Waterless Dyeing Technology
Smart Manufacturing and Materials Division
Textile industry is one of the biggest consumers of water

- On average, an estimated 100–150 liters of water are needed to process 1 kg of textile material
- In garment manufacturing, about 50% of waste water comes from textile dyeing and finishing processes
Stringent control on pollutant discharge

- The contaminated water must be treated prior to disposal or recycling

![Table 1-3: Country Regulations](image)

**Table 1-3: Country Regulations**

<table>
<thead>
<tr>
<th>Country</th>
<th>Obtained a wastewater regulation with effluent values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangladesh</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Brazil</td>
<td>Yes</td>
</tr>
<tr>
<td>Cambodia</td>
<td>Yes</td>
</tr>
<tr>
<td>China</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Honduras</td>
<td>*</td>
</tr>
<tr>
<td>India</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>South Korea</td>
<td>Yes</td>
</tr>
<tr>
<td>Taiwan</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Thailand</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Turkey</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Vietnam</td>
<td>Yes (T)</td>
</tr>
<tr>
<td>Sri Lanka</td>
<td>Yes (T)</td>
</tr>
</tbody>
</table>

*Notes: (T) = Has values specific to the textile industry
* Does not have national regulation regarding industrial wastewater discharge

![Water Ten Plan - Implications Across Target Industries](image)

**Water Ten Plan - Implications Across Target Industries**

<table>
<thead>
<tr>
<th>Target Industries</th>
<th>Compliance By 2016/17</th>
<th>Technological Upgrade</th>
<th>Strictly Control Projects Along 7 Key Rivers</th>
<th>Move, Retrofit or Shutdown Polluting Factories in Urban Areas</th>
<th>Wastewater Reuse</th>
<th>Water Efficiency To Reach Advance Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper &amp; Pulp</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coking</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-ferrous Metals</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Textile Dyeing &amp; Finishing</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Leather</td>
<td>✓</td>
<td>✓</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen Fertiliser</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Pesticide</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Agriculture Food Production &amp; Processing</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
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<tr>
<td>Pharmacy Production</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Source: Textile Industry Wastewater Discharge Quality Standards - ZDHC

*Source: China Water Risk; Water Pollution Prevention & Control Action Plan (Water Ten)
Rising costs of water and wastewater treatment
Dirty Laundry
Unravelling the corporate connections to toxic water pollution in China

WATER MATTERS
DECISIONS TODAY FOR WATER TOMORROW

TODAY’S FIGHT FOR THE FUTURE OF FASHION
Is there room for fast fashion in a Beautiful China?

GREENPEACE

CHINA WATER RISK
Water-Saving Solutions

- **Air-Flow Dyeing Machine**
  - The fabric transport is carried out by air only, no dye liquor or aqueous medium is required to transport the fabric.
  - A **53%** reduction in water consumption.
## Water-Saving Solutions

- **AVITERA® SE Dyes**
  - Poly-reactive dyes with three reactive groups for cotton and other cellulosic fibers
  - Rapid and very high exhaustion
  - High fixation (~90%)
  - Excellent solubility, high diffusion and outstanding washing-off properties, making them suitable for application at ultra-low liquor ratios.

<table>
<thead>
<tr>
<th>Conventional Dyes</th>
<th>AVITERA® SE Dyes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water</strong> 60 – 80 l/kg</td>
<td><strong>Water</strong> 18 – 20 l/kg</td>
</tr>
<tr>
<td><strong>Steam / CO₂</strong> 6.5 / 2.2 kg</td>
<td><strong>Steam / CO₂</strong> 1.7 / 0.7 kg</td>
</tr>
<tr>
<td><strong>Time</strong> 7 h</td>
<td><strong>Time</strong> 4 h</td>
</tr>
</tbody>
</table>
Waterless/Nearly Waterless Dyeing

I) Digital Printing
II) Sublimation
III) AirDye®
IV) Supercritical Fluid Dyeing
What is a Supercritical Fluid?

A supercritical fluid is any substance at a **temperature** and **pressure above** its **critical point**, where distinct liquid and gas phases do not exist.

- It exhibits both the properties of a **gas** and a **liquid**.
  - Dense like a liquid to dissolve materials
  - Low viscosity, high diffusivity, no surface tension like a gas

---

**Table 1. Order of magnitude comparison of physical properties substance**

<table>
<thead>
<tr>
<th>State</th>
<th>Density [g/cc]</th>
<th>Viscosity [g/cm-s]</th>
<th>Diffusivity [cm²/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>0.001</td>
<td>$10^{-1}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Supercritical fluid</td>
<td>0.1–1.0</td>
<td>$10^{-4}$–$10^{-3}$</td>
<td>$10^{-4}$–$10^{-3}$</td>
</tr>
<tr>
<td>Liquid</td>
<td>1.0</td>
<td>$10^{-5}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

*Source: (After Table 1 from “Supercritical Fluid Extraction,” *TechCommentary*, 6(1), Electric Power Research Institute, 1994).*
Carbon Dioxide

Gas

Liquid

Increasing temperature and pressure

Supercritical fluid
Green Solvent — Supercritical Carbon Dioxide

Carbon Dioxide ($\text{CO}_2$)

- Non-toxic
- Non-flammable
- Non-corrosive
- Does not contribute to smog
- No acute ecotoxicity
- Inexpensive
- Readily available
- Inexhaustible resource
Green Solvent — Supercritical Carbon Dioxide

However...

Carbon Dioxide (CO$_2$)

- A greenhouse gas → Global warming
- CO$_2$ concentration in the atmosphere increased from about 280 ppm in 1800 to 315 ppm in 1960, and since the mid-1900s, CO$_2$ levels have been continually increasing at an average annual rate of slightly more than 1 ppm. Nowadays the CO$_2$ concentration is about 380 ppm.

- Processes, which apply CO$_2$ as a solvent, do not increase CO$_2$ emissions, but rather provide an opportunity for recycling of waste CO$_2$. 
Supercritical Carbon Dioxide

Tunable solvating power

- Tuning of solvent properties easily as a function of temperature and pressure.
  - Can dissolve compounds of different chemical structures

A ‘hybrid solvent’

- Can be tuned from liquid-like to gas-like without crossing a phase boundary

<table>
<thead>
<tr>
<th>Critical Pressure (bar)</th>
<th>73.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Temperature (°C)</td>
<td>31.1</td>
</tr>
<tr>
<td>Critical Density (g/cm³)</td>
<td>0.468</td>
</tr>
</tbody>
</table>
Applications

- Food industry
- Cosmetic industry
- Pharmaceutical industry
- Polymer and plastics industries
- Chemical industry
- Material industry
- Wood industry
- Textile industry
- ...
Supercritical Carbon Dioxide Dyeing

Historical Survey

1989  The first experiences of dyeing of PET in a high pressure phase equilibrium plant of 6 mL were made at Deutsches Textilforschungszentrum Nord-West e.V. (DTNW) and Prof. G M Schneider from the Ruhr-University of Bochum (Germany).

1990  A static dyeing apparatus consisting of a 400 mL autoclave with a stirrable, perforated dyeing beam was developed by DTNW.

1991  The first dyeing machine on a semi-technical scale with a volume of 67 L was constructed by Jasper GmbH & Co., Velen (Germany).

1995  UHDE Hochdrucktechnik GmbH, Hagen (Germany) and DTNW developed a new CO₂ dyeing pilot plant with an autoclave of 30 L, including an extraction cycle for removal and separation of excess dyes and for recycling of CO₂.

2009  DyeCoo Textile Systems BV (Netherlands) launched the first commercial CO₂ dyeing machine with a volume of 200 L.
Polyester Fibers Continue To Grow

- The production and demand of polyester have continued to grow at a significantly faster rate than all other fiber types
- Polyester makes up 95%+ of future global synthetic fibre production growth
- From 1980–2014, total fiber demand growth has been 40.7 million tons – 73.4% of which is down to polyester
**Supercritical Carbon Dioxide Dyeing**

- **Supercritical carbon dioxide (scCO₂)**
  - Non-polar solvent – the dipoles of the two bonds cancel one another
  - Direct dissolve of *disperse dyes*

- **Disperse dyes**
  - Typically non-ionic and contain no strong hydrophilic (water loving) groups
  - Dye particles are held in dispersion by *surface-active agent (surfactant)*
  - Have substantivity for hydrophobic fibres, like polyester and acetate
Chemical Structure of Disperse Dyes

Azo Dyes
- Account for more than 50% of the total commercialized disperse dyes
- The characteristic feature is the presence in the structures of one or more azo groups, $-\text{N}═\text{N}-$

[Chemical structure of C.I. Disperse Red 13]

Anthraquinone Dyes
- A significant proportion (20%) of the disperse dyes

[Chemical structure of C.I. Disperse Red 60]

Others
- Nitroarylamino dyes
- Coumarin dyes
- Methine dyes
- Naphthostyryl dyes
- Quinophthalone dyes
- Formazan dyes
- Benzodifuranone dyes
Classes of Disperse dyes

Low Energy
- low molecular weight
- high dyeing rate
- low sublimation fastness

C.I. Disperse Blue 3
C.I. Disperse Yellow 3

Medium Energy
- moderate molecular weight
- moderate dyeing rate
- moderate sublimation fastness

C.I. Disperse Violet 57
C.I. Disperse Yellow 211

High Energy
- high molecular weight
- low dyeing rate
- high sublimation fastness

C.I. Disperse Orange 30
C.I. Disperse Blue 79
1) Some of the dyes dissolve in the water of the dyebath in the form of micelles with the aid of surfactant.

2) Molecules of dye are transferred from solution to the surface of the fibre.

3) The adsorbed dye diffuses monomolecularly into the fibre.
Disperse Dyeing Mechanism

- Rate of dyeing depends on the rate of diffusion
  - Dyes of small molecular size have higher diffusion coefficients
  - The washing fastness is only fair
  - Dyes of higher molecular weight provide adequate fastness

- To increase the dyeing rate and dye in deep shade
  - Higher dyeing temperatures above 100°C
    - The swelling of fibre
  - Utilization of carriers
    - Increases affinity to polyester and swells it
Reduction Clearing

- To remove excess dye on the fiber surfaces
  - Improve wash, sublimation and crock fastness as well as the brightness of the shade
- The dyed fibre is treated in a strong reducing bath made up of sodium hydrosulfite (sodium dithionite, \( \text{Na}_2\text{S}_2\text{O}_4 \)) and caustic soda (sodium hydroxide, NaOH)

**Azo dyes**

\[
\begin{align*}
\text{R}^1 &-\text{N} & \equiv & \text{N} & \equiv & \text{R}^6 \\
\text{R}^2 & & & \equiv & \text{N} & \equiv & \text{R}^7 \\
\text{R}^3 & & & & & \equiv & \text{R}^4 \\
\text{R}^5 & & & & & & \equiv \\
\end{align*}
\]

Reduction

\[\text{Na}_2\text{S}_2\text{O}_4, \text{NaOH}\]

\[
\begin{align*}
\text{R}^1 &-\text{NH}_2 & \equiv & \text{R}^6 \\
\text{R}^2 & & & \equiv & \text{R}^7 \\
\text{R}^3 & & & & & \equiv \\
\text{R}^4 & & & & & & \equiv \\
\end{align*}
\]

Colorless / No substantivity for PET

**Anthraquinone dyes**

\[
\begin{align*}
\text{R}^1 &-\text{O} & \equiv & \text{R}^4 \\
\text{R}^2 & & & \equiv & \text{R}^3 \\
\text{R}^5 & & & & & \equiv \text{R}^8 \\
\end{align*}
\]

Reduction Clearing

Oxidation

\[
\begin{align*}
\text{R}^1 &-\text{O}^- & \equiv & \text{R}^4 \\
\text{R}^2 & & & \equiv & \text{R}^3 \\
\text{R}^5 & & & & & \equiv \text{R}^8 \\
\end{align*}
\]
Conventional Water-Based Dyeing Process

Scouring
- $\text{H}_2\text{O}$
- Base
- Chelating agent
- Wetting agent

Dyeing
- $\text{H}_2\text{O}$
- Dyes
- Dispersing agent
- pH Buffering agent

Reduction
- Clearing
- $\text{H}_2\text{O}$
- Base
- Reducing agent

Sewage

Drying

Product
Supercritical Carbon Dioxide Dyeing Process

Scouring
- Scouring
  - Base
  - Chelating agent
  - Wetting agent
  - $\text{scCO}_2$

Dyeing
- Dyeing
  - Dyes
  - Dispersing agent
  - pH Buffering agent
  - Base
  - Reducing agent
  - $\text{scCO}_2$

Clearing
- Clearing
  - Base
  - $\text{scCO}_2$

Product

Sustainable Process
- A recyclable process medium ($\text{CO}_2$)
- Minimum input of chemicals (only dyes, no auxiliaries)
- Minimum input of energy (short dyeing times, fusion of processes, no drying)
- Minimal emissions
- Minimal waste production

Recycling
- Gaseous $\text{CO}_2$
- Residual dyestuff
Supercritical Carbon Dioxide Dyeing Process

Textile material → Scouring

**Pre-treatment cleaning process**
- 280 bar
- 120°C
- 20–30 min

**Separation of spinning oil and impurities**

**CO₂ recycling**

Dyeing

- 280 bar
- 120°C
- 30–60 min

Clearing

**Removal of excess dye**
- 280 bar
- 120°C → 80°C
- 15–20 min

**Separation of excess dye**

**CO₂ recycling**

**Product**
Supercritical Carbon Dioxide Dyeing Process
ScCO$_2$ Dyeing Systems

- *Lab* and *pilot* scale systems

- *Industrial* scale systems
Processing Cauldron
Carbon Dioxide Storage Tanks
Pressurizing and Circulation Pumps
Chemical Addition and Separation Tanks
Temperature Control Units
Loading and Unloading Unit
Safety Components
System Control Unit
Processing Cauldron

- Two processing cauldrons allow parallel processing
- 500 L capacity
- Process up to 2000 yards of fabric
- Average daily capacity 30,000 yards
- Equipped with a fully automated hydraulic-door with a double locking system
Carbon Dioxide Storage Tanks

- **Two CO₂ storage tanks** store up to 12.5 m³ of CO₂

*Carbon dioxide storage tank (2.5 m³)*

*Carbon dioxide storage tank (10 m³)*
Pressurizing and Circulation Pumps

- **Pressurizing pump** with operating pressure up to **350 bar**
- **Circulation pump** can deliver a continuous flow at a rate up to **50 m³/h**
  - Integrated with an automated valve

*Pressurizing Pump*  
*Circulation Pump*
Chemical Addition and Separation Tanks

- External chemical addition tanks for easy addition of dyes/finishing agents
- Separation tank for easy recovery of residual chemicals
Temperature Control Units

- Heaters, chillers and heat exchangers
Specially designed shaft and trolley for loading and unloading
For textile finishing manufacturers, process conditions of up to 300 bar are very unusual.

- Some mental reservations can possibly arise
  - Handling high pressure is not a problem because the machines are constructed in such a way so as to afford maximum safety levels for the operating staff
  - Withstand up to 350 bar (25% more than the normal operating pressure of 280 bar)
Safety Components

- **Safety valves** are installed at
  - Processing cauldrons
  - CO₂ storage tank
  - Chemical addition tanks
  - Separation tank
  - Pressurizing pump
  - CO₂ incoming pump
**System Control**

- Custom made user friendly software with a process diagram view
  - Monitor and control the system
  - Production parameters are recorded for reference and quality control

- Separated control room
  - Remotely monitors and controls the system
Certification

- Inspected and certificated by Jiaxing Special Equipment Inspection and Testing Institute
ScCO$_2$ Dyeing Systems

DyeCoo
CO$_2$ Dyeing Technology

eCO$_2$Dye

HISAKA WORKS, LTD.
Solubility of dyes

- Low dye solubility \([10^{-4} \text{ and } 10^{-7} \text{ mol dye/mol CO}_2]\)
- Extensive grinding of the pure dyes enhances solubility
  - Increases of the surface area
- Molecular weight
- Dye structure
  - Solubility is decreased by the introduction of highly polar hydroxyethyl \((-\text{CH}_2\text{CH}_2\text{OH})\), amino \((-\text{NH}_2)\), cyano \((-\text{CN})\), acetylamino \((-\text{NHCOCH}_3)\) and carboxy \((-\text{COOH})\) groups
  - Halogen (Cl, Br, I, etc.) and nitro \((-\text{NO}_2)\) groups have a positive effect on the solubility

Static system vs Dynamic system

- A static dyeing apparatus without CO\(_2\) circulation
  - Agglomeration, crystallization and melting of dyes → lower solubility
- Takes 2-3 days to obtain dyeing equilibrium without CO\(_2\) circulation
Quality of Dyeing

Dye distribution between the fibre and CO$_2$

- Dye exhaustion from the solution $\gg$ Sorption into the fibre.
  - Precipitation of the dye on the fibre surface $\rightarrow$ poor fastness properties

CO$_2$ flow rate

- Highest influence on the levelness

Cyclic trimers

- Oligomers, mainly cyclic trimer, diffuse from the inside of the fibre to the surface
  - Visual problems at dark shades and lower brilliancy of shade

Dyeing of Cotton in scCO₂

Cotton has a market share of 37%

Problem of dyeing cotton in scCO₂

• Inability to break the highly hydrogen-bonded cross-linking structure
  ➢ Hindered the diffusion of dyes into the interior

• Disperse dyes only show slight interactions with cotton fibres

• Reactive dyes which are used in conventional water dyeing are nearly insoluble in scCO₂
Dyeing of Cotton in scCO₂

Early attempts with disperse dyes...

• Impregnation of hydrogen bond-breaking substances
  ➢ Swells the cotton fibre by breaking hydrogen bonds between cellulosic polymer chains
    → increase the accessibility of cellulose to the dyes

✗ The impregnation and the removal of the hydrogen bond-breaking substances has to be carried out by aqueous processes

✗ Low wash fastness properties
  ➢ Colour strength decreases remarkably after washing
  ➢ Weak interaction between cotton fibre and dyes
Dyeing of Cotton in scCO$_2$

Fibre modification

• Introduction of hydrophobic functional groups which can interact with disperse dyes
  1) Dicyclohexylcarbodiimide (15-20% owf) in chloroform
  2) Benzoylthioglycollate (BTG)
  3) Benzoyl chloride (22% owf)

✗ Pre-treatment and in some cases after-cleaning have to be carried out in water or other solvents
  ➢ Require additional energy-consuming treatment and drying step

✗ High concentrations of the modifying agent are needed
  ➢ Significant changes in the fibre properties
Reactive Dyes

- Soluble in water
- Containing reactive groups like chlorotriazine or vinyl sulphone groups
- Forms covalent bond with the fibre through the reaction with the hydroxyl groups of cellulose
- Polyfunctional dyes to improve fastness and/or fixation degree
Chlorotriazine type reactive dyes

- Nucleophilic substitution ($S_{\text{NAr}}$)

1) Nucleophile (the cellulosate anion) attacks at the carbon atom bearing the leaving group, i.e. chloride, to form a resonance-stabilized intermediate;

2) The substitution reaction is completed by the elimination of the leaving group.
Reactive Dyeing Mechanism

Vinyl sulphone type reactive dyes

• Nucleophilic addition

  1) Sulfatoethylsulphone group converses by an elimination reaction into the highly reactive vinyl sulphone group under alkaline conditions;

  2) The cellulosate anion attacks on the vinyl sulphone and leads to the a resonance-stabilized anionic intermediate;

  3) The addition reaction is completed by protonation.
Dyeing of Cotton in scCO$_2$

Use of co-solvents

- Water or alcohols are the most important co-solvents
  - To increase the polarity and the solvent power of carbon dioxide
- The solvent properties of scCO$_2$ can be vastly improved by the incorporation of surfactant
  - Surfactants, such as perfluoropolyether (PFPE) based and sodium bisethylhexyl sulfoccinate (AOT), etc., are amphiphilic molecules containing both a CO$_2$-phobic and a CO$_2$-philic portion
Water-in-CO$_2$ Microemulsions
Dyeing of Cotton in scCO₂

Development of CO₂-soluble dyes for cotton

- Disperse Dyes
- Reactive Dyes

- Introduction of reactive functional groups
- Introduction of CO₂-solublizing groups
Dyeing of Cotton in scCO$_2$

Reactive disperse dyes

Disperse dye + Reactive group $\rightarrow$ Reactive disperse dye

SCF-Y1

SCF-B1

SCF-P1
## Dyeing of Cotton in scCO₂

<table>
<thead>
<tr>
<th>Dye</th>
<th>Fastness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wash</td>
</tr>
<tr>
<td>Reactive Disperse Yellow SCF-Y1</td>
<td>4–5</td>
</tr>
<tr>
<td>Reactive Disperse Purple SCF-P1</td>
<td>4</td>
</tr>
<tr>
<td>Reactive Disperse Blue SCF-B1</td>
<td>3–4</td>
</tr>
</tbody>
</table>

### Reactive group

| Reactive group                        | Colour yield | Fastness | 
|---------------------------------------|--------------|
|                                       |              | Wash     | Rub | Light |
| Trichlorotriazine (TCT)               | Low          | 1,3,5    | 5   | 4     |
| 2-Bromoacrylic acid ester or amide (BAA) | Mid–High    | 4–5      | 5   | 5     |
| Vinyl sulphone                        | Mid–High     | 1–2      | 4–5 | 1–2   |

- Highly corrosive hydrochloric acid from TCT and hydrobromic acid from BAA are released
  - Damages the fibre as well as the machinery equipment
Integration of Functional Treatment Process

Scouring
- scCO$_2$
- Base
- Chelating-agent
- Wetting-agent

Dyeing
- scCO$_2$
- Dyes
- Dispersing-agent
- pH Buffering-agent

Clearing
- scCO$_2$
- Base
- Reducing-agent

Functional Treatment
- scCO$_2$
- Functional material

Product

Gaseous CO$_2$

Recycling

Residual dyestuff and functional material
# Economic Evaluation of scCO₂ Dyeing

## I. Capital Costs

<table>
<thead>
<tr>
<th></th>
<th>scCO₂ Dyeing</th>
<th>Aqueous Dyeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment cost (HK$)</td>
<td>8,500k</td>
<td>2,000k</td>
</tr>
<tr>
<td>Annual capital charge (HK$)</td>
<td>1,150k</td>
<td>270K</td>
</tr>
<tr>
<td>Labour cost (HK$/month)</td>
<td>8,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Batch time (min)</td>
<td>120</td>
<td>210</td>
</tr>
<tr>
<td>Production capacity (kg/batch)</td>
<td>150</td>
<td>300</td>
</tr>
<tr>
<td>Production capacity (kg/year)</td>
<td>315k</td>
<td>360k</td>
</tr>
<tr>
<td><strong>Capital charge (HK$/kg)</strong></td>
<td>3.96</td>
<td>1.02</td>
</tr>
</tbody>
</table>

\(^a\)The annual capital charge is 13.5%; \(^b\)1 operator for each machine; \(^c\)14 hr/day and 25 days/month
## Economic Evaluation of scCO₂ Dyeing

### II. Operational Costs

<table>
<thead>
<tr>
<th>Compound/utility</th>
<th>scCO₂</th>
<th>Aqueous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount/batch</td>
<td>Price (HK$)</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>60 kWh</td>
<td>78</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 m³</td>
<td>0</td>
</tr>
<tr>
<td>Wastewater treatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 m³</td>
<td>0</td>
</tr>
<tr>
<td>Steam</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90 kg</td>
<td>18</td>
</tr>
<tr>
<td>CO₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 kg</td>
<td>0.9</td>
</tr>
<tr>
<td>Dyes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 kg</td>
<td>300</td>
</tr>
<tr>
<td>Dispersing agent</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 kg</td>
<td>0</td>
</tr>
<tr>
<td>Other chemicals</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 kg</td>
<td>0</td>
</tr>
<tr>
<td>Maintenanceᶜ</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td><strong>Operating cost (HK$/kg)</strong></td>
<td>2.73</td>
<td></td>
</tr>
</tbody>
</table>

ᵃFor dyeing, washing and rinsing; ᵇFor dyeing, washing, rinsing and drying; ᶜMaintenance is 3% of equipment cost
Economic Evaluation of scCO$_2$ Dyeing

III. Total Processing Costs

<table>
<thead>
<tr>
<th></th>
<th>scCO$_2$ Dyeing</th>
<th>Aqueous Dyeing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Costs (HK$)</td>
<td>3.96</td>
<td>1.02</td>
</tr>
<tr>
<td>Operational Costs (HK$)</td>
<td>2.73</td>
<td>5.97</td>
</tr>
<tr>
<td>Processing Costs (HK$/kg)</td>
<td>6.69</td>
<td>6.99</td>
</tr>
</tbody>
</table>

As energy and water/wastewater costs differ very much from country to country, a concrete comparison of the water and scCO$_2$ dyeing process is not possible in great detail.

- The water cost in Netherlands is much higher (2.27 €/m$^3$) and the processing for scCO$_2$ dyeing is 50% lower comparing water dyeing.
## Environmental Considerations

<table>
<thead>
<tr>
<th>Compound/utility</th>
<th>scCO₂</th>
<th>Aqueous</th>
<th>scCO₂</th>
<th>Aqueous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount/batch</td>
<td>Amount/kg</td>
<td>Amount/batch</td>
<td>Amount/kg</td>
</tr>
<tr>
<td>Electricity</td>
<td>60 kWh</td>
<td>0.4 kWh</td>
<td>100 kWh</td>
<td>0.33 kWh</td>
</tr>
<tr>
<td>Water</td>
<td>0 m³</td>
<td>0 m³</td>
<td>5 m³</td>
<td>0.017 m³</td>
</tr>
<tr>
<td>Steam</td>
<td>90 kg</td>
<td>0.6 kg</td>
<td>1380 kg</td>
<td>4.6 kg</td>
</tr>
<tr>
<td>CO₂</td>
<td>15 kg</td>
<td>0.1 kg</td>
<td>0 kg</td>
<td>0 kg</td>
</tr>
<tr>
<td>Dyes</td>
<td>3 kg</td>
<td>0.02 kg</td>
<td>6 kg</td>
<td>0.02 kg</td>
</tr>
<tr>
<td>Dispersing agent</td>
<td>0 kg</td>
<td>0 kg</td>
<td>6 kg</td>
<td>0.02 kg</td>
</tr>
<tr>
<td>Other chemicals</td>
<td>0 kg</td>
<td>0 kg</td>
<td>3 kg</td>
<td>0.01 kg</td>
</tr>
</tbody>
</table>

- ScCO₂ dyeing requires less energy with 95% of the CO₂ is recycled and therefore is associated with about 45% lower CO₂-emission, reduces about 100,000 kg of CO₂-emission for yearly production of 300,000 kg polyester fabric.
- ScCO₂ dyeing requires only dyes and therefore can save 60% of chemicals.
Does scCO₂ dyeing have a future in the textile industry?

✔ Environmental advantages

- Waterless process → no wastewater discharge
- Reuse of CO₂
- Requires less chemicals and energy
- Lower CO₂-emission

✔ Fully met all of the quality standards for polyester as in water dyeing

- High colour yields are obtained
- High levelness of dyeing, i.e. no colour differences at the inside, middle, and outside of the fabric pack
- Very good washing, rubbing and sublimation fastness properties
Does scCO$_2$ dyeing have a future in the textile industry?

- High investment costs of the plant
  - Partly compensated through the lower processing costs
  - Only companies with deep pockets will be able to make such investments
  - The dye industry is typically a very low-margin industry, the price of the dyeing machines must come down

- ScCO$_2$ dyeing process now can only be used for polyester, not cotton
  - Several methods have been developed, however...
    - Requires the use of co-solvents or additional chemicals, like surfactant
    - The results were not satisfactory, such as poor fastness properties or deterioration of the fibre properties
  - Much more research based on new concepts and ideas