

Optimisation in catalysed low temperature hydrogen peroxide bleaching of cotton with different stabilizers by using design expert 6.0

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The present study investigates the potential of employing gelatin-metal complexes as catalysts for cotton bleaching with low-temperature hydrogen peroxide (H_2O_2). Eight gelatin-metal complexes were developed and tested against sodium silicate and silicate-free stabilizers such as RUCOSTAB OKM and LENETOL GLAD-LQ-(TH). Using the Design-Expert 6.0 programme, a statistical model was created to maximise the bleaching process at lower temperatures (70–80°C). The optimized results showed that sodium silicate stabilised with gelatin-copper/cobalt complex can be a viable method for bleaching cotton at low temperatures, producing necessary whiteness with less damage to fibre and perhaps less energy. Furthermore, the optimized mix design of gelatin-copper complex with RUCO-STAB OKM emerged as the most effective formulation among all the optimized mix designs that outperformed the conventional bleaching the best. It recorded a whiteness index of 71.27%, the lowest fabric weight loss at 6.4%, and the highest bursting strength of 104.1 psi. Besides, the copper-based systems consistently outperformed cobalt counterparts in whiteness, fabric preservation, and mechanical strength attributed to the controlled radical generation by Cu^{2+} ions.

Keywords: Bursting strength, Gelatin-metal complex, RUCO-STAB OKM, Whiteness index

1 Introduction

The textile industry holds a vital socio-economic role worldwide, providing substantial employment opportunities and contributing significantly to global economic output. According to recent data, the global textile market is currently valued at USD 610.91 billion, with projections indicating growth to USD 755.38 billion by 2027¹. On the other hand, the various stages in textile wet processing such as sizing, scouring, bleaching, dyeing etc. impose a significant environmental burden, consuming huge quantity of non-renewable resources (98 million tons) and contributing to around 20% of global water pollution². The effluent textile industry contains hazardous substances such as volatile organic compounds, heavy metals, dyes, ionic liquids, salts, and surfactants. It is characterized by high COD/BOD levels and intense coloration, posing significant risks to both human health and aquatic ecosystems^{1,3}. For instance, the textile industry consumes approximately 79 billion cubic meters of water each year, and textile dyeing

and finishing processes alone are responsible for nearly 20% of global industrial water pollution⁴. Not only textile processing but also the environmental footprint of its supporting industries like dyes, chemicals, and machinery also add to it. Furthermore, the share of energy costs in the total production cost has escalated over the past few decades following the oil shocks⁵. Thus, textile waste directly impacts production expenses by increasing material and disposal costs. Therefore, immediate action is crucial to implement sustainable practices throughout the entire textile production chain. Eco-friendly wet processing techniques are essential for all processors to achieve overall sustainability.

Cotton is widely used in the textile industry due to its excellent moisture absorption, comfort, and dyeability. However, raw cotton contains yellowish impurities and surface materials like wax, pectin, and fat, which affect its whiteness and hinder dyeing and finishing⁶. Therefore, during textile wet processing in order to create desirable fabric qualities bleaching is carried out, particularly for dyeing and printing⁷. Hydrogen peroxide, the industry's primary bleaching

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agent offers high, stable whiteness, it is cost-effective, versatile in application, and provides advantage of a combined scouring and bleaching process in a single bath⁸. However, conventional method require high-temperature, high-alkaline bleaching with hydrogen peroxide (for effective peroxide decomposition⁹), raises significant environmental concerns due to energy consumption, fibre damage, and pollution¹⁰. Fortunately, low-temperature bleaching offers a sustainable alternative. This technique addresses the environmental drawbacks of conventional bleaching by reducing energy use and minimizing pollution. Research in recent years has focused heavily on developing and optimizing this eco-friendly process of low-temperature and low-alkali bleaching technique using activated or catalytic processes¹¹⁻¹⁴.

Catalysts play a vital role in accelerating chemical reactions by lowering the activation energy barrier, thereby enabling bleaching processes to occur at reduced temperatures. Among various catalytic systems, metal complexes have demonstrated significant potential, particularly in facilitating hydrogen peroxide (H_2O_2) decomposition in biological systems^{15,16}. The exploration of catalytically activated bleaching systems, such as the H_2O_2 /binuclear manganese complex system, holds substantial promise for advancing sustainable textile processing technologies¹⁴. Several studies have highlighted the efficiency of transition metal catalysts in low-temperature H_2O_2 bleaching of cotton. Notably, binuclear manganese complexes like 1,4,7-trimethyl-1,4,7-triazacyclononane and copper-based catalysts such as $[Cu(TPMACl)ClO_4 \cdot \frac{1}{2}H_2O]$ have shown effective bleaching performance under mild conditions^{17,18}. Use of potassium persulfate ($K_2S_2O_8$) as a catalyst in an activated peroxide system enabled low-temperature bleaching of cotton with reduced energy consumption and improved fibre integrity compared to conventional alkaline peroxide methods¹⁹. H_2O_2 /nano- TiO_2 system enhanced whiteness by approximately 13% over traditional H_2O_2 bleaching, attributed to TiO_2 -driven photocatalytic activity²⁰. Furthermore, Madhu and Chakraborty (2019) investigated an enzymatic bio-bleaching approach where glucose oxidase (GOX) immobilized on chitosan generated H_2O_2 in situ. This method enabled a sustainable bleaching process with reusability of the enzyme system. By reducing the activation energy of H_2O_2 decomposition, catalysts promote faster and gentler bleaching. However, widespread adoption of low-temperature catalytic

H_2O_2 bleaching in the textile industry remains limited. Therefore, developing a new catalytic H_2O_2 bleaching technology and thoroughly investigating its mechanism is crucial. This will pave the way for widespread low-temperature and low-alkali H_2O_2 bleaching in the textile industry.

This study examined the effects of various gelatin-metal complexes, particularly gelatin-copper and gelatin-cobalt as catalysts in enhancing the bleaching efficiency of cotton fibres under low-temperature conditions. The bleaching process was carried out using both silicate-based and silicate-free stabilizers i.e., RUCOSTAB OKM (ATUL) and LENETOL GLAD-LQ-(TH) (CRODA). To optimize the process parameters for effective low-temperature bleaching, a statistical approach was employed using Design-Expert 6.0 software with a half-factorial central composite design. The performance of the optimized bleaching conditions was then compared with that of a conventionally bleached sample to evaluate improvements in bleaching efficiency.

2 Materials and Methods

2.1 Materials

The substrate used in this study was 100% cotton single jersey knitted fabric, sourced from Piyush Syndicate, Mumbai, India. The chemicals used in this study included bleaching agent Hydrogen peroxide (30% w/w), alkaline support medium sodium hydroxide (40% w/w), stabilizersodium silicate, and a non-ionic wetting agent all supplied by S. D. Fine Chemicals Pvt. Ltd., Mumbai. While RUCO-STAB OKM, sourced from Rudolf Atul Chemicals Limited and LENETOL GLAD-LQ-(TH) from Croda International were employed as silicate-free stabilizers. Additionally, gelatin reagent, titanium dioxide (TiO_2) and various metal salts including manganese sulphate ($MnSO_4$), zinc sulphate ($ZnSO_4$), iron sulphate ($FeSO_4$) copper sulphate ($CuSO_4$) and cobalt sulphate ($CoSO_4$) were also supplied by S. D. Fine Chemicals Pvt. Ltd., Mumbai. These components were used to investigate the effect of various gelatin-metal complex catalysts on the bleaching efficiency of cotton fabric.

2.2 Equipment and Apparatus

The experimental procedure relied on various specialized equipment. For the bleaching process, a Rotary dyer facilitated high-temperature and pressure treatment of the textiles. A hot air oven efficiently dried the fabric after bleaching and cleaning.

Computer colour matching provided accurate whiteness index measurements of the bleached samples. Catalyst synthesis involved a hot magnetic stirrer for proper mixing and a round-bottom flask as the reaction vessel. The digital bursting strength tester evaluated the fabric's strength after bleaching. Water quality was assessed using a TDS tester to measure total dissolved solids in the effluent water before and after treatment. Finally, a dropping funnel precisely dispensed measured amounts of chemicals during catalyst synthesis, while a weighing balance ensured accurate measurement of both fabric samples and required chemicals throughout the experiment²².

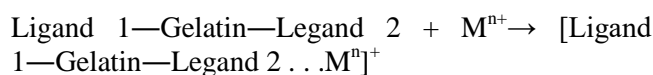
2.3 Methods

2.3.1 Synthesis of Catalysts

Based on the synthesis process of gelatin copper complex adopted by Wang and Tang (2017) and the methodology implemented by Wang and Gao (2019) to determine bleaching efficacy of cotton at 70°C using the H₂O₂/gelatin copper complex system, the following procedure was devised.

To prepare the reaction mixture, 25 g of gelatin were first dissolved in 125 ml of distilled water (1:5 ratio) at 40°C and left for 20 min. Separately in a container, 1 g of metal complex was dissolved in 5 ml distilled water. The gelatin solution was then transferred to a three-necked, round-bottom glass flask (250 ml) and the metal complex solution was added dropwise using a funnel. After that the mixture of gelatin and metal complex solution was stirred through a magnetic stirrer. During this, an aqueous solution of 40% sodium hydroxide was used to adjust and maintain the pH between 10.5 and 11.4. The mixture was stirred at 25-30°C for 3 h to ensure sufficient reaction. Gelatin contains several functional groups like carboxyl, amino and hydroxyl. Presence of these surface moieties in abundance makes it easier for gelatin to form metal complexes through various interactions like electrostatic where the negatively charged carboxyl groups on the gelatin polypeptide chains attract and bind with the positively charged metal ions. Likewise, in chelation (stable form) a single ligand (in this case, the gelatin polypeptide

chain) binds to a metal ion at multiple points. The side chains of certain amino acids such as histidine can also act as multidentate ligands forming stable chelate rings with the metal ion. In this reaction, metal ion forms coordinate covalent bonds with the electron-donating atoms of ligand.



The following gelatin-metal complexes were prepared according to the aforementioned procedure.

1. Gelatin-manganese sulphate complex
2. Gelatin-zinc sulphate complex
3. Gelatin-titanium dioxide complex
4. Gelatin-iron (II) sulphate complex
5. Gelatin-copper (II) sulphate complex
6. Gelatin-cobalt (II) sulphate complex
7. Gelatin-chromium trioxide complex
8. Gelatin-manganese-titanium complex

2.3.2 Conventional Bleaching (without any complex)

The conventional bleaching process involved several steps. First, a bath was prepared with a material to liquid ratio of 1:20 and a pH of 11-12. This bath contained 10 g/L of hydrogen peroxide (30% w/w), 2 g/L of sodium hydroxide (40% w/w), and 7 g/L of stabilizer. The bleaching operation was carried for 60 minutes at 4 different temperatures i.e., 60/70/80/90°C. Following the bleach, the fabric was washed for 10 minutes at 90°C. Finally, the fabric was rinsed with cold water and dried in an oven at 100°C for two min

The detailed experimental design is provided in Table 1.

2.3.3 Bleaching Using Gelatin Metal Complex

The bleaching experiments using gelatin-metal complex as catalyst were conducted as per the parametric combinations enumerated in Table 2. In this experimental design, the cotton fabric underwent a two-stage treatment process to enhance its properties. In the first stage, it was submerged in a warm aqueous solution (ranging from 60 to 90°C) containing hydrogen peroxide and a gelatin-metal complex for 20 min at a slightly acidic pH. Afterward

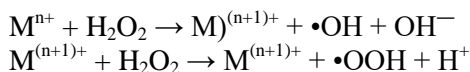
Table 1 — Experimental design for conventional bleaching without gelatin-metal complex

H ₂ O ₂ , g/L	Na ₂ SiO ₃ , g/L	NaOH, g/L	Non-Ionic wetting agent, g/L	Bleaching time, min	Ratio of material to liquor	Bleaching temperature, °C
10	7	2	1	60	1:20	60
10	7	2	1	60	1:20	70
10	7	2	1	60	1:20	80
10	7	2	1	60	1:20	90

Table 2 — Experimental design for bleaching using gelatin-metal complex

Gelatin complex, g/L	H ₂ O ₂ , g/L	Na ₂ SiO ₃ , g/L	Non-Ionic wetting agent, g/L	Bleaching time, min	Ratio of material to liquor	Bleaching temperature, °C
2	10	4	1	60	1:20	60
2	10	4	1	60	1:20	70
2	10	4	1	60	1:20	80
2	10	4	1	60	1:20	90

in the second stage, 4 g/L stabilizer was added into the mix while maintaining the same temperature for an additional 40 min. Finally, the fabric was washed, rinsed with cold water and dried in an oven at 100°C for two min. A total of 32 experiments were conducted on eight gelatin-metal complexes. The two-step process is carefully selected to facilitate bleaching at low temperature and mild alkaline condition, so that use of NaOH can be avoided. During the first stage, gelatin-metal complex acts as a catalyst under the mild acidic environment and promotes decomposition of H₂O₂ into reactive oxygen species. Gelatin is a protein, and its polypeptide chains can chelate metal ions. This metal ions in the complex facilitate redox reaction with H₂O₂, leading to formation of highly reactive free radicals like hydroxyl (•OH) and hydroperoxyl (•OOH). A simple reaction mechanism is shown below



These radicals are extremely powerful oxidizing agents, capable of breaking down the conjugated double bonds in the chromophores of the impurities, rendering them colourless. Over the 20-min period, the radicals generated by the gelatin-metal complex begin to oxidize the impurities present on the fabric surface and within the fibre structure. The second stage is introduced to sustain the bleaching action for a longer period and prevent the uncontrolled, rapid decomposition of the remaining hydrogen peroxide. Addition of sodium silicate stabilizer, elevates the pH of the solution to alkaline range. At this stage peroxide is dissociated to form the perhydroxyl anion (HO₂⁻), which is the most effective and stable bleaching species for conventional peroxide bleaching. This shift in pH allows the bleaching to proceed efficiently for the additional 40 min. The perhydroxyl anion attacks and oxidizes the remaining impurities, including those that were not fully removed in the first stage. By employing this approach, low-temperature bleaching is not only facilitated and alkali consumption is reduced, but

similar whiteness is also achieved without the fibre damage that can result from excessive oxidation in conventional bleaching.

2.4 Test Methods

2.4.1 Whiteness Index

The whiteness index (WI) of bleached cotton knit fabrics was measured using a CIELAB colour space reflectance spectrophotometer (Computer Colour Matching System-Spectra Scan 5100+, Data Colour International, USA). The measurements were reported as a percentage with a standard illuminate D65, a 10° standard observer, and a sample hole size of 6.6 mm. The percentage of fabric weight loss was calculated using the following relationship²⁵

$$\text{Weight loss of fabric \%} = [(M1-M2)] * 100$$

where, M1 and M2 represent the oven-dried weights of the fabric samples before and after bleaching, respectively.

2.4.2 Total Dissolved Solids (TDS)

Total dissolved solids refer to the total amount of inorganic salts and organic materials dissolved in water. The IS 3025-16(1984) method is a standard technique for quantifying TDS. It involves measuring the filterable residue, which is the amount of solid material left behind after filtering a water sample. This measurement is typically done at room temperature and expressed in parts per million (ppm) or milligrams per Liter (mg/L)²⁶. The filterable residue can be calculated by the following relation

$$\text{Filterable residue (mg/L)} = 1000 * (\text{Mass of residue in mg/volume of water in mL})$$

2.4.3 Bursting Strength

The bursting strength of the fabric samples was evaluated according to ISO 13938-2:2019 using a Paramount Digital Burst Strength Tester²⁷. Each sample was carefully positioned beneath the tester's bell, ensuring it was flat, wrinkle-free, and undistorted. The standard flow rate, which determines the inflation speed of the bell, was then selected. Finally, the test commenced upon pressing the start button. The tester automatically inflated the

Table 3 — Experimental design for bleaching using gelatin-metal complex

Gelatin-Metal Complexes	Whiteness Indices, %			
	60°C	70°C	80°C	90°C
CoSO ₄	59.55	68.31	71.08	74.29
MnSO ₄ +TiO ₂	46.19	52.34	63.87	68.92
TiO ₂	49.36	52.86	59.46	69.62
ZnSO ₄	41.3	52.87	50.57	68.19
FeSO ₄	42.42	54.53	58.32	71.08
MnSO ₄	43.56	57.32	61.88	74.71
CuSO ₄	59.61	71.66	72.87	72.02
CrO ₃	43.3	54.25	65.75	69.98
Conventional	49.82	57.69	60.41	70.52

diaphragm until the fabric burst. Bursting strength, measured in pounds per square inch (psi), was recorded. The fabric's overall bursting strength was obtained by averaging the results of five consecutive tests.

3 Results and Discussion

3.1 Whiteness Indices of Cotton

The whiteness indices of the cotton fabric bleached by conventional method and by gelatin-metal complex as per the experimental design mentioned in Table 1 and Table 2 are presented in Table 3. While, Fig. 1 shows the whiteness index variations with respect to bleaching media and temperature.

Among the tested gelatin-metal complexes for cotton fabric bleaching, both gelatin-cobalt sulphate (CoSO₄) and gelatin-copper sulphate (CuSO₄) complexes exhibited superior whiteness index up to 80°C, with the CuSO₄ complex achieving the highest at 60, 70, and 80°C. Therefore, both gelatin-copper and gelatin-cobalt complexes were selected as catalysts for further bleaching experimentations. Interestingly, the influence of the complex type on whiteness index lessened as the temperature increased from 60°C to 90°C. By 90°C, the difference in whiteness index between various complexes became negligible, highlighting the dominant effect of temperature on bleaching at higher temperatures. The conventional bleaching method (without any gelatin-metal complex) produced varying degrees of whiteness. In some cases, it achieved better results than certain complexes, while in other cases, it was less effective.

3.2 Low Temperature Bleaching Using Gelatin-Metal Complex Catalyst and Sodium Silicate Stabilizer

In order to investigate the influence of varying dosages of gelatin-copper/ gelatin-cobalt complex and sodium silicate stabilizer on cotton fabric

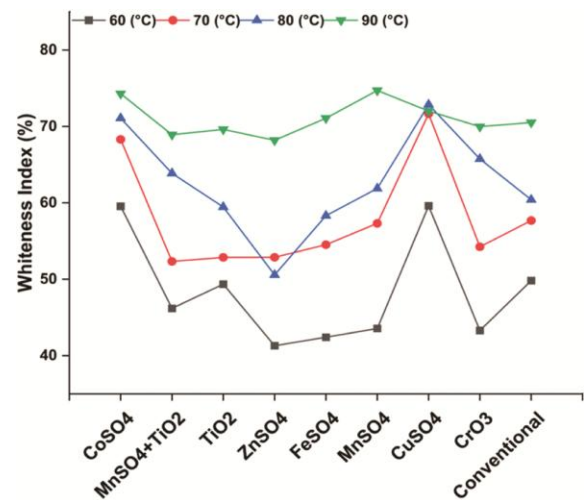


Fig. 1 — Whiteness index variation with respect to bleaching media and temperature

bleaching, a statistically designed experiment was conducted. Seventeen experimental conditions were created using Design-Expert software (version 6.0) and the whiteness index was evaluated for each condition (Table 4).

It is important to note that several factors like material-to-liquor ratio (1:20), non-ionic wetting agent concentration (1 g/L) and hydrogen peroxide concentration (10 g/L) were kept constant throughout the experiments. The plot illustrated in Fig. 2 (a) suggests that the brightest whiteness (72.90%) in bleached cotton fabric was achieved when a combination of 4g/L sodium silicate stabilizer and 1.5 g/L gelatin-copper complex was used during bleaching at a higher temperature of 90°C (Exp. No. 12). This is likely because sodium silicate stabilizer helps prevent degradation of cellulose fibres at high temperatures, allowing the bleach to work more effectively. Whereas, the gelatin-copper complex might act as a catalyst enhancing the bleaching process at a higher temperature. Besides, there exists

Table 4 — Whiteness indices of cotton fabric bleached using gelatin-metal complex catalyst and sodium silicate stabilizer as per the experimental design produced through Design-Expert

Run	Factor 1	Factor 2	Factor 3	Whiteness indices, %	
	Stabilizer Sodium Silicate, g/L	Catalyst Gelatin-metal complex	Temperature, °C	Gelatin-copper complex	Gelatin-cobalt complex
1	2	3	90	69.61	72.52
2	0	1.5	60	47.75	45.32
3	4	3	75	69.82	68.69
4	2	0	90	68.17	64.55
5	2	1.5	75	68.36	63.93
6	2	1.5	75	68.23	67.81
7	2	1.5	75	65.35	66.41
8	0	0	75	50.41	40.99
9	0	1.5	90	55.94	65.14
10	2	1.5	75	71.01	65.82
11	2	0	60	43.57	50.33
12	4	1.5	90	72.90	71.83
13	4	0	75	53.95	52.54
14	2	3	60	61.04	58.02
15	4	1.5	60	60.63	56.54
16	2	1.5	75	69.04	65.45
17	0	3	75	36.48	63.68

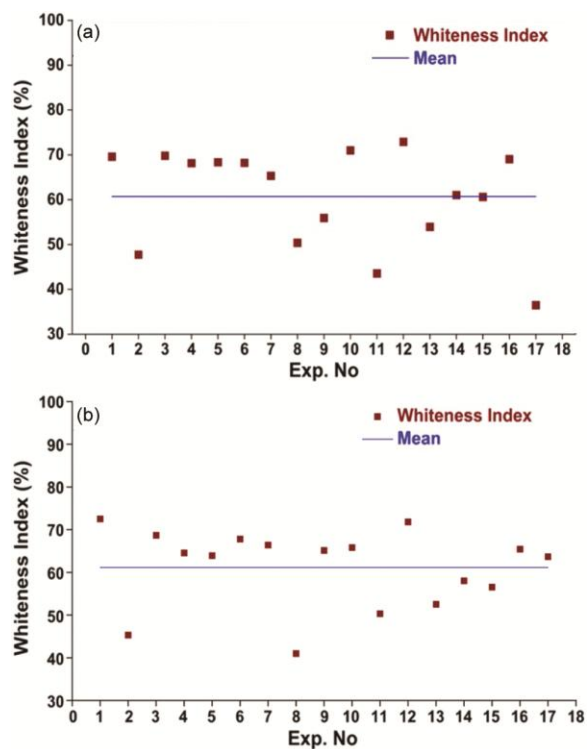


Fig. 2 — Whiteness index variation vs experimental run (a) stabilizer + gelatin-copper complex, and (b) stabilizer + gelatin-cobalt complex

a bit variation in the whiteness index around the mean value of 60.72% with 11 experiments recording higher whiteness index values than mean value, while 6 experiments showing lower values (Exp. No. 2, 8, 9, 11, 13, 17). Surprisingly, among the 6 experimental combinations that resulted lower than mean whiteness

index value, 4 experimental combinations i.e., Exp. No 2, 8, 9 and 17 were conducted in the absence of stabilizer implying significant effect of stabilizer during bleaching operation. Additionally, in the 11 experiments that showed higher whiteness values than mean whiteness value, the combined effect of both stabilizer and gelatin-copper complex could be synergistic, meaning their interaction creates a greater impact than the sum of their individual effects. Therefore, optimizing the concentration of these additives and the bleaching temperature appears to be crucial for achieving maximum fabric whiteness.

On the other hand, the highest whiteness index of 72.52% was achieved using a 3 g/L gelatin-cobalt complex and 2 g/L sodium silicate at 90°C during the bleaching process (Fig. 2 (b)). Interestingly, the average whiteness value (61.15%) for all 17 experiments with the gelatin-cobalt complex was slightly higher than that observed with the gelatin-copper complex. Since all other experimental conditions remained constant, this difference suggests a slight advantage for the gelatin-cobalt complex in promoting whiteness. Furthermore, Fig. 2 (b) reveals a tighter clustering of whiteness index values around the mean for the gelatin-cobalt complex compared to the gelatin-copper complex. This indicates a more consistent bleaching performance. Notably, among the experimental runs with a lower whiteness index than the average, only two (Exp. 2 and 8) lacked sodium silicate. Interestingly, Exp. 8 lacked both sodium silicate and the gelatin-cobalt complex and had the least whiteness index of 40.99%. This

observation suggests that unlike the gelatin-copper system, the presence of a stabilizer alone has a less significant impact on whiteness in the gelatin-cobalt system. Here, the gelatin-cobalt complex appears to be the primary contributor to achieving a high whiteness index. This may be attributed to the higher stability of cobalt complexes compared to those of copper, despite cobalt ions having a lower redox potential than copper ions.

3.3 Low Temperature Bleaching Using Gelatin-Copper Complex Catalyst with RUCOSTAB OKM Stabilizer and LENETOL GLAD-LQ-(TH) Stabilizer

Building on the sodium silicate stabilizer experiments, 17 similar runs were designed using Design Expert software to investigate the influence

of silicate-free stabilizer (RUCOSTAB OKM and LENETOL GLAD-LQ-(TH)) on cotton fabric's bleaching response in the presence of a gelatin-copper complex. All other parameters were held constant. The experimental design and whiteness index values generated for each combination is summarized in Table 5. The variations in whiteness index across the mean whiteness index obtained in the 17 independent experimental runs taking gelatin-copper complex as catalyst with RUCOSTAB OKM and LENETOL GLAD-LQ-(TH) as silicate free stabilizers are plotted in Fig. 3.

The average whiteness for RUCOSTAB OKM (60.45) was slightly higher than LENETOL GLAD-LQ-(TH) (59.31). Interestingly, both stabilizers

Table 5 — Whiteness indices of cotton fabric bleached using gelatin-copper complex catalyst with RUCOSTAB OKM and LENETOL GLAD-LQ-(TH) stabilizer

Run	Silicate Free Stabilizer, g/L	Gelatin-copper complex, g/L	Temperature, °C	Response Whiteness Index, %	
				(RUCOSTAB O km)	(LENETOL GLAD-LQ-(TH))
1	2	3	90	70.61	68.88
2	0	1.5	60	46.73	47.14
3	4	3	75	70.70	70.80
4	2	0	90	67.21	68.11
5	2	1.5	75	68.35	68.53
6	2	1.5	75	70.02	68.76
7	2	1.5	75	68.11	67.14
8	0	0	75	32.21	30.87
9	0	1.5	90	54.84	55.97
10	2	1.5	75	66.30	63.54
11	2	0	60	42.56	43.56
12	4	1.5	90	71.80	71.58
13	4	0	75	52.89	53.03
14	2	3	60	68.01	56.01
15	4	1.5	60	61.58	60.78
16	2	1.5	75	67.32	67.32
17	0	3	75	48.42	46.32

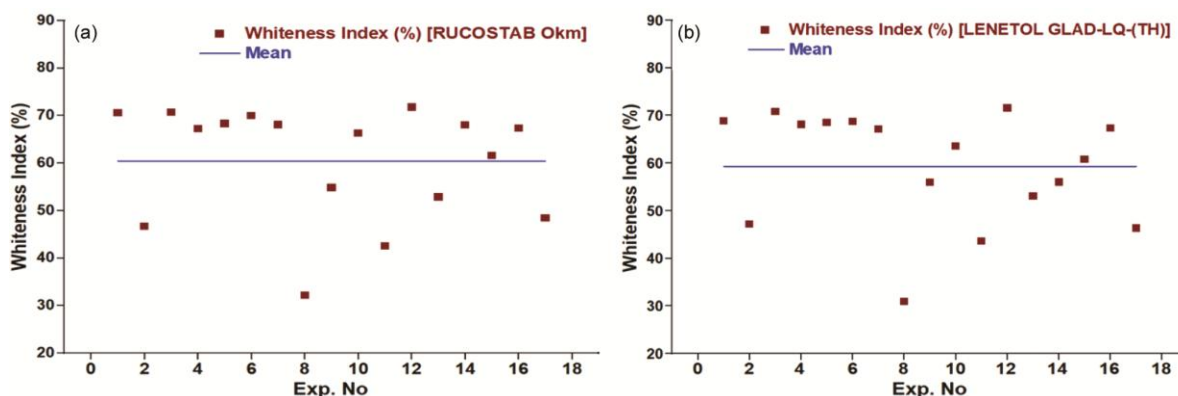


Fig. 3 — Whiteness index variation vs experimental run in case of gelatin-copper complex catalyst with (a) RUCOSTAB OKM stabilizer, and (b) LENETOL GLAD-LQ-(TH) stabilizer

showed a similar trend with more experiments falling below the mean value (6 for RUCOSTAB OKM, 7 for LENETOL GLAD-LQ-(TH)). Notably, Experiment No. 12 (using 4g/L stabilizer, 1.5g/L gelatin copper complex, and 90°C processing) achieved the highest whiteness index in both categories, with RUCOSTAB OKM showing a marginally higher value (71.8).

Additionally, the mean value of whiteness index obtained in both the RUCOSTAB OKM and LENETOL GLAD-LQ-(TH) was lower than the mean value whiteness index (60.72%) obtained in sodium silicate stabilizer for the same gelatin-copper complex. Besides, in all three-stabilizer case, Exp. No 12-combination resulted highest whiteness index among the 17 experiments in each category.

3.4 Low Temperature Bleaching Using Gelatin-Cobalt Complex Catalyst with RUCOSTAB OKM Stabilizer and LENETOL GLAD-LQ-(TH) Stabilizer

Likewise in case of gelatin-copper complex, the influence of silicate-free stabilizers, RUCOSTAB OKM and LENETOL GLAD-LQ-(TH), on the whiteness index of cotton fabric was investigated in the presence of a gelatin-cobalt complex. Seventeen experimental runs were conducted for each stabilizer as enumerated in Table 6, and the results are presented in Fig. 4. Contrary to the observation made in case of gelatin-copper complex, the mean values of whiteness index in case of LENETOL GLAD-LQ-(TH) stabilizer (60.28%) was higher than that of RUCOSTAB OKM (60.07%). Additionally, across most experimental conditions, LENETOL GLAD-LQ-(TH) demonstrated consistently higher whiteness

Table 6 —Whiteness indices of cotton fabric bleached using gelatin-cobalt complex catalyst with RUCOSTAB OKM and LENETOL GLAD-LQ-(TH) stabilizer

Run	Silicate Free Stabilizer, g/L	Gelatin-cobalt complex, g/L	Temperature, °C	Whiteness Index, % (RUCOSTAB O km)	Whiteness Index,% (LENETOL GLAD-LQ-(TH))
1	2	3	90	70.22	70.78
2	0	1.5	60	44.32	42.32
3	4	3	75	67.65	71.58
4	2	0	90	63.59	64.57
5	2	1.5	75	62.8	66.78
6	2	1.5	75	66.79	62.47
7	2	1.5	75	65.35	67.8
8	0	0	75	39.14	40.19
9	0	1.5	90	64.41	63.27
10	2	1.5	75	64.28	66.12
11	2	0	60	51.31	51.38
12	4	1.5	90	70.26	62.96
13	4	0	75	51.39	50.48
14	2	3	60	57.04	60.79
15	4	1.5	60	55.61	60.65
16	2	1.5	75	64.29	66.34
17	0	3	75	62.87	56.28

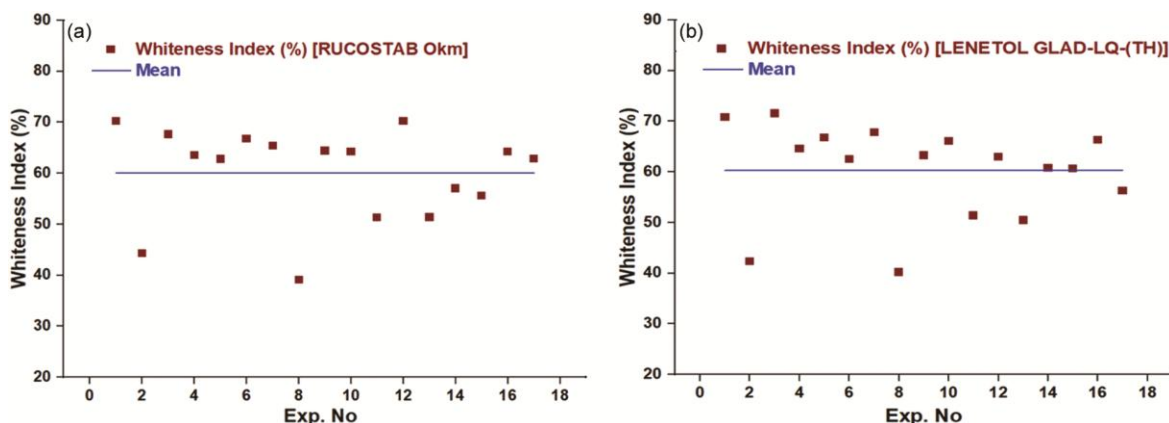


Fig. 4 — Whiteness index variation vs experimental run in case of gelatin-cobalt complex catalyst with (a) RUCOSTAB OKM stabilizer, and (b) LENETOL GLAD-LQ-(TH) stabilizer

indices than RUCOSTAB OKM, suggesting superior peroxide stabilization and better control over hydroxyl radical ($\bullet\text{OH}$) generation. The maximum whiteness for LENETOL (71.58%) was achieved in Run 3 (4 g/L stabilizer, 3 g/L catalyst, 75 °C), whereas RUCOSTAB reached its peak whiteness (70.26%) in Run 12 (4 g/L stabilizer, 1.5 g/L catalyst, 90 °C).

3.5 Optimization

3.5.1 Gelatin-metal complex catalyst with sodium silicate stabilizer

To optimize the bleaching process for a bleached substrate, the effects of various factors were investigated. This involved comparing the properties achieved with a novel gelatin-metal complex catalyst to those obtained using the conventional high-temperature bleaching method without the catalyst. Statistical modelling was employed to identify the optimal process conditions. Three factors were considered in the model: stabilizer concentration (0-4 g/L), gelatin-metal complex catalyst concentration

(0-3 g/L), and bleaching temperature (60-90 °C). The specific combinations of these factors used for the gelatin- CuSO_4 complex and gelatin- CoSO_4 complex are detailed in Table 7. Experiments were then conducted using the predicted optimal combination for whiteness index (a measure of bleaching effectiveness) and the results are presented in Table 8.

3.5.2 Comparison of Responses of Modified Catalyzed Bleaching Process with Conventional Bleaching Process

A novel low-temperature bleaching process for cotton was investigated using sodium silicate (Na_2SiO_3) stabilizer, silicate-free stabilizers (RUCOSTAB OKM and LENETOL GLAD-LQ-(TH)), and gelatin-copper/gelatin-cobalt complexes. Statistical analysis was employed to identify the optimal combination of bleaching parameters for each category and the performance of these new methods with their respective optimal combinations were compared to conventional high-temperature bleaching (90°C). The

Table 7 — Range of input parameters and responses using gelatin-metal complex catalyst and sodium silicate stabilizer

Constraints name	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
Stabilizer, g/L	Is in range	0	4	1	1	3
Gelatin-metal complex catalyst, g/L	Is in range	0	3	1	1	3
Temperature, °C	Is equal to 75	60	90	1	1	3
Whiteness Index, %	Maximize					
gelatin-copper complex + sodium silicate Stabilizer		30.9	73.1	1	1	3
gelatin-cobalt complex + sodium silicate Stabilizer		31.4	72.9	1	1	3
gelatin-copper complex + RUCOSTAB-Okm Stabilizer		33.5	72.3	1	1	3
gelatin-cobalt complex + RUCOSTAB-Okm Stabilizer		32.21	71.8	1	1	3
gelatin-copper complex + LENETOL GLAD-LQ-(TH)Stabilizer		30.87	71.58	1	1	3
gelatin-cobalt complex + LENETOL GLAD-LQ-(TH)Stabilizer		40.19	72.96	1	1	3

Table 8 — Optimized Recipes and Predicted Whiteness Indices for Cotton Bleaching (Gelatin-Metal Complexes with various Stabilizers)

Gelatin-metal complex	Factor 1 Stabilizer,	Factor 2 Catalyst	Factor 3 Temperature,	Whiteness Index, %	Whiteness Index, %
	g/L	Gelatin-metal complex, g/L	°C	Predicted	Experimental
gelatin-copper complex + sodium silicate Stabilizer	3.47	2.34	75	72.18	71.51
gelatin-cobalt complex + sodium silicate Stabilizer	2.51	2.55	75	70.20	69.82
gelatin-copper complex + RUCOSTAB-Okm Stabilizer	3.02	2.62	75	72.37	71.27
gelatin-cobalt complex + RUCOSTAB-Okm Stabilizer	2.77	1.94	75	71.88	70.02
gelatin-copper complex + LENETOL GLAD-LQ-(TH)Stabilizer	3.01	2.26	75	71.21	70.13
gelatin-cobalt complex + LENETOL GLAD-LQ-(TH)Stabilizer	3.16	2.70	75	70.46	69.36

Table 9 — Performance evaluation of modified catalysed bleaching process vs Conventional bleaching process

Bleaching Method (Optimum Combination)	Whiteness Index, %	Weight loss, %	Bursting strength, psi	TDS, ppm
Conventional Bleaching	70.52	10.9	82.5	2203
Bleaching with gelatin-copper complex and sodium silicate stabilizer	71.51	7.1	101.8	2656
Bleaching with gelatin-cobalt complex and sodium silicate stabilizer	69.82	6.8	99.6	2745
Bleaching with gelatin-copper complex and RUCOSTAB OKM Stabilizer	71.27	6.4	104.1	2671
Bleaching with gelatin-cobalt complex and RUCOSTAB OKM stabilizer	70.02	8	102.1	2712
Bleaching with gelatin-copper complex and LINETOL GLAD LQ(TH) stabilizer	70.13	6.5	101.9	2637
Bleaching with gelatin-cobalt complex and LINETOL GLAD LQ(TH) stabilizer	69.36	7.6	100.3	2688

detailed performance of these methods is listed in Table 9.

The comparative evaluation between conventional bleaching and modified catalysed bleaching processes using gelatin-metal complexes revealed some interesting observations. Firstly, among all tested methods, the optimized combination of gelatin-copper (CuSO_4) complex with RUCO-STAB OKM stabilizer demonstrated the most balanced and superior performance across key parameters. The specific combination i.e., 3.02g/L RUCO-STAB OKM stabilizer and 2.62g/L gelatin-copper complex formulation achieved a whiteness index of 71.27%, exceeding that of conventional bleaching (70.52%), which indicates enhanced oxidative degradation of chromophores. The superior bleaching efficacy is primarily attributed to the redox catalytic activity of the gelatin-Cu complex, which promotes the generation of hydroxyl radicals ($\bullet\text{OH}$) from hydrogen peroxide via Fenton-like reactions. These highly reactive species improve stain degradation even at moderate temperatures while preserving the integrity of the fabric. This is further evidenced by the lowest fabric weight loss (6.4%), reflecting minimal cellulose degradation and superior fabric preservation. On the other hand, although optimum amount of Na_2SiO_3 and gelatin-copper complex provided slightly higher whiteness index of 71.51%, it showed higher fibre damage than RUCO-STAB OKM stabilizer. This signifies the role of RUCO-STAB OKM stabilizer in stabilizing the hydrogen peroxide, thereby regulating radical formation and limiting uncontrolled oxidative damage. Additionally, the optimum gelatin-copper complex and RUCOSTAB OKM stabilizer showed maximum bursting strength (104.1 psi), a significant improvement from 82.5 psi in conventional bleaching. However, the modified approach of bleaching did lead to slightly higher total dissolved solids (TDS) in the wastewater due to possible presence of residual metal ions, stabilizers and unreacted reagents. Meanwhile, gelatin-copper,

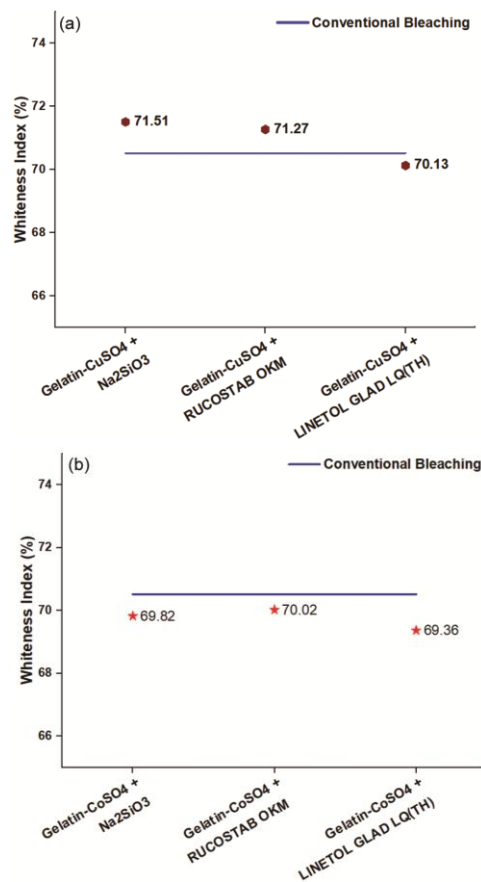


Fig. 5— Comparison of Whiteness Index (%) of cotton fabrics bleached using optimal combinations of stabilizer and (a) Gelatin-Copper Complex, and (b) Gelatin-Cobalt Complex

systems consistently outperform their cobalt counterparts across all major performance metrics. Copper-based formulations not only achieve higher whiteness values (up to 71.51%) compared to cobalt-based systems (maximum 70.02%) but also result in lower weight loss (as low as 6.4%) versus cobalt systems (up to 8.0%) and higher bursting strength (up to 104.1 psi) in comparison to maximum 102.1 psi in cobalt system. The controlled radical generation by Cu^{2+} ions might be the factor dictating the superior performance. To have more visual clarity, graphs

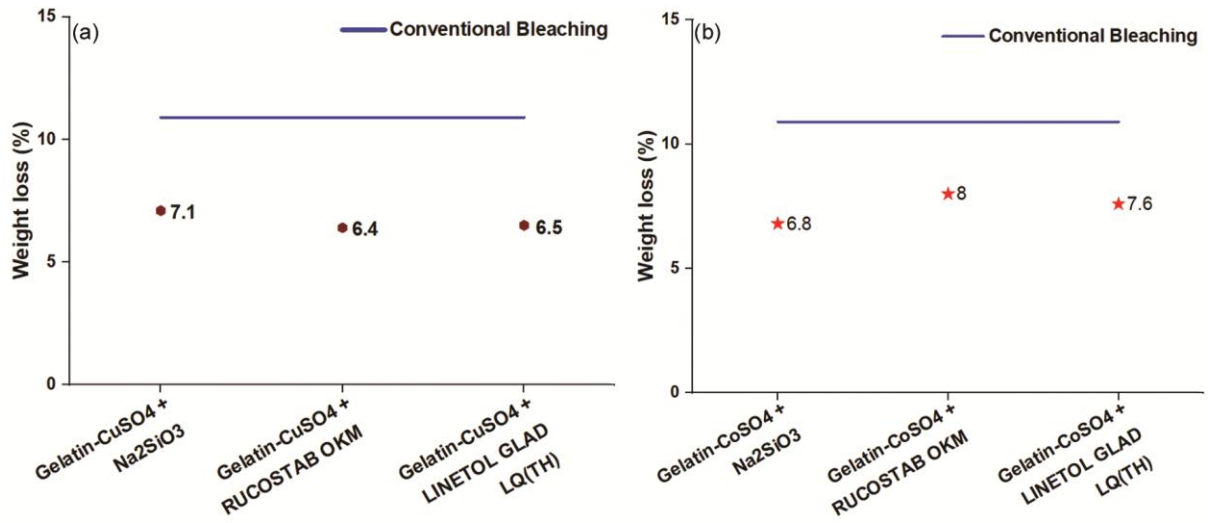


Fig. 6 — Comparison of Weight loss (%) of cotton fabrics bleached using optimal combinations of stabilizer and (a) Gelatin-Copper Complex, and (b) Gelatin-Cobalt Complex

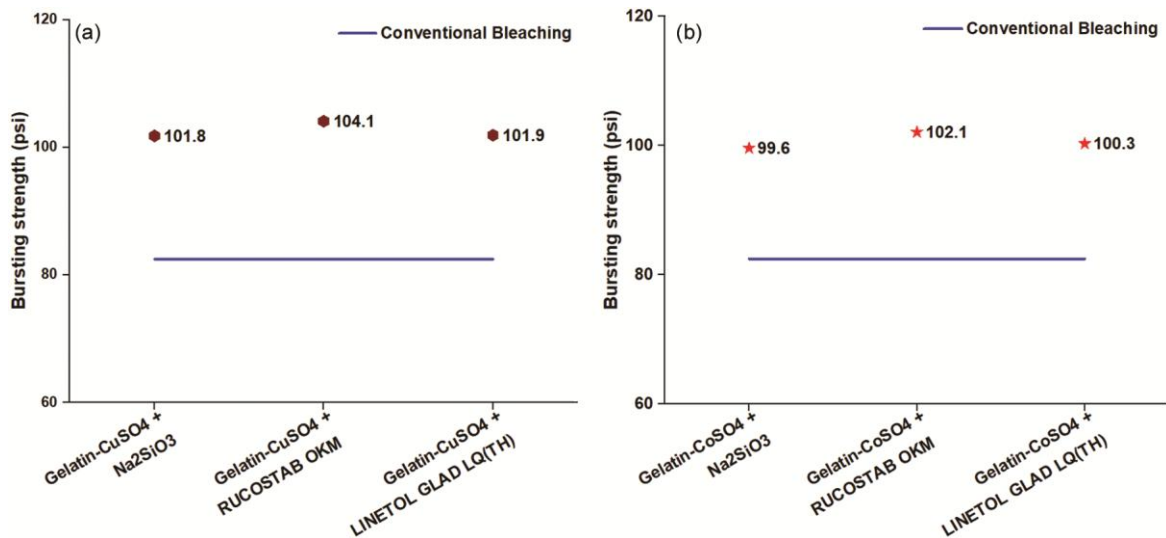


Fig. 7 — Comparison of Bursting strength (psi) of cotton fabrics bleached using optimal combinations of stabilizer and (a) Gelatin-Copper Complex, and (b) Gelatin-Cobalt Complex

were plotted to compare the performance of gelatin copper complex and gelatin cobalt complex across various responses taking conventional bleaching performance as baseline. Figure 5, 6 and 7 clearly shows the superior performance of gelatin-copper complex over gelatin-cobalt complex at all combinations of stabilizer.

4 Conclusion

Industrial cotton fabric bleaching with hydrogen peroxide (H₂O₂) typically uses high temperatures (around 98°C), which can damage the fabric and consume excessive energy. Researchers are looking for ways to lower the bleaching temperature. This

study investigated eight newly created gelatin-metal complexes as catalysts for the process. Gelatin-copper and gelatin-cobalt complexes showed promising results.

The study also explored using alternative stabilizers to Na₂SiO₃ for the bleaching process on knitted cotton fabrics. These stabilizers, such as RUCOSTAB OKM (ATUL) and LENETOL GLAD-LQ-(TH) (CRODA), are silicate-free alternatives to traditional sodium silicate stabilizers. They were used in conjunction with the gelatin-copper and gelatin-cobalt complex catalysts.

A statistical model was developed to optimize bleaching at lower temperatures. Using a half factorial

central composite design and Design-Expert 6.0 software, optimal recipe for the bleaching process was created for all combinations of gelatin metal complex and stabilizer. This optimized process achieved similar whiteness and less fabric weight loss compared to the conventional method, all at a lower temperature (75°C). Optimized combination of gelatin-copper (CuSO₄) complex with RUCO-STAB OKM stabilizer demonstrated the most balanced and superior performance across key parameters. However, the new system did result in a higher total dissolved solids (TDS) level.

The key advantage of the H₂O₂/Na₂SiO₃/gelatin-copper and gelatin-cobalt complex bleaching system in comparison to conventional bleaching with H₂O₂/Na₂SiO₃ is its ability to lower the bleaching temperature while achieving desired results and reducing fibre damage. Additionally, alternative stabilizers like RUCOSTAB OKM and LENETOL GLAD-LQ-(TH) can also be effectively used in this system for low-temperature cotton fabric bleaching.

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