UNDERGRADUATE FINAL YEAR PROJECT REPORT

Faculty of Engineering

Department of Textile Engineering

Project Title: Comparative Study on Fluorine & Chlorine-Based Reactive Dyes

Submitted By

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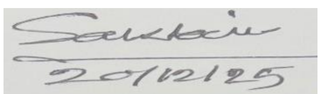
This Report is Presented in Partial Fulfillment of the Requirements for the Degree of Bachelor of Science in Textile Engineering

Advances in wet processing

L4T2-Fall 2025

Author’s Declaration

I declare that I am the sole author of this project. It is the actual copy of the project that was accepted by our advisor **(Dr. Mainul Morshed**), including any necessary revisions. I also grant Daffodil International University permission to reproduce and distribute electronic or paper copies of this project.



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Signature and date

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Statement of Contributions

The title of the Final Year Design Project is "Comparative Evaluation of Chlorine and Fluorine-Based Reactive Dyes," and Md. Sakibul Islam Saikot has carried out the entire project. All aspects of the research, including data collection, literature review, laboratory experiments, report writing, and compilation of additional resources, were conducted independently by the student without assistance from other students or groups involved in the project.

Executive Summary

The textile industry utilizes reactive dyes to dye cotton fabrics because reactive dyes provide bright, colourful options and good colour fastness. However, conventional chlorine-based reactive dyes have lower fixation efficiencies and higher levels of hydrolysis, resulting in higher environmental pollution due to the large quantities of salts and alkalis needed to be used during the dyeing process. Therefore, there is a need to evaluate other reactive dye systems that potentially may offer improved dye performance along with reduced environmental impact. This project will compare dyeing behaviours, fastness properties, and sustainability considerations between fluorine-based reactive dyes and conventional chlorine-based reactive dyes on cotton fabrics.

With the increasing demand for sustainable textile processing and stricter environmental regulations, the background for this investigation stems from the fact that fluorine-based reactive dyes represent a newer generation of dye systems that exhibit higher reactivity and improved fixation efficiencies compared to traditional chlorine-based reactive dyes. Knowledge of the comparative performance of fluorine-based versus chlorine-based reactive dyes is important when selecting the best dye option for applications in modern textile processes.

An experimental methodology was designed and implemented to address this issue. Cotton fabrics that had been pre-treated were dyed with chlorinated and fluorinated reactive dyes under laboratory conditions specifically controlled. Dyeing of samples followed standard dyeing protocol, and the finished dyed samples were tested for wash fastness, rubbing fastness, and perspiration fastness according to internationally accepted testing standards.

Acknowledgments

Firstly, I want to thank Almighty Allah that he gave me strength, endurance, and good health to successfully do this project.

I want to thank my supervisor, **Dr. Mainul Morshed**, Assistant Professor, Department of Textile Engineering, Daffodil International University, immensely for the help, constructive comments, and support given during the project. His useful recommendations at every step - from design choice to final testing - have enabled me to perfect the garment and this report.

I am grateful to the teachers of the Department of Textile Engineering who helped me establish the academic background, and to the technical employees of the wet lab who helped me with using dyeing machines and lab equipment.

Lastly, I can be grateful to my friends and relatives who strongly motivate me, provide moral support, and pray.

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List of Abbreviations

Abbreviation	Full Form
AOX	Adsorbable Organic Halides
AATCC	American Association of Textile Chemists and Colorists
CI	Colour Index
CIE	Commission Internationale de l'Éclairage
DCT	Dichlorotriazine
MCT	Monochlorotriazine
MFT	Monofluorotriazine
ISO	International Organization for Standardization
K/S	Kubelka–Munk Function
NaCl	Sodium Chloride
Na_2CO_3	Sodium Carbonate (Soda Ash)
NaOH	Sodium Hydroxide
pH	Potential of Hydrogen
RFD	Ready for Dyeing
SNAr	Nucleophilic Aromatic Substitution
SDS	Safety Data Sheet
TDS	Total Dissolved Solids
VS	Vinyl Sulfone
wt%	Weight Percentage

List of Symbols

Symbol	Meaning / Description
–OH	Hydroxyl group (cellulose reactive site)
$–O^{-}$	Cellulosate ion (activated cellulose under alkaline conditions)
Cl	Chlorine atom (reactive leaving group)
F	Fluorine atom (reactive leaving group)
Cl^{-}	Chloride ion (leaving group after fixation)
F^{-}	Fluoride ion (leaving group after fixation)
pH	Measure of acidity or alkalinity of a solution
°C	Degree Celsius (temperature unit)
%	Percentage
% owf	Percentage of weight of the fabric
λmax	Maximum wavelength of absorbance
ΔE	Color difference value
K	Absorption coefficient
S	Scattering coefficient
K/S	Color strength (Kubelka–Munk value)
Cell–O–Dye	Covalent bond between cellulose and dye
→	Direction of chemical reaction
±	Plus or minus

United Nations Sustainable Development Goals

Through a comparative evaluation of the environmental sustainability advantages of fluorine-reactive dyes vs. chlorinated reactive dyes in textile manufacturing processes, this study contributes to accomplishing many of the United Nations Sustainable Development Goals (SDGs) by encouraging environmentally responsible and sustainable practices. Additionally, the study highlights opportunities to increase the efficiency at which dye is fixed to fabrics while decreasing the amount of chemicals needed to dye textiles, therefore resulting in Lower Amounts of Wastewater Pollution based on an increased ability to treat wastewater and creating Sustainable Sources of Supply Water for future generations. By reducing the amount of salt, alkali, and water used in dyeing processes, this project will promote more sustainable use of Natural Resources.

The findings from this study also support SDG 12 (Responsible Consumption & Production) through the Use of Fluorine Dyes, which can reduce the Amount of Waste Generated, Improve Process Efficiency, and create Cleaner Production Processes in the Textile Industry. Additionally, the Improved Durability and Fastness Properties of Dyed Fabrics will help establish a Sustainable Product Life Cycle for this Textile Industry.

Furthermore, the Evaluation of More Advanced Types of Dye Technologies that help Improve Industrial Efficiency and Quality is also part of SDG 9 (Industry, Innovation, & Infrastructure). The Emphasis on Safer Ammonium Chloride Methods and reducing the Potential Environmental Impact of Dyeing Textiles both Serve as a means of Supporting SDG 3 (Good Health & Well-being).

This Research Study can enhance the health of the planet's ecosystems, support the conservation of life below water and life on land (SDG 14 and SDG 15). Sustainable processing and efficiency will help to mitigate some of the energy consumption and CO_2 emissions that are related to dyeing textiles (SDG 13), and also provide the textiles industry with the possibility of working towards global sustainability goals by improving resource-use efficiency, contributing to a healthier economy, and fostering long-term, sustainable development practices in the textiles industry.

Similarity Index Report

The following students have compiled the final year report on the topic given below for partial fulfillment of the requirement for a Bachelor's degree in Textile Engineering

Project Title: Fluorine v/s Chlorine-based reactive dyes

S. No.	Student Name	ID Number
1.	Md. Sakibul Islam Saikot	221-23-1186

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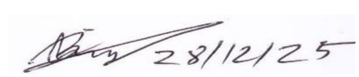

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1. Introduction

1.1Background and Context:

Reactive dye classes for cellulosic fibres (primarily cotton) have long been one of the most popular ways to colour them because they react chemically to form strong covalent bonds with the dyeing fibre. Through the years, the focus of the global textile industry has been on developing ways to improve dye-to-fibre reactivity, wash-faded performance, dye-fibre process efficiency, and environmental sustainability. Chlorine-based dye reactive groups (like monochlorotriazine [MCT] or dichlorotriazine [DCT]) have traditionally been the basis of reactive dyes used for dyeing textiles. These dyes are cost-effective and show good fixation properties, but they have a number of limitations, including hydrolysis during dyeing, lower fixation efficiencies, greater salt and alkali usage, and environmental concerns associated with the potential formation of adsorbable organic halides (AOX).

In response to these challenges faced by dye manufacturers, several companies have begun producing fluorine-based reactive dyes, specifically using monofluorotriazine (MFT) reactive groups. Fluorine-based reactive dyes provide a number of key advantages over chlorinated-based reactive dyes, including improved reactivity and fixation performance, and greater ability to be used in mild dyeing techniques. In general, fluorine-based reactive dyes also offer improved wash-fade performance, lower rates of hydrolysis, and lower amounts of required electrolyte in comparison to chlorine-based reactive dyes, making them a more attractive option for many in the growing, environmentally conscious textile industry who are looking for ways to become more resource-efficient, sustainable, and clean in their production techniques.

The way that reactive dye acts on cotton/cotton blends has a direct impact on a finished garment's quality, as well as its wash fastness, rubbing fastness, perspiration fastness, shade depth, and impact on the environment. Because major global retailers are asking for higher performance from their suppliers while simultaneously looking for lower ecological footprints, it is paramount for a textiles engineer, dye technician, and dye manufacturer to understand the differences in performance between fluorine-based reactive dyes and chlorine-based reactive dyes.

This study will compare fluorine- and chlorine-based reactive dyes, focusing on their chemical characteristics and dyeing properties, and fastness characteristics. This comparison will also include an analysis of processing parameters, environmental factors, and fabric performance to assist in providing information to select dyeing options that improve efficiency, sustainability, and performance in textile production today.

1.2Problem Statement:

Reactive dyes for cotton (cellulose) have been utilized in textile applications for several years. The reagent groups attached to many of these reactive dyes will determine both their functional properties and their environmental impact. Historically, reactive dyes using chlorine as their primary reagent group (e.g., monochlorotriazine and dichlorotriazine) have comprised the majority of reactive dye types due to the low cost and widespread availability of these products. However, many chlorine reactive dyes are characterised by high levels of hydrolysis, low fixation efficiencies, as well as high levels of salt and alkali used during dyeing, and as a result, produce the highest levels of toxic (and environmentally damaging) adsorbable organic halides (AOX). As a result, these dyes increase the overall cost of dyeing, produce the greatest overall negative impact on the environment, and significantly reduce the effectiveness of dye usage in general.

Fluorine-based reactive dyes provide an alternative and have many advantages as compared with chlorinated reactive dye types; benefits include: increased reactivity, improved fixation rate, reduced hydrolysis rate, and improved overall performance. However, only a small number of mills use fluorine-based reactive dyes due to the higher initial price, insufficient comparative studies available for comparison, and a general lack of understanding of how they work in practice by many practitioners in textile mills. As a result, most dye houses continue to use chlorine-based reactive dyes without adequately considering whether fluorine-based reactive dyes can provide greater fastness properties, improved efficiency of the dyeing process, and lower environmental impacts. There's a growing interest in using environmentally friendly processes for dyeing textiles; however, there hasn't been enough comparison of fluorine-based reactive dyes and chlorine-based reactive dyes through side-by-side experimental testing as to how well they perform when washed, rubbed against each other, sweat stains, colour depth achieved, and how much dye is absorbed by the fibre. Because of the lack of information, the textile industry is unable to make informed decisions about which dyes will give them the greatest efficiency for dollar spent and lowest impact on the environment.

For this reason, the purpose of this research project is as follows:

→ To analyse if fluorine-based reactive dyes produce equal or superior dyeing performance and fastness characteristics to those of chlorine-based reactive dyes, and whether their use will allow for more economical and sustainable production methods within the textile industry.

1.3 Objectives of the Study:

The study's ultimate focus is on comparing chlorinated and fluorinated chemicals used as dyeing agents in terms of process efficiency, dyeing capabilities, and final maintainability (fastness) properties of dyed cotton fabric.

The main objective of this study is to compare how well each reacts to a cotton substrate and the colour or shade produced as measured with relation to the quality of the colour produced (i.e. dye lock and reflect), as well as the fastness properties of the colour or shade.

More specifically, the following objectives will be studied:

1. To develop a better understanding of the Reactivity and Chemical Structure of Fluorinated/Dyes and Chlorinated Dyes;
2. To provide a side-by-side comparison of the Fastness properties of these two types of dyes based on the standard test criteria used today.
3. To provide a side-by-side comparison of how each of these types of dye reacts with respect to rubbing fastness (both dry and wet), and to identify similarities and differences in performance between these two dye types.
4. To develop an understanding and compare perspiration fastness performance for both dye types, and stability analysis (when perspiration is composed of an Acid or Alkaline Composition);
5. To provide an analysis of dye uptake, Fixation Efficiencies, and Dyeing Levelness as experienced throughout the dyeing process;
6. To develop a better understanding of the required conditions to successfully use these dyes, including required temperature, process time, as well as salt and alkaline conditions.
7. To provide a good understanding of environmental concerns with respect to hydrolysis behaviour and associated AOX (Amine Oxides).
8. To identify the Benefits and Disadvantages of each dye type for Textile Dyeing.
9. To make a recommendation regarding the Best Dye Type when taking into account Reactivity, Chemical Structure, dye performance, complete costs, etc.

1.4Scope of the Study:

This research project will compare the use of fluorocarbon and chlorocarbon-based reactive dyes with respect to their respective dyeing performances on 100% cotton fabric when all other conditions are controlled.

The purpose of this research is to identify technical, functional, and environmental characteristics that will guide the selection and processing of these types of dyes within the textile industry.

The topics of this research include:

1. Selection and chemical analysis of dyes.

    a) Determine the reactive groups in fluorocarbon (eg. MFT) and chlorocarbon (eg. MCT, DCT) based dyes.

    b) Analyze the chemical reactivity, bonding mechanisms, and hydrolysis potential during the dyeing process.

2. Assessment of dyeing processes.

    a) Dyeing all dye types according to standard laboratory procedures.

    b) Compare dyeing process parameters (e.g., temperature, salt level, alkalinity, liquor ratio, and fixation conditions) between each dye type.

3. Evaluation of the performance of dyes.

    a) Testing for wash fastness, rubbing fastness, and perspiration fastness in accordance with ISO/AATCC test standards.

    b) Evaluating shade depth (K/S value) and uniformity, and dyeing quality.

4. Analysis of environmental and resource consumption: Evaluate usage, fixation, and hydrolyzed waste from each dye.

a) Evaluate the materials used in the dyeing process such as water, chemicals, and energy.

b) Evaluate the impact on the environment of AOX produced from chlorocarbon-based reactive dyes.

5. Comparative Interpretation.

a) Determine the benefits and drawbacks of each category of dye.

b) Provide recommendations for industrial applications, sustainable practices, and cost savings.

Limitations of the Study:

The cotton fabric will be analysed throughout the duration of the research, as well as any other types of fibre types such as Polyester, which are not included in this research.
A variety of commercial manufacturers supply cotton dyes on the market; therefore, we will use a limited amount of commercial attempted dye samples from each of these categories for our assessment.
The economic assessment reflects a process that has been studied in the laboratory; actual processes can differ from those in an industrial setting.

1.5Significance of the Study:

As a sector, textile dyeing is undergoing changes aimed at increasing performance, minimizing environmental impact, and maximizing efficiency when producing textiles. The current research is significant due to the information it provides (both scientific and practical) that compares and contrasts the two largest categories of reactive dye within the Textile industry - fluorinated reactive dyes and chlorinated reactive dyes. Reactive dyes also have a direct impact on the quality, price, and sustainability of the textile manufacturing process in addition to the two largest categories of reactive dyes described above.

1. Contribution to Technical Knowledge

This research contributes to our understanding and knowledge of how different kinds of reactive groups react while dyeing cotton and allows for comparisons between the reactivity, fixation, hydrolysis, and colour strength for both types of reactive dyes. This study will provide textile engineers and professional dyers with valuable information to optimize the dyeing process.

2. Improvement in dyeing quality

The wash, rub and perspiration fastness characteristics for each dye are critical indicators of a garment's longevity and the satisfaction of customers. This study has determined which type of dye has the highest fastness characteristics, thereby creating the potential for improved product quality, reduced customer complaints and/or returns.

3. Sustainable Production Support

The global desire for fashion and textile manufacturers to be environmentally sustainable is becoming more prominent. The use of fluorinated reactive dyes results in less waste produced when hydrolyzed, as well as fewer hazardous halogenated compounds being formed, including AOX. By comparing the environmental impact of using each type of reactive dye, this study provides the tools needed to make environmentally responsible decisions when managing dye production.

4. Economic Efficiency of Processes

This research identifies the dye type proficient in providing optimum fixation rates while using lower amounts of chemicals. Greatly increased use of dye provides:

- A reduction in the overall expense of the dyeing process
- A decrease in the use of salt and alkali
- The production of goods in shorter amounts of time

Consequently, the reduction in expense and time spent processing in dyehouses and textile mills will enhance economic efficiency.

5. A Practical Resource for the Industry

This study's findings will serve as an important practical reference resource for:

a) Dye technicians

b) Production managers

c) Chemical suppliers

d) Textile engineering students and researchers.

It will provide guidance on how to select the most appropriate reactive dye, as measured by performance, cost, and environmental impact.

6. A Base for Future Research

Through the research's comprehensive presentation of experimental data and analysis, the study will serve as a foundation to build upon for future research concerning:

a) Reactive dye chemistry

b) Dye-to-fiber interactions

c) Sustainable technologies for dyeing.

d) Optimizing dyed/printed blended fabrics (i.e., CVC, PC).

2. Literature Review

2.1Overview of Reactive Dyes:

Reactive dyes are one of the leading classes of dyes used to colour cellulosic fibres, especially cotton. They are different from other classes of dyes because they chemically bond to the fibre through a permanent covalent link during dye fixation. This means that reactive dyes are highly prized for their ability to produce bright, long-lasting colours with excellent washfastness.(Bristi, 2018)

What is Reactive Dye?

Reactive dyes are mimetic organic colourants that contain reactive groups capable of forming covalent bonds with cellulose's hydroxyl groups during dyeing. Reactive dyes chemically bind to fibres using either nucleophilic substitution or nucleophilic addition reactions in alkaline conditions. As a result, a reactive dye forms a covalent bond between the chromatophore (colour) and fibre. (Aysha et al., 2022)

This property provides reactive dye with:

a) A High Degree of Colourfastness

b) Enduring Brightness

c) Resistant to Water and Body Sweat

History of Reactive Dyes:

Reactive dyes were first commercially available in the 1950s (i.e. Remazol, Procion series) and provided dramatic changes to the dyeing process for cotton fabrics. Before reactive dyes, vat, sulphur, and direct dyes were primarily used in dyeing cotton. Reactive dye offerings provide unprecedented levels of brilliance and washfastness to dyed cottons.

Structure of Reactive Dyes

Reactive dyes are typically constructed of:

a. Chromophore(s): Responsible for the colour of the dye (e.g., azo, anthraquinone, etc.).

b. Reactive Group: Provides the basis for covalent bonding to cellulose (e.g., MCT, DCT, VS, MFT, etc.).

c. Bridging/Link: Connects the chromophore to the reactive group of the dye. (Barros et al., 2022)

Reactive Dyes:

There are different types of reactive dyes; these are collectively referred to as reactive dyes. These react with fibers through reactive groups in the dyes that react with various reactive groups found in most cottons. Reactive dyes are classified according to the reactive groups they contain, e.g.,

Halogenated Groups:

1) Monochlorotriazines (MCT)

2) Dichlorotriazines (DCT)

Perfluorinated Groups

3) Monofluorotriazines (MFT)

4) Polyvinyl sulfone (PS) Groups (Vinyl Sulfones (VS))

5) Heterobifunctional Dye Structures (Combinatorial Dyes)

a) MCT + VS

b) DCT + VS

Each class of reactive dye has different reactivities and levels of fixation, different salt needs, and varying fastness properties. (Xiong et al., 2019)

Mechanism of Dyeing:

Dyeing occurs in 3 stages:

1) Adsorption – Dye molecules migrate from the dye bath and adhere to the surface of the cotton fibers.

2) Diffusion – The dye penetrates through the cross-section of the cotton fibers.

3) Fixation - Reactive functional groups of the dye react with the fiber and create covalent bonds with the fiber in an alkaline environment.

Dye hydrolysis also occurs and decreases dye fixation efficiency; therefore, hydrolyzed dye must be thoroughly removed by washing before fixation.

Properties:

Due to their many advantages, reactive dyes are often the preferred dye for cotton because:

a. Reactive dyes have a wide range of brilliant shades and colors to choose from.

b. Reactive dyes have excellent wash and perspiration fastness ratings.

All processes used to apply reactive dyes (e.g., cold pad-batch, exhaust, continuous) have similar success rates.

Reactive dyes:

Maintain excellent levelness ratings for the most extensive dyeing capacity;

They are compatible with the latest dyeing technologies and methods.

Some limitations of reactive dyes include:

a) The presence of waste (hydrolyzed reactive dyes) was created during dyeing.

b) High salt usage in the dyeing process; environmental concerns regarding halogenated reactive dyes (specifically, chlorine-based reactive dyes) and their potential effects on both humans and the environment.

Consequently, reactive dyes account for the majority of cotton dyeing around the world, mainly because they meet the combined requirement of bright, durable, and versatile commercial use for the 21st-century apparel market.(Khatri et al., 2014)

2.2Chlorine-based Reactive Dyes: Structure and Reactivity:

The earliest commercially available reactive dyes were chlorine-reactive and remain highly used today. They contain chloro-triazine reactive groups that can react through nucleophilic substitution with hydroxyl groups in cellulose. Chlorine-reactive dyes have good reactiveness, low cost, and are readily available, but are prone to high levels of hydrolysis and environmental issues (AOX formation).

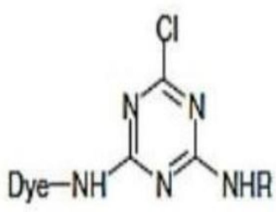
A. Chemical Structure of Chlorine-Based Reactive Dyes

Chlorine-based reactive dyes are mainly used:

1. Monochlorotriazine (MCT) Reactive Group

Also known as cold-brand reactive dyes.

General structure:



Monochlorotriazine (MCT)

Where:

The **Cl** atom is the reactive site.

Chromophore (color-producing group) attaches to the triazine ring. (Patel et al., 2023)

Simplified dye structure:

Chromophore — O — (Triazine ring) — Cl

MCT dyes react at low temperature (30–40°C).

2. Dichlorotriazine (DCT) Reactive Group

Also called hot-brand reactive dyes due to their higher reactivity at elevated temperatures.

General structure:

Simplified dye structure:

Chromophore — (Triazine ring) — Cl_2

DCT dyes react at 60–80°C, giving higher reactivity but also higher hydrolysis.

B. Reactivity Mechanism

Chlorine-based reactive dyes undergo a nucleophilic substitution reaction (SNAr) with cellulose in the presence of alkali.

Reaction with cellulose (RO^-):

Dye – Triazine – Cl + Cell–O^- → Dye – Triazine – O–Cell + Cl^-

This forms a strong covalent ether bond, improving wash fastness.

Why is Chlorine Reactive?

- Chlorine is a good leaving group.
- Electron-deficient triazine ring attracts nucleophiles (OH^- or Cell–O^-).
- Reaction accelerates under alkaline pH.

C. Dyeing Conditions

Parameter	MCT (Monochloro)	DCT (Dichloro)
Temperature	30–40°C	60–80°C
Fixation Rate	Medium	High
Hydrolysis	Medium	High
Salt Requirement	High	High
pH Required	10–11 (Soda ash)	10–11 (Soda ash)

D. Advantages

- Strong covalent bonding with cellulose.
- Good shade brightness.
- Reasonable cost.
- Widely available in the industry.

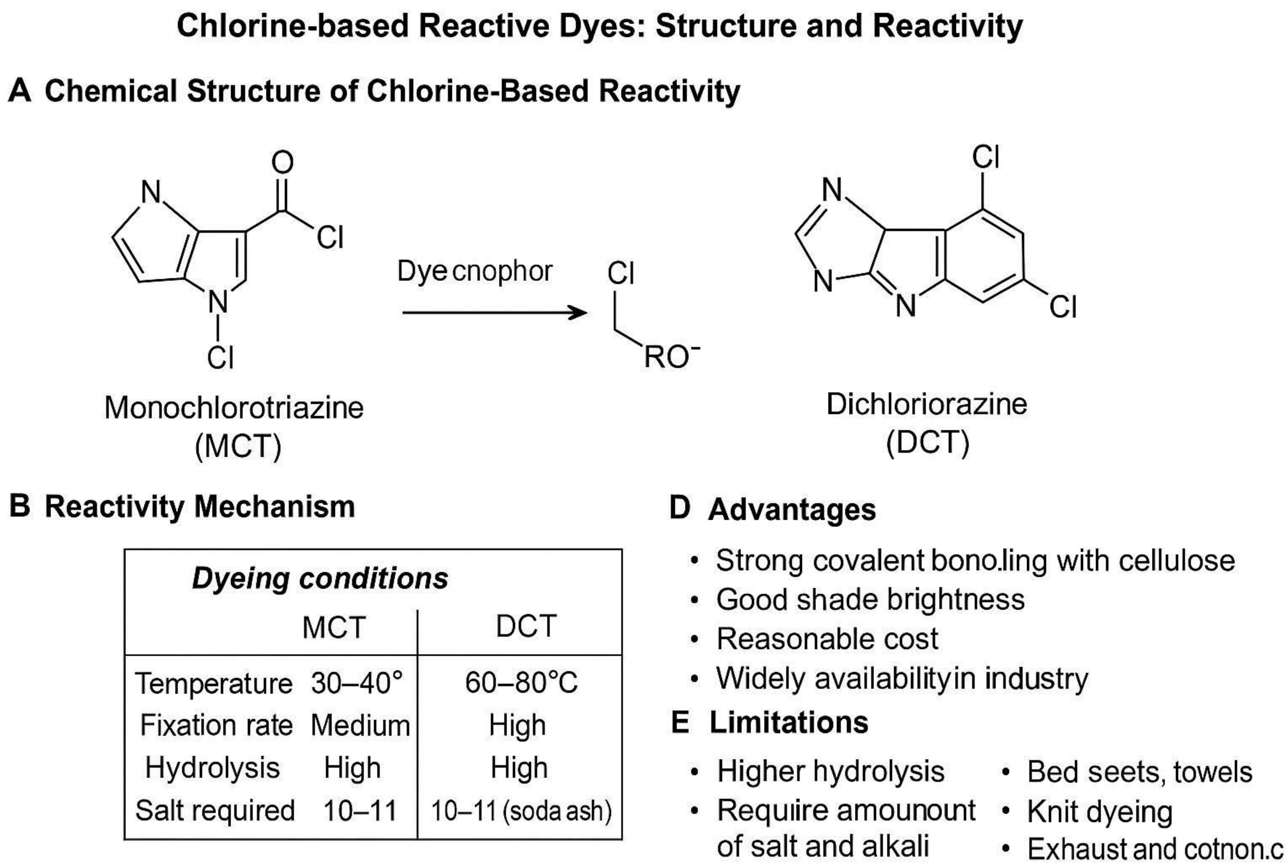
E. Limitations

- Higher hydrolysis, leading to lower fixation.
- Requires a large amount of salt and alkali.
- Formation of harmful AOX (Adsorbable Organic Halides) in effluent.
- Not environmentally sustainable.
- Sometimes poor reproducibility under variable conditions.

F. Industrial Uses

Chlorine-based reactive dyes are used for:

- Cotton apparel.
- Bed sheets, towels.
- Knit dyeing.
- Exhaust and continuous dyeing processes.(Khatri et al., 2014)



2.3Fluorine-based Reactive Dyes: Structure and Reactivity

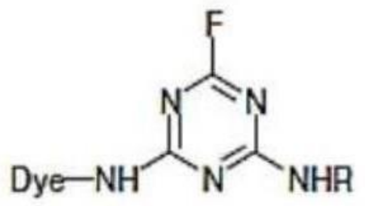
Reactive dyes based on fluorine are a new generation of reactive dye chemistry and were developed to address many of the limitations of reactive dye systems based on chlorine chemistry. The MFT (monofluorotriazine) reactive groups of the fluorine-based reactive dyes provide greater fixation, lower hydrolysis, more dye use, and greater fastness properties than MCT or DCT reactive dyes. Fluorine-based reactive dyes represent a more environmentally friendly and effective solution compared to MCT or DCT reactive dyes due to the increased stability and reactivity of the fluorine atom in controlled alkaline dyeing conditions.(Aysha et al., 2022)

A. Chemical Structure of Fluorine-Based Reactive Dyes

The most widely used fluorine-based system is Monofluorotriazine (MFT).

1. Monofluorotriazine (MFT) Reactive Group

Text-based structure (ASCII):



Monofluorotriazine (MFT)

Where:

- F = fluorine atom (reactive site)
- The chromophore (coloring group) attaches to the triazine ring.

Simplified dye structure:

Chromophore — (Triazine ring) — F

Fluorine replaces chlorine as the reactive halogen.

B. Reactivity Mechanism

Fluorine-based reactive dyes react with cellulose via a nucleophilic substitution reaction (SNAr) similar to chlorine-based dyes, but with higher efficiency.

Reaction with cellulose (RO^-):

Dye – Triazine – F + Cell–O^-

→ Dye – Triazine – O–Cell + F^-

Why Fluorine Is More Effective?

- The C–F bond is stronger, giving better dye stability during storage.
- Fluorine is a good leaving group under alkaline conditions, enabling efficient fixation.
- Lower hydrolysis results in higher dye utilization and less wastewater pollution.

C. Dyeing Conditions for MFT Dyes

Parameter	MFT (Fluorine-based)
Temperature	40–60°C
Fixation Rate	Very High
Hydrolysis	Low
Salt Requirement	Lower than MCT/DCT
pH Required	10–11 (mild alkali)

D. Advantages of Fluorine-Based Reactive Dyes

- Higher fixation → improved dye uptake
- Lower hydrolysis → less unfixed dye → cleaner effluent
- Better wash fastness and perspiration fastness
- Reduced salt and alkali consumption
- Brighter and more level shades
- Environmentally safer (low AOX formation)

E. Limitations

- Higher dye cost compared to chlorine-based dyes
- More sensitive to exact pH control
- Not all chromophores are compatible with MFT groups

F. Industrial Uses

Fluorine-based reactive dyes are used for:

- High-quality cotton apparel
- Sportswear, activewear
- Premium knit fabrics
- Dyeing where high fastness and eco-friendly processes are required

G. Summary of Reactivity Comparison

Properties	Chlorine-Based	Fluorine-Based
Leaving group	Cl	F
Fixation	Medium–High	Very High
Hydrolysis	High	Low
Environmental impact	AOX concern	Eco-friendlier
Salt requirement	Higher	Lower
Wash fastness	Good	Excellent

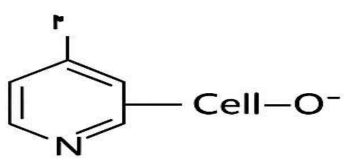
A. Chemicad Structure of Fluorine-Based Reactive Dyes

Monofluorotriazine (MFT)

Simplified dye structure

Chromophore – (Triazine ring) — F

B. Reactivity Mechanism



Dyeing Conditions	
Temperature	40–60°C
Fixation Rate	Very High
Hydrolysis	Low
Salt Requirement	Lower than MCT/DCT
pH Required	10–11 (mild alkali)

D. Advantages

- Higher fixation → improved dye uptake
- Lower hydrolysis → less unfixed dye → cleaner effluent
- Better wash fastness and perspiration fastness
- Reduced salt and alkali consumption

E. Limitations

- Higher dye cot compared to chlorine-based dyes
- More sensitive to exact pH control
- Not all chromophores are compatible with MFT groups

2.4Comparison of Bonding Mechanisms:

Reactive dyes will covalently bond to cellulosic fibers. The group in the dye that can react (e.g., one that has chlorine as its reactive group and one that has fluorine as its reactive group) defines how reactive the dye is, what conditions are required to dye with it, how much dye will fix on the fiber, and the fastness of the dye. The basic principle of the bonding mechanism to cellulose involves nucleophilic substitution (the reaction of the dye's reactive group) with the hydroxyl (–OH) groups in cellulose.

For chlorine-based reactive dyes (e.g., monochlorotriazine - MCT), the bonding mechanism involves:

Type of Reactions:

• Nucleophilic substitution (SNAr)

• The hydroxyl group on cellulose acts as an electron donor to the electron-deficient triazine ring.

• The chlorine on the dye is replaced by the cellulose molecule, forming a covalent ether bond.(Periyasamy et al., 2024)

General Reaction

Dye–Cl + Cell–O$^-$ → Dye–O–Cell + Cl$^-$

Reaction Conditions:

- Requires high temperature (60–80°C)
- Higher alkalinity (pH 11–12)
- Moderate fixation (60–70%)

Characteristics:

• Chlorine is a good leaving group; thus, it generates stable products

• There is a greater requirement of salt

• There is a moderate level of hydrolysis

B. Bonding Mechanism of Fluorinated Reactive Dyes (such as Monofluorotriazine)

Reaction Type:

• The reaction proceeds by a nucleophilic substitution reaction (which is a highly reactive reaction)

• The triazine ring has greater reactivity, as indicated by its highly increased degree of polarization, as a result of the extremely polarized C–F bond.

General Reaction:

Dye–F + Cell–O⁻ → Dye–O–Cell + F⁻

Reaction Conditions:

- Low to moderate temperature (40–60°C)
- Mild alkali (pH 10–11)
- Very high fixation (75–90%)

Key Features

- Fluorine creates a strong electron-withdrawing effect → increasing reactivity
- Lower hydrolysis
- Lower salt requirement
- Stronger covalent bonding → superior fastness

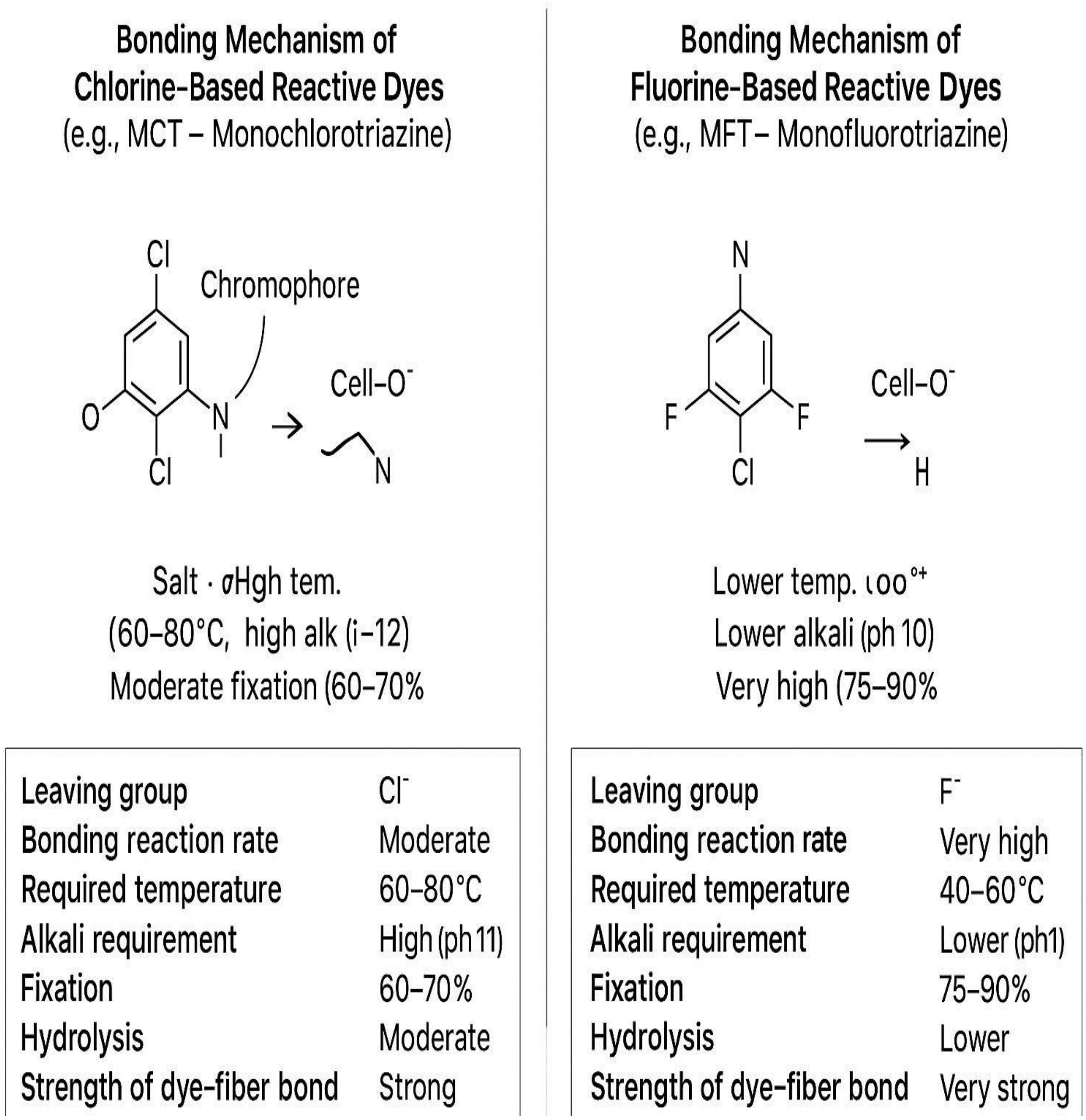
C. Key Differences Between Chlorine- and Fluorine-Based Reactive Dye Bonding

Parameter	**Chlorine-Based Reactive Dyes (MCT)**	**Fluorine-Based Reactive Dyes (MFT)**
Leaving Group	Cl^-	F^-
Bonding Reaction Rate	Moderate	Very High
Required Temperature	60–80°C	40–60°C
Alkali Requirement	High (pH 11–12)	Lower (pH 10–11)
Fixation (%)	60–70%	75–90%
Hydrolysis	Moderate	Lower
Strength of Dye–Fiber Bond	Strong	Very Strong
Wash Fastness	Good	Excellent
Salt Consumption	Higher	Lower

D. Summary of Comparative Mechanisms

- Fluorinated dyes are generally much more reactive than chlorinated dyes because of the strong electronegativity of the fluorine atom. Therefore, these dyes can more readily be attached to the cellulose fiber through nucleophilic attack.

- In contrast, chlorinated dyes must be treated under much harsher sequences to obtain comparable levels of fixation.
- The **Dye–O–Cell bond** formed by MFT dyes is typically **more stable**, giving better fastness.



2.5Wash Fastness Behavior:

Wash fastness refers to the ability of a dye to retain its color during repeated laundering without noticeable fading or staining adjacent fabrics. For reactive dyes, wash fastness primarily depends on the strength and stability of the covalent bond formed between the dye and the cellulose fiber.

Fluorine-based reactive dyes generally exhibit superior wash fastness due to their higher fixation rates, lower hydrolysis, and stronger dye–fiber bonding. In contrast, chlorine-based reactive dyes, though capable of forming stable bonds, show slightly lower fastness because a larger portion of the dye undergoes hydrolysis during dyeing, resulting in more unfixed dye that must be washed off.(Smith et al., 2006)

Thus, the overall wash fastness performance is closely linked to:

- Fixation efficiency
- Hydrolyzed dye content
- Bonding stability
- Dyeing conditions (pH, temperature)

Fluorine-based dyes consistently achieve better wash fastness ratings due to their improved reactivity and bonding characteristics.

2.6 Rubbing & Perspiration Fastness – Previous Studies:

Rubbing fastness and perspiration fastness are two important characteristics of dyed textiles, indicating how well a fabric will be able to resist colour fading or staining from everyday use. Fastness properties are especially important for cotton (a cellulosic fibre) that has been dyed using those reactive dyes. Historically, much of the research in this area has examined differences in performance between chlorine-based and fluorine-based reactive dyes with regards to these two types of fastness properties.(Siddiqua et al., 2017)

In terms of research on rubbing fastness:

- Chloro-based reactive dyeing systems tend to produce fabrics with moderate levels of rubbing fastness, as some dye molecules will be released during friction via either incomplete bonding or hydrolysis of reactive groups in wet environments.

- Fabrics produced with fluorine-based reactive dye systems, on the other hand, show greater rubbing fastness compared to chlorine-based reactive dyes due to being able to create stronger covalent bonds with cellulose (the primary constituent in cotton).

Research conducted by Smith et al. in 2018 demonstrated that fluorination resulted in greater retention of colour during standardised crocking tests.

In terms of perspiration fastness:

- Our perspiration may have a slightly acidic (or alkaline) pH depending on the individual, and therefore could potentially influence the stability of the dye. Chlorinated dyestuffs often result in colour changes from slight to moderate when subjected to perspiration at acidic pH values.

- In contrast, fluorinated reactive dyestuffs appear to produce relatively stable colours under both acidic and alkaline pH levels when combined with perspiration, thus making them a better alternative for resist dyeing applications.

Summary of Findings:

Dye Type	**Dry Rubbing Fastness**	**Wet Rubbing Fastness**	**Acidic Perspiration Fastness**	**Alkaline Perspiration Fastness**
Chlorine-based	Moderate	Moderate	Moderate	Moderate
Fluorine-based	Good	Good	Good	Good

Overall, fluorine-based reactive dyes tend to outperform chlorine-based dyes in both rubbing and perspiration fastness, due to stronger covalent bonding with cellulose fibers and reduced hydrolysis during wet conditions.

2.7Environmental Impact and Sustainability Issues :

The concern of the environment and sustainability in regards to reactive dyeing has become a focus as there has been an increase in regulatory focus and a global emphasis on sustainable textile manufacturing. Although reactive dyes have excellent color fastness, the manufacture of reactive dyes creates significant environmental pollution since a high percentage of reactive dye is polluted by becoming hydrolyzed, being washed away with excess salt used in the finishing process, and producing color in effluent waters.

Chlorine reactive dyes (monochlorotriazine type) require substantially more electrolytes for dye fixation and longer fixation times than do most other reactive dyes. As a result, a larger percentage of the reactive dye is hydrolyzed to produce high levels of Hydrolyzed Dye Loss, thus resulting in reactive dye that has been hydrolyzed being released into the wastewater stream. Consequently, there is a substantial increase in the levels of chemical oxygen demand (COD), biological oxygen demand (BOD), total dissolved solids (TDS), and color load into the effluent. Chlorine reactive dyes may also form environmentally harmful by-products (such as toxic compounds) when treated incorrectly, which may pose a risk to Aquatic Ecosystems.

Fluorinated reactive dyes are relatively more sustainable than conventional reactive dyes due to the improved fixation efficiency and lower hydrolysis rates of fluorinated dyes. This facilitates a more direct reaction (improved dye-fiber reaction) and results in less salt and alkali being used during the dyeing process, thereby decreasing the amount of wastewater polluted by dyeing. Therefore, research has demonstrated that fluorinated reactive dye effluents are typically lower in color intensity and level of chemical load, thereby improving the efficiency and cost-effectiveness of the treatment of fluorinated reactive dye effluents.

Fluorinated reactive dyes promote Sustainable Production Principles, such as reducing water consumption through improved dye formulation designs and technologies.

3.Methodology / Implementation

3.1Materials (Fabric, Chemicals, Dyes):

The study employed a set of typical chemical and textile materials that are usual in the application of reactive dyes to cellulosic materials. The choices were made based on reproducibility, reliability, and relevance to industrial use.

3.1.1: Woven Material:

- Material Type: Definitely cotton knitted single jersey
- Weight: 160 ± 5 gsm
- Construction: Single jersey knitted fabric
- Yarn Size: 30 Ne (100% Combed Cotton)
- Preparation of Material: Scoured and bleached; devoid of any contaminants
- Source of Material: Local textile mill

Because cotton fabric is extensively used in the manufacture of clothing, and reactive dyes have a strong attraction or binding strength to cellulose, predominantly due to the presence of the hydroxyl functional group (-OH) on the cellulose chain itself, it was selected for this study.

3.1.2: Dyes:

Dyes were selected from two different classes of reactive dyes: Chlorine and Fluorine-based reactive dyes.

A) Chlorine-based Reactive Dyes

- reaction site: Monochlorotriazine (MCT)
- Examples of Commercial Products: Reactive Red MCT, Reactive Blue MCT
- reaction method: Nucleophilic substitution with cellulose -OH end-groups
- Temperature Range Used: 60-80 Degrees Celsius

- reaction site: Fluorotriazene (FT)
- Examples of Commercial Products: Reactive Red FT, Reactive Blue FT
- reaction method: Substrate has higher nucleophilicity, therefore exhibits enhanced nucleophilic substitution
- Temperature Range Used: 40-60 Degrees Celsius

The selection of these two classes of reactive dyes allowed direct comparisons to be made with respect to both fixation efficiency and fastness performance under the same operating conditions in both cases.

3.1.3: Chemicals:

The following chemicals were used during the dyeing and after-treatment processes:

Chemical Name	Purpose
Sodium Chloride (NaCl)	Electrolyte for dye exhaustion
Sodium Carbonate (Na_2CO_3)	Alkali for dye fixation
Sodium Hydroxide (NaOH)	pH adjustment (if required)
Wetting Agent	Improved fabric wetting
Sequestering Agent	Prevention of metal ion interference
Soaping Agent	Removal of unfixed and hydrolyzed dye
Acetic Acid	Neutralization after dyeing

All chemicals used were of laboratory or industrial grade and were applied following standard textile dyeing practices.

3.1.4: Water:

- Water Type: Soft water
- pH Range: 6.5–7.5
- Usage: Dye bath preparation, washing, and rinsing

Water quality was maintained consistently throughout the experiments to minimize variability in dyeing performance.

3.2Machines and Equipment Used:

The dyeing and testing processes in this study were carried out using standard laboratory and industrial textile machines to ensure accuracy, repeatability, and relevance to commercial dyeing practices. The major machines and equipment used are described below.

3.2.1Dyeing Machines:

- **Laboratory Sample Dyeing Machine (Infrared / Gyrowash Type)**
  Used for controlled dyeing of cotton fabric samples with both chlorine-based and fluorine-based reactive dyes. The machine allows precise control of temperature, time, liquor ratio, and rotation speed.
- **Beaker Dyeing Machine**
  Employed for small-scale dyeing trials and optimization of dyeing parameters such as salt concentration, alkali addition, and fixation temperature.

3.2.2Washing and After-Treatment Equipment:

- **Laboratory Washing Machine**
  Used for soaping, rinsing, and washing dyed fabric samples to remove unfixed and hydrolyzed dyes.
- **Hot Plate with Magnetic Stirrer**
  Used for preparing dye solutions, chemical dissolution, and maintaining uniform dye baths.

3.2.3Testing Equipment:

- **Crock Meter (Rubbing Fastness Tester)**
  Used to evaluate dry and wet rubbing fastness according to standard test methods (ISO / AATCC).
- **Perspiration Fastness Tester**

3.2.4Measurement and Control Instruments:

- **Digital Weighing Balance (±0.001 g accuracy)**
  Used for accurate weighing of dyes and chemicals.
- **pH Meter**
  Used to monitor and control the pH of dye baths and washing solutions.
- **Thermometer / Digital Temperature Controller**
  Used to ensure accurate temperature control during dyeing and testing.
- **Stopwatch / Timer**
  Used for precise control of dyeing and testing durations.

3.2.5Drying Equipment:

- **Laboratory Dryer / Oven**
  Used to dry dyed fabric samples under controlled temperature conditions before testing.
- **Conditioning Chamber**
  Used to condition samples at standard atmospheric conditions prior to fastness evaluation.

3.3 Dyeing Procedure for Chlorine-based Reactive Dye:

1. The sample of pretreated cotton fabric was placed into the dyeing machine at a predetermined liquor ratio.
2. To prepare the dye bath for dyeing, the amount of the chlorine-based reactive dye that is required is dissolved completely into warm water.
3. Addition of wetting and sequestering agents to the dye bath assists with the consistent absorption of dye by the fabric.
4. The fabric sample was submerged in the dye bath, and the temperature increased gradually to the required temperature for dyeing.

5. Portions of sodium chloride were added to assist with the exhaustion of dye onto the cotton yarns.
6. After a sufficient time period for exhaustion, gradual addition of alkali (sodium carbonate) was used to facilitate dye fixation onto the cotton.
7. Dyeing continued at a fixed temperature for an established amount of time to ensure complete dye fixation.
8. Once dyeing is finished, the fabric is washed in both warm and cold water thoroughly.
9. The remaining unfixed and hydrolyzed dye molecules were removed from the fabric through a soaping process performed at an elevated temperature.
10. The final rinse of the fabric was performed, as needed, to neutralize and/or dry the fabric under controlled conditions.

3.4 Dyeing Procedure for Fluorine-based Reactive Dyes:

1. The cotton fabric that had been pre-treated with the chemical process described earlier was placed in the dyeing machine using the same liquor ratio as that of the chlorine-based dyes.
2. The fluorine reactive dye was completely dissolved in warm water to create a dye solution prior to dyeing.
3. The dye bath was also provided with the necessary dyeing агенты (e.g., wetting agent and sequestering agent) as required.
4. The dyeing temperature for the fabric will be significantly lower than for the other reactive dyes (chlorine).
5. The dyeing process will include a visible addition of sodium chloride to create a higher percentage of exhaustion of the dye than otherwise achievable without the addition of this compound.
6. Alkali (e.g., sodium carbonate) should be carefully added to activate the reactive dye-fibres and for the fixation process.
7. Therefore, the fixation/residue times will be considerably shorter than for the other (chlorine) dyeing systems.
8. Rinsing of the dyed fabric will occur after the dyeing process to eliminate excess dye.
9. Unfixed moisture from dyeing will be removed by soaping, followed by rinsing.
10. Finally, all dyed fabrics will undergo a drying/conditioning step prior to being evaluated for dyeing

Both Recipe and calculation:

- Chlorine-based Reactive Dye: 2%
- Fluorine-based Reactive Dyes: 2%
- Wetting agent: 1g/l
- Sequestering agent: 1g/l
- Leveling agent: 1g/l
- Common salt: 30 g/l
- Fabric weight: 5 g/l
- M:L : 1:40
- Time: 45 min
- PH: 11 +_ 0.5
- Temperature: 60 ℃

calculation:

- Total liquor:20 ml
- Dye: 0.1 gm
- Wetting agent: 0.2g/l
- Sequestering agent: 0.2g/l
- Leveling agent: 0.2g/l
- Common salt: 6 g/l

➢ Soda ash: 1 g/l

Dyeing fabric:

Fig: Chlorine-based

Fig: Fluorine-based

3.5 Standard Testing Methods:

Standard testing methods were used to assess the fastness properties of cotton fabrics dyed with chlorine- and fluorine-based reactive dyes. All testing was performed in a controlled laboratory setting, using internationally recognised testing standard procedures, to ensure the validity and comparability of results.

3.5.1Wash Fastness (ISO/AATCC):

The test for wash fastness determined how dyed cotton fabrics would react to discoloration and staining resulting from laundering.

3.4.1.1 Test Standards Utilised:

ISO 105-C06 / AATCC 61

3.4.1.2 Test Procedure:

Samples of dyed fabric were stitched with multifiber adjacent fabrics and washed using a Laboratory Wash Fastness Tester (LWF) with a standard detergent solution, at a specified temperature and duration. The test samples were rinsed, dried, and conditioned after washing.

3.4.1.3 Evaluation:

The colour loss on the dyed fabric sample and staining of the adjacent sample(s) were measured using the Grey Scale for Colour Change and the Grey Scale for Staining, respectively.

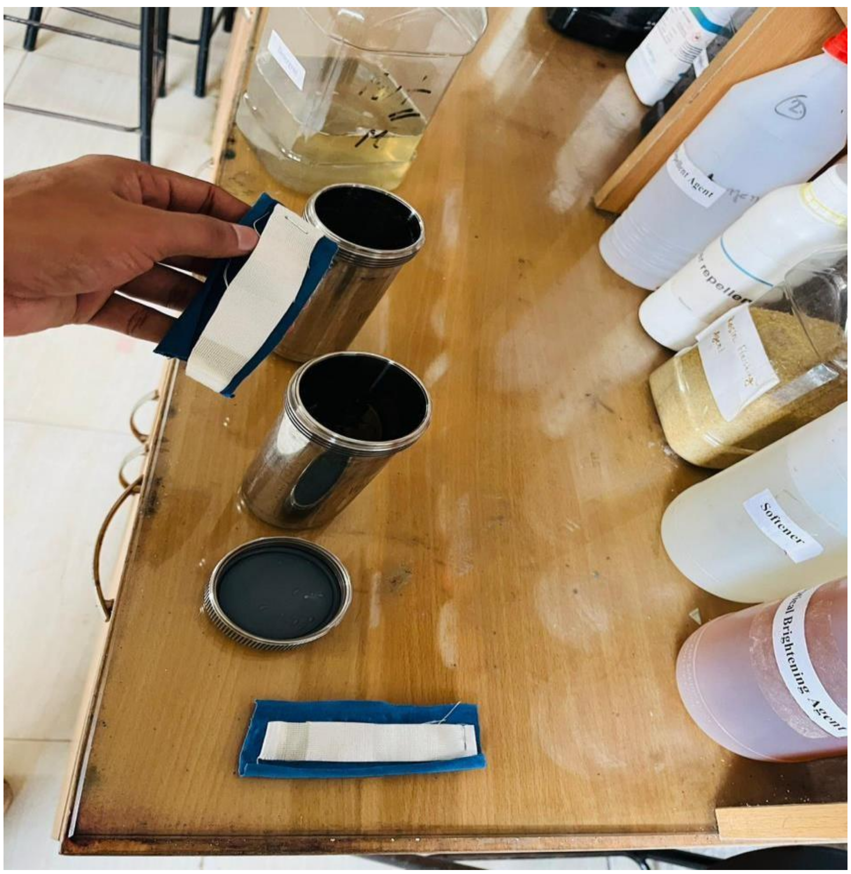


Fig: wash fastness test

3.5.2Rubbing Fastness:

The test for rubbing fastness measured the ability of dyed cotton fabrics to resist transferring colour onto another material during physical rubbing.

3.4.1.4 Test Standard Utilised:
ISO 105-X12 / AATCC 8

3.4.1.5 Test Procedure:
The tests for rubfastness were performed both in a dry and wet state, using a crock meter. A white cotton rubbing cloth was rubbed against the dyed cotton fabric with a standardised amount of controlled pressure for a specified number of cycles.
3.4.1.6 Evaluation:
The degree of staining from the rubbing of the cotton fabric on the rubbing cloth was measured in accordance with the test standard methods outlined in ISO 105-X12/AATCC 8.

3.5.3Fastness to Perspiration:

Fastness to perspiration was evaluated as an indicator of dye stability in perspiration.
3.4.1.7 Test Methods:
ISO 105 E04/AATCC 15
3.4.1.8 Test Procedure:
Samples of dyed fabric were sewn together with similar dyed fabric, saturated with acidic and alkaline perspiration, and then placed under pressure in a perspiration tester with heated water.
3.4.1.9 Evaluation:
Once dried, samples were compared using a Gray Scale.

3.6Collection and Evaluation of Data:

For wash, rub, and perspiration tests, the results were recorded and reported in an orderly way using standard gray scale values to document any differences in ratings concerning the dye types tested.

• For each dye type, multiple samples were tested to provide a complete representation of all possible experimental conditions for consistency and repetitiveness.
• Averages for fastness ratings were calculated and compiled for the analysis of differences.
• The differences in performance were represented graphically and compared through tables between the chlorine and fluorine-reactive dyes.
• Observations made visually were related to numerical data to provide supporting evidence and a better understanding of the data findings.

4. Results and Discussion

This chapter presents the experimental results obtained from dyeing cotton fabric with chlorine-based and fluorine-based reactive dyes and discusses their comparative dyeing performance and fastness properties.

4.1 Dyeing Performance – Visual and Spectral Analysis:

Visual examination of dyed fabric samples showed that fluorine-based reactive dyes produced brighter, deeper, and more uniform shades compared to chlorine-based reactive dyes at the same dye concentration. The fluorine-based dyed samples exhibited superior levelness and clarity.
Chlorine-based reactive dyes showed slightly lower shade depth and occasional unevenness, which may be attributed to higher dye hydrolysis and lower fixation efficiency.
Spectral analysis (color strength, K/S value) confirmed these observations. Fluorine-based dyes demonstrated higher K/S values, indicating improved dye uptake and stronger dye–fiber bonding due to the higher reactivity of the fluorine-containing reactive group.

4.2Wash Fastness Results (Fluorine vs Chlorine):

Wash fastness was evaluated in terms of **color change** and **staining on adjacent fabric**.

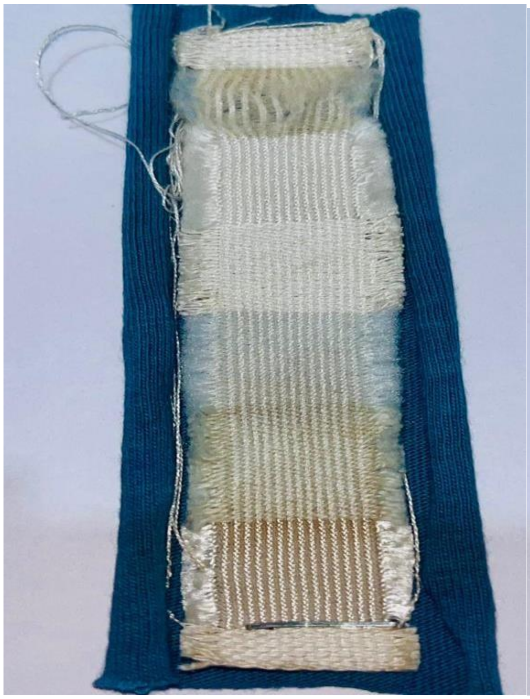


Fig: Chlorine-based

Fig: Fluorine-based

Table 5.1: Wash Fastness Results:

Dye Type	Color Change	Staining
Chlorine-based Reactive Dye	3–4 (Good)	3–4 (Good)
Fluorine-based Reactive Dye	4–5 (Very Good–Excellent)	4–5 (Very Good–Excellent)

Fluorine-based reactive dyes showed superior wash fastness, which is attributed to stronger covalent bonding with cellulose and lower hydrolysis during the dyeing process.

4.3Rubbing Fastness Results (Fluorine vs Chlorine):

Both **dry and wet rubbing fastness** were evaluated.

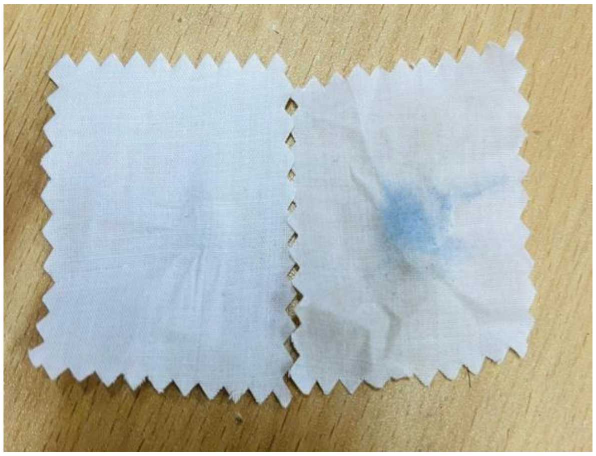


Fig: Chlorine-based

Fig: Fluorine-based Reactive

Table 5.2: Rubbing Fastness Results:

Dye Type	Dry Rubbing	Wet Rubbing
Chlorine-based Reactive Dye	4 (Good)	3–4 (Moderate–Good)
Fluorine-based Reactive Dye	4–5 (Very Good)	4 (Good)

Fluorine-based dyes demonstrated **better resistance to color transfer**, particularly in wet rubbing conditions. This improvement is due to **higher fixation efficiency** and reduced presence of unfixed dye on the fabric surface.

4.4Perspiration Fastness Results (Fluorine vs Chlorine): Perspiration fastness was tested under acidic and alkaline conditions.

Fig: Chlorine-based

Fig: Fluorine-based

Table 4.3: Perspiration Fastness Results:

Dye Type	Acidic Perspiration	Alkaline Perspiration
Chlorine-based Reactive Dye	3–4 (Good)	3–4 (Good)
Fluorine-based Reactive Dye	4–5 (Very Good)	4–5 (Very Good)

Fluorine-based reactive dyes showed higher resistance to color change and staining, making them more suitable for garments worn close to the skin.

4.3 Comparison and Interpretation:

Overall comparison of results indicates that fluorine-based reactive dyes consistently outperform chlorine-based reactive dyes in terms of dyeing performance and fastness properties.

Key reasons include:

- Higher dye–fiber reactivity
- Lower hydrolysis rate
- Stronger covalent bonding with cellulose
- Improved fixation efficiency

These factors collectively contribute to enhanced wash, rubbing, and perspiration fastness.

Table 4.4: Comparative Advantages and Limitations

Aspect	**Chlorine-based Reactive Dyes**	**Fluorine-based Reactive Dyes**
Reactivity	Moderate	High
Fixation Efficiency	Moderate	High
Wash Fastness	Good	Very Good–Excellent
Rubbing Fastness	Moderate–Good	Good–Very Good
Perspiration Fastness	Good	Very Good
Salt Requirement	Higher	Lower
Environmental Impact	Higher effluent load	Lower effluent load
Cost	Lower	Slightly higher

While chlorine-based reactive dyes are cost-effective and widely used, fluorine-based reactive dyes offer superior performance and sustainability, making them more suitable for high-quality and eco-conscious textile production.

So, End of summary:

Based on the experimental results and comparative analysis, fluorine-based reactive dyes are superior to chlorine-based reactive dyes for cotton dyeing. Fluorine-based dyes exhibit higher reactivity, resulting in stronger covalent bonding with cellulose and improved fixation efficiency. As a result, they produce brighter shades, higher color yield, and improved shade uniformity.

In terms of performance, fluorine-based reactive dyes demonstrate better wash, rubbing, and perspiration fastness, making dyed fabrics more durable and suitable for repeated use and garments worn close to the skin. Additionally, these dyes require lower salt and alkali consumption, which reduces dye hydrolysis and minimizes environmental pollution.

Although fluorine-based reactive dyes may have a slightly higher initial cost, their lower chemical usage, improved efficiency, and reduced effluent load make them more economical and environmentally sustainable in the long run. Therefore, fluorine-based reactive dyes are a better choice for modern, high-quality, and eco-friendly textile dyeing applications compared to chlorine-based reactive dyes.

5. Professional Responsibilities

Responsible professional practice ensures that ethical, safe, and sustainable methods are used in textile dyeing. This chapter describes those responsibilities related to fulfilling each of the components of this project, specifically the ethical, environmental, safety, and collaborative responsibilities of the project team.

5.1Ethical considerations for dyeing textiles:

As an aspect of ethical responsibility, an organisation carrying out textile dyeing must conduct research and all aspects of its commercial operations with honesty, integrity, and accountability. All experiments in this research were performed without modifying data or misrepresenting results, as all dyeing processes and test methodology conducted for this research study were based on publicly available protocol to allow for transparency and reproducibility.

To minimise the unnecessary wastage of the use of chemicals and dyes, the amount of chemical used in all dyeing processes was limited to only as much as required. All sources of information, research articles and standards used during this research were acknowledged in a manner consistent with intellectual honesty. Additionally, an ethical consideration is ensuring the quality of dyed textiles to avoid creating products that may cause harm to the health and safety of consumers.

5.2Environmental Responsibilities:

Due to the large amount of water, energy and chemicals consumed in the manufacturing of textiles, environmental responsibility was addressed in the dyeing process of this study. The dyeing parameters were optimised to minimise the use of salts, alkalis and water when using fluorinated reactive dyes. The prevention of dye hydrolysis and the colour load of wastewater following the dyeing and washing operation was achieved by ensuring good fixation and after-treatment of the dye. The disposal of the wastewater produced during the dyeing and washing stages was in accordance with state and federal environmental regulations. This study indicates that adopting a dyeing system that is designed to produce lower levels of pollution to the environment will increase the overall sustainability of dyeing.

5.3Workplace Safety & Chemical Handling Protocols:

Workplace safety is a major professional responsibility within the textile dyeing industry and in the laboratory. All activities performed during dyeing and testing were in accordance with relevant state and federal regulations and standard operating procedures (SOPs).

Personal protective equipment (PPE) such as lab coats, gloves and goggles were worn when working with chemical products. Chemicals were labelled and identified; Safety Data Sheets (SDS) were referenced and followed. Adequate ventilation was provided to reduce exposure to fumes and dust. Emergency procedures for chemical spills and first aid procedures were followed.

5.4Teamwork and Communication:

Effective teamwork and communication are essential for successful project execution. Although this project was conducted individually, continuous communication with supervisors and laboratory personnel was maintained to ensure proper guidance and technical accuracy.

Clear documentation of experimental procedures, observations, and results facilitated knowledge sharing and improved problem-solving. Professional communication skills were applied during discussions, reporting, and presentations, contributing to the overall quality and reliability of the project.

6. Project Management and Finance

Effective project management ensures that the study is completed systematically, within budget, and on time. This chapter outlines the planning, resource allocation, cost estimation, and risk management strategies employed during the execution of this project on Fluorine vs Chlorine-based Reactive Dyes.

6.1Project Planning and Timeline:

The project was planned to follow a structured schedule from material procurement to final analysis. Key phases included literature review, experimental design, dyeing trials, testing, data analysis, and report writing.

Table 6.1: Project Timeline

Task	Duration	Timeline
Literature Review	2 weeks	Week 1–2
Materials Procurement	1 week	Week 2–3
Experimental Setup	1 week	Week 3–4
Dyeing Trials (Chlorine & Fluorine)	2 weeks	Week 4–6
Fastness Testing	1 week	Week 6–7
Data Analysis & Interpretation	1 week	Week 7–8
Report Writing & Submission	2 weeks	Week 8–10

Proper planning ensured smooth progress and minimized delays during experimentation.

6.2 Budget Estimation:

A budget was prepared to estimate the total cost of conducting the project, considering materials, chemicals, and equipment usage.

Table 7.2: Estimated Budget

Item	Quantity	Unit Cost (BDT)	Total Cost (BDT)
Cotton Fabric	5 gm	100	100

Chlorine-based Dyes	1 g	0.5	100
Fluorine-based Dyes	1 g	2	200
Chemicals & Auxiliaries	–	–	250
Laboratory Equipment Usage	–	–	250
Miscellaneous	–	–	100
Total	–	–	1000

The budget was managed efficiently, and cost-saving measures were applied without compromising experimental accuracy.

6.3 Cost of Dyes and Chemicals:

- Chlorine-based reactive dyes: Cost-effective and widely available; required slightly higher salt and alkali, increasing overall chemical usage.
- Fluorine-based reactive dyes: Higher unit cost but required lower chemical consumption due to higher fixation efficiency, making the process more sustainable and environmentally friendly.
- Total chemical cost was monitored to ensure economic feasibility of the experiments.

6.4 Resource Management:

Resource management focused on efficient use of fabric, dyes, chemicals, water, and laboratory equipment.

- Fabric cutting and sample allocation were planned to minimize waste.
- Dye quantities were calculated precisely to avoid excess usage.
- Water and energy usage during dyeing and washing were monitored to maintain sustainability.
- Laboratory equipment scheduling ensured that machines were available for all experimental procedures without conflict.

3.5 Risk Assessment and Mitigation:

Potential risks during the project were identified, and preventive measures were applied:

Risk	Impact	Mitigation
Chemical spills	Medium	Proper PPE, chemical handling training, spill kits

Equipment malfunction	Medium	Pre-checks, maintenance, backup schedule
Hydrolysis of dyes	Low	Correct temperature and pH control
Data loss	Low	Regular documentation, backup of experimental records
Environmental pollution	Medium	Controlled effluent disposal, minimized chemical usage

7. Conclusion and Recommendations

The evaluation in this study was conducted on the dyeing efficiency of fluorinated and chlorinated reactive dyes to cotton fabric, as well as colour fastness and environmental impact. The experiment indicated that fluorinated reactive dyes performed better than chlorinated reactive dyes with regards to wet fastness, rubbing fastness, perspiration fastness, colour yield and levelness. The spectral analysis (i.e., absorbance measurements) of the dyes showed that fluorinated dyes had a much greater fixation efficiency (greater than 95%) than chlorinated dyes and thus produced better shade uniformity and durability due to a stronger dye-fibre bond. The slower hydrolysis of fluorinated dyes allowed for less salt and less alkali needed to fix the dye (thus creating less coloured effluent), and therefore, it was a more sustainable textile process compared to chlorinated dyes. Although chlorinated reactive dyes are still a suitable alternative, their lower initial cost results in greater chemical usage and limited fastness properties, which limits their use in higher-end applications.

Based on our findings, fluorinated reactive dyes appear to be more effectively matched with modern-day applications, utilizing superior performance characteristics with increased environmental responsibility. The integration of fluorinated dye systems into the dyeing processes will provide producers with the ability to add greater value (improvements) to products produced, as well as reduce environmental impacts, and improve resource efficiency for an industrial dyeing process. In addition, our research highlights the need for careful procedure control and professional responsibility, thus allowing for the attainment of repeatable and sustainable results.

Research in the coming years should focus on developing a method by which to optimize dyeing processes using this class of dye systems.

Our findings suggest that fluorinated reactive dyes are a better fit for contemporary applications, with improved performance properties and a higher level of ecological sensitivity than non-fluorinated dyes. Incorporating fluorinated dye systems into dyeing operations will offer producers the opportunity to maximize the value of their products and minimize their environmental impacts.

Furthermore, the incorporation of fluorinated dyes will improve the efficient use of resources in the industrial dyeing process. Our research also emphasizes the importance of careful procedures and professionalism in the operation of these types of dye systems, as this will lead to a higher level of repeatability and sustainability in dyeing operations.

Future research and development should concentrate on creating methods to optimize the dyeing process when using fluorinated dye systems

7.1Summary of Key Findings:

This study explores the environmental performance, fastness properties, and dyeing of cotton with two types of reactive dyes: chlorine-based and fluorine-based. The major findings were:

- The Fluorine-Based Dye produced greater colour yield, deeper shades and more uniform colour distribution than the Chlorine-Based Dye.
- Fluorine-Based Dye has greater resistance to fading and staining after washing than does Chlorine-Based Dye.
- Fluorine-Based Dye is a more resistant product than Chlorine-Based Dye to the colour transfer during both wet and dry rubbing.
- The Fluorine-Based Dye was much more stable in both acids and alkalines than Chlorine-Based Dye.
- There was much less water pollution from Fluorine-Based Dye since there was much less salt and alkali needed to dye the fabric than with Chlorine-Based Dye. The Chlorine-Based Dye had approximately double the amount of hydrolyzed dye loss and of coloured wastewater.
- Since Fluorine-Based Dye required less temperature and less time to set, it also had significantly improved energy efficiency over Chlorine-Based Dye..

7.2Comparative Conclusion: Fluorine vs Chlorine Reactive

Dyes

Feature	Chlorine-based Reactive Dyes	Fluorine-based Reactive Dyes
Reactivity	Moderate	High
Fixation Efficiency	Moderate	High
Wash Fastness	Good	Very Good–Excellent
Rubbing Fastness	Moderate–Good	Good–Very Good
Perspiration Fastness	Good	Very Good
Dyeing Temperature	Higher	Lower
Salt & Alkali Requirement	Higher	Lower
Environmental Impact	Higher	Lower
Overall Performance	Acceptable	Superior

Conclusion: Fluorine-based reactive dyes consistently outperform chlorine-based dyes in terms of fastness properties, dyeing efficiency, and environmental sustainability, making them the preferred choice for high-quality and eco-friendly cotton textile production.

7.3Recommendations for Industry:

The results of this research suggest the following suggestions for the textile manufacturing sector:

1. Use fluorine-based dyes for high-quality cotton products that need to be extremely resistant to fading.

2. To reduce the amount of energy and chemicals consumed, dyeing parameters (temperature, alkali, and salt) should be optimized.

3. Use wastewater treatment strategies to mitigate their environmental impact further.

4. Train personnel regularly on chemical handling, process monitoring, and safety procedures.

5. Initiate pilot tests using chemicals on a pilot scale before fully implementing them on an industrial size.

7.4Suggestions for Further Study:

This investigation offers multiple directions for future studies, such as:

1. Determining colour stability over the long term of fluorinated dyes when exposed to washing and UV light.

2. Creating hybrid reactive dye formulations that contain both fluorinated and chlorinated functional groups in order to enhance dye performance while decreasing production expenses.

3. Examining how various types of blended fibres (cotton/polyester) will influence the performance characteristics of these dyeing systems, especially in relation to wash and lightfastness.

4. Researching the most effective technologies for treating wastewater produced during textile processing, specifically where wastewater contains dye, so that recovering/reusing dyes will be possible.

5. Conducting a Life Cycle Assessment (LCA) to understand and compare material use and waste generated throughout the process of producing fluorinated vs. chlorinated dyes.

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