing.[15, 16]

Supercritical

A supercritical fluid is any substance that exists at a temperature and pressure above its critical point and

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does not have separate liquid and gas phases. It can dissolve substances as a liquid and effuse (pour, shed) through solids as a gas. Furthermore, because tiny changes in temperature or pressure induce significant changes in density, many properties of a supercritical fluid can be "fine-tuned" around the critical point.

Supercritical fluids can be utilized in place of organic solvents in many industrial and laboratory applications. Carbon dioxide and water are the most commonly used supercritical fluids for power generation, along with a variety of solvents such as methanol, ethylene, propylene, propane, methanol, ethanol, and acetone. [17]

Critical properties

- No liquid/gas phase boundary
- Can be "tuned" to be more liquid- or more gas-like by adjusting the pressure and temperature of the fluid
- Soluble in the fluid's substance
- At constant temperature, solubility in a supercritical fluid tends to rise with density.
- As pressure increases, solubility tends to decrease because all supercritical fluids are perfectly miscible with one another, if the critical point of a mixture is exceeded, a single phase can be guaranteed. The critical point of a binary mixture can be determined by taking the arithmetic mean of the critical pressures and temperatures of the two components.[18]

When supercritical fluids are utilized instead of water in the wet processing of textiles, their unique properties may result in considerable benefits. These fluids contain the viscosity and diffusion coefficients of gases, as well as densities and solvating properties similar to liquid solvents. Because of these properties, supercritical carbon dioxide (SC-CO2) is one of the most beneficial and ecologically friendly solvents utilized in manufacturing processes today. As a result, it is expected that commercial textile processes utilizing SC-CO2 will offer numerous advantages over current aqueous methods. [19, 20]

By eliminating wastewater discharges, successful commercialization of SC-CO processing will improve the economics of dyeing and other textile chemical operations. lowering energy use, avoiding drying as well as lowering air pollution. As a result, the use of SC-CO2 in textile manufacturing is projected to be more cost-effective and environmentally benign.[19] [21-23]

Different between conventional &supercriticalCO_2 treatment as shown in table (1)

Supercritical Carbon Dioxide

Carbon dioxide is a readily available, cheap, recyclable and is non-toxic and non- flammable. Above the temperature of 31.6 C and pressure of 73 Atm carbon dioxide exhibits physical properties, which are intermediate between those of gases and liquids.

These conditions are called supercritical conditions and are readily achievable using commercially available equipment. Supercritical carbon dioxide is able to dissolve a range of chemical substances including organic substrates, catalysts, and light gases. Its main advantage however comes from the fact that this solvent can be easily turned into a gas by simply releasing the pressure leaving no solvent residues and requiring no evaporation or separation.[16, 17, 24-26] As shown in figure 1.

Table 1. Different between conventional & supercritical CO2 treatment

conventional	supercritical
High volumes of waste water with the residual dye chemicals, High levels of salt and alkali	No waste water at all. Dye remains as powder. No need for dispersing, leveling agents
High-energy requirements.	Only 20% energy requirement
Dyeing/washing, drying times is 3-4 hrs. per batch	Only 2 hours.
Hydrolysis of dye molecules Costly water purification	No hydrolysis of dye molecules No production of polluted water
Drying step of textile	No drying step (energy saving)
Overall cost comparing to scCO2is high	Machine cost is high
Water treatment (ETP) and recycling is difficult and costly	CO2 can be easily recycled up to 95%

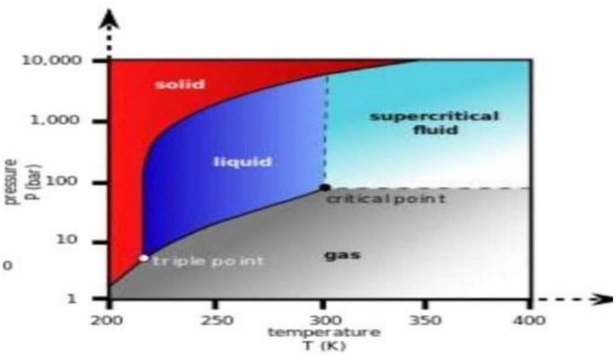

Figure 1. CO2 pressure-temperature

Some of the advantages of supercritical carbon dioxide are:

- It has high efficiency in heat and mass transfer, and can improve the performance of industrial and natural processes related to energy, environment, pharmacy and others
- It is a green and safe solvent that does not leave any residue or cause any pollution
- It is tunable and can change its physical and chemical properties easily by adjusting the pressure and temperature, allowing for control over solubility, volume, density, viscosity and others.
- supercritical have low viscosities and high diffusion. [27]

And Some of the possible drawbacks of using supercritical carbon dioxide (sCO2) as a solvent or a heat transfer medium are

a) Low solubility: Some important pharmaceutical compounds have limited or no solubility in sCO2, which limits the effectiveness of extraction or formulation processes.

b) Design challenges: sCO2 requires strong and heat-resistant materials, precise and complex engineering design, and advanced and reliable control system to ensure the stability and safety of the process.

c) High cost: sCO_2 needs high investment and operational cost compared to conventional solvents or heat transfer media.[28]

Impregnation in $scCO_2$

scCO2 impregnation of additives can be performed based on two mechanisms. The first mechanism works if the solute molecule is readily soluble in scCO2 solvent. When polymers are introduced into scCO2 bath containing solutes, the small CO2 molecules penetrate to the free volume of the amorphous region and swell the material creating additional free volumes. This causes plasticization of the material due to a decrease in the glass transition temperature (Tg). Then, the dissolved solutes are transported to the fiber surface and subsequently penetrate and diffuse into the swollen polymer matrix. Finally, upon depressurization, the CO2 molecules are removed by the shrinking polymer, and the impregnate molecules are trapped inside the polymer matrices. The second mechanism applies for solute molecules, which are poorly soluble but having high affinity to the polymer. In this case, the solute molecules partition preferably toward the polymer matrix than the fluid because of their higher affinity to the polymer. This is the key mechanism by which polar dye molecules are incorporated into the polymer matrix in scCO2 dyeing and impregnation of drug molecules into polymers. Therefore, the impregnation process is feasible when the active principle (solute) is soluble in scCO2 or the partition coefficient is favorable toward the polymer charging enough solute, and the polymer itself is well swollen by the scCO2 solvent. The general steps of impregnation of polymeric fibres in scCO2 are illustrated in Figure2.

Functional active principles such as functional dyes, antimicrobial agents, flame retardant, antioxidants, fragrances, pharmaceutical drugs, and others can be [29, 30]

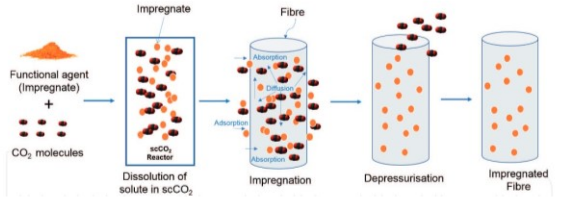

Figure 2. Impregnation mechanism of polymeric fibres with functional agent in scCO2

Mechanism of $scCO_2$

The system must have a pump for co_2, and a means of maintaining pressure in the system and a collecting vessel. The process is carried out following the following steps

- The dye must be dissolved in highly critical liquids of CO_2
- Fiber penetration (absorption)
- Adsorption of the dye on the surface of the fiber and Diffusion of dye molecules into the fiber particles

To dye textiles, the material must first be looped around a perforated stainless-steel tube. It is then placed inside the autoclave. After placing the colour powder at the bottom of the tank, the carbon dioxide is heated to supercritical conditions. The crucial carbon dioxide is then poured into the autoclave via a pump, and the pressure is kept above 74 bar for 50 to 70 minutes until the bath is dropped. The pressure is reduced to atmospheric pressure by opening the shut-off valve, and the surplus carbon dioxide and dyes are separated and recycled. The residual dyes are removed after this dyeing technique by rinsing with acetone, if necessary.[31]

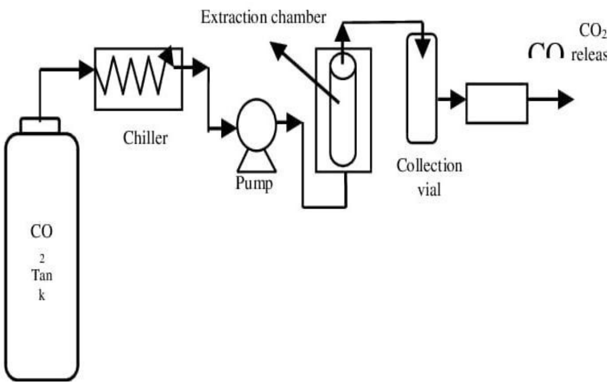

Figure 3. mechanism of scCO2

Funtionalization Of Fabrics Using ScCO2

Antimicrobial groups

Microorganisms grow on textiles during storage and use, causing injury to both the wearer and the fabric. Human wastes (such as perspiration and sebum) encourage germ growth in clothing, which can lead to functional, sanitary, and aesthetic difficulties. Fungi and bacteria are the most dangerous microorganisms. Fungi can cause issues like discoloration, staining, and fiber breakdown. Although bacteria do not affect fibers as much as fungi do, they can cause some damage, an unpleasant odor, and a slick, slimy texture. Most synthetic fibers are more resistant to microbial development than natural fibers due to their high hydrophobicity.[32]

Under certain situations, carbohydrates in cotton and proteins in keratinous fibers can serve as a source of nourishment for bacteria. Wool is more susceptible to bacterial infection than cotton, whilst cotton is more susceptible to fungal attack. The growth of microbes on textiles causes unpleasant odors, fabric discoloration, and a decline in fabric strength and other beneficial features. For these reasons, it is particularly important to limit microbial growth on textiles during storage and use. Antimicrobial treatments can be applied to textiles to decrease or eliminate the negative effects. Consumer attitudes toward hygiene and an active lifestyle have recently resulted in a substantial demand for antimicrobial treated garment materials, driving extensive research. R&D stands for research and development. For example, supercritical carbon dioxide (scCO2) is an interesting method for imbuing textile textiles with antimicrobial qualities. claiming that it is "Green" technology that is safe.[33]

Direct, cationic, reactive and disperse dyes provide antimicrobial property to the fabric.[34]

Disperse dyes are changed to include functional groups dependent on the functionality required with order to make protective clothes, fluorescent functional dyes such as dispersion bright yellow 82 were dyed with scCO2. The results revealed that polyester fabric colored in scCO2 medium successfully, with improved photostability and fastness qualities and no morphological alteration.[34]

Facile Bifunctional Dyeing of Polyester Under Supercritical Carbon

New antibacterial hydrazonopropanolnitrile dyes have been used in supercritical carbon dioxide medium New hydrazonopropanolnitrile dyes with antibacterial effect have been used for dyeing clothes made of polyester. Experimental settings were modified to achieve optically and spectroscopically homogeneous dye absorption in the fabric. Dye absorption was clearly demonstrated by Raman microscopic analysis through all layers of the fabric. K/S scales have been used to evaluate the color strength of fabric, which has been shown to be greater than that of conventional dyeing. The fastness properties of the dyed fabric were evaluated and found to be outstanding. Antimicrobial testing was performed using the AA-TCC method, and the results were documented.

Through water-free supercritical CO2 dyeing procedure, to manufacture multi-functional polyester fabric using natural bioactive color curcumin. Curcumin powder dye was applied directly to polyester fabric in CO2 medium without the use of harsh chemicals or fabric pre-treatment procedures by simple dyeing method. According to what was studied, the color of the colored samples, their biological activity, and their durability properties. The results showed that the higher the concentration of the dye, the stronger the color. Moreover, the dyed materials showed good anti-bacterial, antioxidant and UV-protective properties, as well as suitable color fastness to washing and rubbing. We thus obtain the colorful and bioactive polyester fabric using curcumin via the resource-efficient and environmentally friendly scCO2 dyeing technology.[29]

A series of disperse azo dyes with potential antibacterial activity were also applied to nylon 6 fabric using scCO2 technique and compared with aqueous dyeing. The comparison showed that samples dyed under scCO2 medium had excellent antibacterial efficiency and better colour fastness properties compared with the conventional exhaust dyeing with the advantage of the elimination of auxiliary chemicals.[35]

The factors affecting dyeing conditions:

- dye concentration
- time
- temperature
- pressure

Using supercritical carbon dioxide as a solvent a covalent force was successfully formed between the terminal amine group of nylon 6 and the vinyl sulfone group of the dye molecule. The work indicated that both solubility and affinity have an effect on the dye adsorption of nylon 6-6 with hydrophobic dyes and the dispersion reactive using supercritical CO2 as the solvent system. Light fastness was acceptable for common applications and wash fastness was better.[36]

Supercritical CO2-dyed nylon 6 fabrics have good fastness properties, especially light fastness compared to traditional fatigue dyeing. The antibacterial activity of the stained samples was evaluated under supercritical conditions and the results showed excellent antibacterial efficiency.[37]

Another way to impart antibacterial qualities in supercritical CO2 medium is to color the process with bioactive components such as chitosan. Supercritical carbon dioxide was used to inject chitin/chitosan with molecular weights ranging from 3000 to 5000 into nontoxic, nonflammable, affordable, and easily recyclable poly (ethylene terephthalate) (PET) fabric. The ultimate goal is to give exceptional antibacterial characteristics on PET fabric while maintaining extremely high wash durability. A chitosan-lactic acid salt with a molecular weight of about 5,000 has been successfully impregnated into PET fibers using supercritical carbon dioxide, and the salt has been impregnated in most of the materials tested, except chitin. The finding that 70% of the chitosan was impregnated with PET and retained antibacterial characteristics following 50 cycles of household laundry.[38]

Antifungal Textiles Composed of Silver Deposition in Supercritical Carbon Dioxide The antifungal properties of two silver-coated natural cotton fiber structures prepared using a supercritical carbon dioxide (scCO2) solvent were investigated. Electron microscopy confirmed that the scCO2 process can be used to produce cotton fiber textiles with nanoparticle layers of silver. A version of the Kirby-Bauer disk diffusion test was used to assess the ability of these textiles to inhibit fungal growth. Cotton tissue samples modified with Ag(hepta) and Ag(cod) (hfac) showed measurable zones of inhibition. On the other hand, the uncoated tissue had no zone of inhibition. Possible applications of antifungal textiles prepared using scCO2 processing include their use in hospital uniforms and wound dressings. Noble metals such as copper, gold and silver have broad spectrum antimicrobial activity. Silver has many effects on microorganisms, including blocking the electron transport system and preventing DNA replication. scCO2 was used as a solvent to dissolve metal-organic precursors to form thin films of metals and metal oxides.[38]

The scCO2 treatment was used to impart polymers and porous structures with antimicrobial functions by impregnating these materials with silver nanoparticles. [30, 39]

<u>Other functional</u>

Water repellent

There is an increasing demand for water-resistant textiles on the textile materials market, so that the problem of obtaining household and industrial fabrics with high hydrophoby is pressing. Water-repellent finishing of textile materials is to give them the capacity of not being wet with water while retaining air and vapor permeability.

A water repellent property is defined as the ability of a surface to withstand penetration of liquid water under static conditions. The interface between the water droplet and textile surface is characterising its ability to absorb or repel water. fibres and fabrics can obtain hydrophobic properties by the addition of water repellents to lower the surface energy (tension) and/or an increase of the surface roughness. Superhydrophobic properties require both a high surface roughness (multi scale) and low surface tension based on the Wenzel and Cassie−Baxter theorie [40]One type of waterborne resin for textile insulation and water repellency would be silicone Emulsions, polyurethane emulsions and fluoropolymer dispersions.[41]

Scientific articles can be found which are dealing with the water repellent and/or oil repellent treatment of textiles in supercritical carbon dioxide. Two of the most commonly used approaches include the rapid expansion of supercritical solutions or suspensions (RESS) method and the supercritical antisolvent (SAS) method. In the RESS method, a polymer and SC-CO2 solution is exposed to the gaseous phase by spraying it onto the substrate. Thereby the gaseous phase acts as an antisolvent and the polymer loses its solubility which leads to its deposition on the substrate surface. In the SAS method the SC-CO2 acts as the antisolvent when a polymer and liquid solvent solution is exposed to it. A third method for the deposition of uniform coatings from solution in supercritical carbon dioxide is using this medium as a solvent for the polymer. When the pressure and/or temperature is decreased the polymer loses its solubility in the medium and is deposited on accessible surfaces.[40]

Silicones are used commercially in the textile industry as coatings or additives due to their unique surface properties. Besides the water repellent properties, Silicones exhibit good surface diffusivity, long term flexibility, and stability under challenging conditions (extreme temperatures, chemicals, UV and oxidation), Aging and inertness resistance and excellent dielectric properties. the basic repeating unit of silicon is known as a 'siloxane'. A common silicone used as a water repellent is polydimethylsiloxane (PDMS) which exhibits methyl groups attached to the silicone atom in the polymer backbone. The water-repellent properties of silicone arise from the hydrophobic functional groups (such as methyl groups) incorporated into the silicone molecule and thus a low surface energy is obtained. Due to the high flexibility and mobility of the polymer backbone, the methyl groups They can easily rotate themselves and orient themselves towards the outer surface of the fibers which generates the water repellent function.[40]

Silicon has been applied to supercritical carbon dioxide using polydimethylsiloxane (PDMS) are in their liquid state at room temperature and show solubility in SC-CO2 at high pressures due to their low surface tension. it was found that PDMS is very sensitive to temperature. The mixing pressure initially decreases rapidly with increasing temperature, the trend reverses and the mixing pressure increases with a further increase in temperature. It is obtained at low temperatures instead of high temperatures, and the results showed that increasing the pressure will lead to an increase in the weight ratio in the medium until reaching. saturation point. On the other hand, the results of high temperature did not show a clear trend in some cases. Where PDMS surfactants were used because of their solubility in SC-CO2. Increasing the solubility of these materials can add properties water repellent and hydrogen-containing silicones (SiH) and modified compounds show higher solubility in SC-CO2 than hydroxyl-containing silicon (SiOH).[42]

The strong permeability of supercritical carbon dioxide makes it an ideal textile finishing medium. A supercritical carbon dioxide medium with an organo fluorine solution was used to create water/oil repellent polyester fiber fabrics. The results showed that fluorine spreads evenly on the surface of the polyester fibers. The treated fabrics showed a good level of water/oil repellent properties and improved mechanical properties while maintaining the character of well air permeability. It is believed that the fluoropolymer layer formed on the surface of polyester fabric reduces the surface energy of polyester fabrics.[43]

It was shown that an ultrathin continuous fluoropolymer film that replicates the microrelief of the fibres forming the fabric is formed on the surface of polyester fabric when it is treated with a solution of a low- molecular-weight fraction of polytetrafluoro-ethylene in supercritical carbon dioxide. The protective coating formed is ultra hydrophobic and has extremely low water absorption. An additional increase in the degree of hydrophoby of polyester fabric can be attained by using the chemical method of preliminary modification of the fabric which gives the surface of the polyester fabrics additional roughness.

The method is based on weak alkaline hydrolysis of surface macromolecules of the fibre-forming polymer with poly (ethylene terephthalate) ester bonds so that oxygen-containing groups are formed as a result that is, preliminary modification causes a slight additional increase in the hydrophoby of the textile material to a level close to super hydrophoby by increasing the surface roughness of the fibres. **[47-44]**

solving the problem of creating a low-energy coating is to form a thin and use-resistant fluoropolymer film on the surface of the filaments forming the multifilament fibre. The film is applied from a solution of ultra disperse polytetrafluoroethylene in supercritical carbon dioxide (SC- CO2) polytetrafluoroethylene. It consists of a mixture of low-molecular- weight and high-molecular-weight perfluorinated linear chains, and the chain length in the low-molecular-weight fraction can attain tens of units. The low molecular-weight fraction of Forum is readily soluble in supercritical carbon dioxide.

When the solution attained the equilibrium state at constant volume (iso chronically), the temperature in the autoclave was reduced.

Decreasing the temperature in the iso chronic process also decreased the pressure. As a result, the fluoropolymer lost solubility and was deposited on the inner surface of the autoclave and on the PET material. On completion of the process, the autoclave was degassed and the treated material was removed. Formation of ultrathin coatings of fluoropolymer materials on the surface. [45]

UV protective

Presently UV ryas are causing various harmful effects. UV protective dyes enhance the UPF (Ultraviolet Protection Factor) of the textiles. UPF means how much a fabric can protect the wearer from harmful UV rays. In general, all dyes act as a UV absorber because spectral region falls into UV region. Various kind of synthetic dyes are commercially available to enhances the UPF of the fabric. Direct, vat and reactive dyes increases the UPF of fabric. Various researches reported that natural dyes can also enhances the UPF of the fabric. Absorption characteristics of natural dyes generally determines the UPF of the fabric. Phenolic compounds in natural dyes work as UV protective agent as these molecules absorb. It is also reported in various studies that, Natural dyes from henna dye extract, chitosan, and pomegranate peels banana peel, enhances the UPF of textile. Mordants are used with natural dyes to enhances the fastness properties of the dyes. [31, 34, 48]

The establishment of the nondestructively chemical linking between organic phase and inorganic particles has become a hot direction for polymeric surface modification due to the rising demand of antiultraviolet (UV) products. Herein, aramid fiber (AF) with coordination of ZnO was developed by a facile supercritical CO2 (Sc-CO2) drying technique to improve its UV resistance. Through adjusting the Zn2+ concentrations, the ZnO nanoparticles (NPs) with different decentralized system were synthesized and deposited to AF surface with stirring and dried in Sc-CO2 fluid for bonding. Results indicate that coordination between ZnO NPs and AF was established with the formation of C single bond O single bond Zn bond. This ZnO-bonded fiber not only shows the greatly enhanced UV resistance, but it was also endowed with higher mechanical and thermal performances than the original. For the AF-ZnO fibers in the optimum conditions, Its was severely increased, compared to the pure AF, Therefore, this research shows a fantastic success for nondestructively improving the UV resistance of AF.[49]

Flame retardants (FRs)

used in textiles, furniture, electronics, and insulation can be divided into two main categories: halogenated and non-halogenated FR.

Halogenated FRs typically contain bromine or chlorine, but due to environmental and health concerns, they are becoming restricted in the marketplace. Current research is shifting towards non-halogenated FRs due to their non-toxic byproducts and lower environmental impact. Non- halogenated FR, often contain phosphorus, nitrogen, sulfur, and silicon. Phosphorus and nitrogen containing FRs are gaining more attention due to their combined effect of reducing flammable gases generated near the cotton surface and retarding fires. Molecules that contain bothphosphorus and nitrogen exhibit better FR properties and higher char yields for example, phosphazene derivatives impart high thermos oxidative stability and excellent flame retardancy.

Additionally, phosphazene is easily modified, offering various synthetic routes that can provide different functionalities, properties, and novel FRs. Different methods, including pad-dry-cure and inclusion, have been used to incorporate FRs into cotton textiles.

Conventional pad-dry-cure is extensively used to incorporate FRs into cotton fabric by dipping the fabric into the FR solution, padding to remove excess solvent, and drying and curing the fabric. however, a drawback of this method is the release of molecules due to the re-swelling of cotton fabric with water. Given its limitations, inclusion is not widely used to incorporate FRs. An alternative method to enclose molecules into fabrics involves the use of a supercritical fluid SCFs are solvents that exist above the specific SCF's critical pressure and temperature. SCFs are inexpensive, environmentally friendly, non-flammable, sustainable, and are known for their high diffusion in organic matter. React with the cotton fabric to produce a permanent attachment.[50]

Due to its environmentally benign nature, supercritical carbon dioxide (scCO2) is considered in green chemistry, as an alternative to organic solvents in chemical reactions. An innovative method was obtained to prepare flame-retardant cotton fabric using supercritical carbon dioxide with a co-solvent. A new phosphorus and nitrogen derivative containing the piperazine derivative, tetraethylpiperazine-1,4-diphosphonate (PDP) and a nitrogen and sulfur derivative containing tetramethylpiperazine-1,4-diphosphonothioate (PDPT) (PDPT) were then used to treat fabrics. Cotton wool treated in scCO2. Thermal gravimetric analysis (TGA), vertical flame test, and specific oxygen index (LOI) were performed on treated cotton fabrics and showed promising results. When the treated fabrics were tested using vertical flames, we noticed that the burning fabrics self-extinguished. Additional flame treated fabrics are not consumed, and do not produce an amber glow when self-extinguishing. Results from cotton fabrics treated with new piperazine derivatives containing phosphorus and nitrogen showed a higher LOI value as well as increased charcoal yield due to the effectiveness of phosphorus and nitrogen as flame retardants for cotton fabrics.[51]

Summary

From the studies reviewed in this review, it has been shown that scCO2 is aviable technique for the fabrication of various functional materials if appropriate agents suitable for the process are used. It can be an attractive alternative to traditional aqueous or organic solvents as it avoids toxic auxiliary chemicals and the use of water. Further studies are still required in selecting suitable functional agents which works best under scCO2 solvent through investigation of their solubility, compatibility, and process optimizations. Due to its environmental advantages, the scientific community and the industrial compartment would expect an increase in research in this area as scCO2 has the potential to replace the current water and solvent-based textile chemical processes in the future.

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Conflict of Interest

There is no conflict of interest in the publication of this article.

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