# HYDROGEN PEROXIDE BLEACHING OF DEINKED PULP

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This research study focused on the impacts of some crucial process variables on the single-stage hydrogen peroxide bleaching of recycled deinked pulp. The impacts of hydrogen peroxide and sodium hydroxide doses, temperature, retention time, pulp consistency, and sodium silicate addition were analyzed systematically. The results obtained indicated that an increase in the dose of peroxide increases the brightness and reduces absorption; however, excess doses result in yield loss, without improving the performance further. Sodium hydroxide is vital for the activation of peroxide, with an optimal range of 1.50–2.00% leading to maximum brightness and higher doses promoting alkaline darkening. Temperature and time have high impact on the bleaching performance; optimal values of 70 °C and 3 h retention give the best combination of brightness and yield. Pulp consistency of medium (10.00%) value is the most advantageous for achieving effective use of chemicals, in contrast to lower and higher consistencies. The addition of sodium silicate (2.00–3.00%) stabilized peroxide, increased scattering effect, and prevented ink redeposition. Overall, the optimization of chemicals and process variables considerably improves the brightness and optical characteristics of recycled deinked pulp. Single-stage peroxide bleaching of recycled deinked pulp yielded pulp brightness of 65.00% ISO, with a yield of 95.20%.

***Keywords***: deinked pulp, hydrogen peroxide bleaching, brightness, scattering coefficient, absorption coefficient

## INTRODUCTION

Recycling helps considerably reduce the environmental effects of the papermaking process. Indeed, the production of one tonne of paper made of 100% recycled wastepaper preserves about 24 trees. Nevertheless, there are many different kinds of pulps, fillers, retention aids, and sizing materials that may be included in the recycled furnish; thus, bleaching becomes complicated. Due to the greater use of recycled fibres in the paper production process, there appears a higher demand for clean and brighter deinked pulps. In order to satisfy this demand, there appeared the necessity to bleach deinked pulps. Since the sources of the waste papers are of lower quality, it becomes harder and harder to accomplish this task. Hence, bleaching deinked pulps is gradually replaced by bleaching with oxygen compounds like $O_2$, $O_3$, and $H_2O_2$.

Environmental protection demands for new bleaching technologies increase rapidly in view of the bans on using chlorine compounds. The most popular substitute is hydrogen peroxide due to its efficiency and low amounts of toxic emissions. Bleaching in the pulp and paper industry is a chemical processing of fibres in order to increase their brightness in the visible range, particularly at 457 nm. Thus, brightness refers to the reflection coefficient of pulp or paper.

The fibres used for the manufacture of paper consist mainly of cellulose, hemicelluloses, and lignin, which come from wood. In lignin, there are chromophoric elements, such as the carbonyl group and the aromatic ring, which absorb light and cause a reduction in brightness. The efficiency of the bleaching process is measured through brightness improvement and lignin removal and alteration. Deinked pulp (DIP) is unique in its bleaching process since, unlike the kraft pulp, the former requires more than lignin removal. DIP consists of residual ink, filler, extractive, dispersants, and transition metals, which may cause peroxide breakdown and colour reversion. Bleaching of deinked pulp is done to improve brightness and prevent yellowing, and to remove dyes or colours from wastepaper.[1] Therefore, the performance of peroxide bleaching depends on the control of dosing, alkalinity, stabilization, temperature, and retention time, among others.[2,3]

In alkaline environment, hydrogen peroxide produces the perhydroxyl anion ($HOO^-$), which is responsible for the bleaching action.[4,5,6,7] Peroxide oxidizes chromophores, however, it may be

decomposed to water and oxygen in the presence of metal ions (Fe, Cu, and Mn). Competing reactions could decrease the bleaching action and even lead to brightness reversion because of the formation of coloured lignin compounds.[1] To avoid peroxide loss because of the interaction with metal ions, stabilizers (sodium silicate, magnesium salts, and chelating agents such as DTPA, EDTA) are added. It is well known from the literature and practical experience that silicate and magnesium salts work efficiently as co-stabilizers.[4,8,9] Latest investigations have been devoted to the development of silica-free stabilizers (*e.g.*, acrylic-acid/$MgSO_4$ complexes), which provide brightening and do not have the negative properties of silicates.[8,10-12] Bleaching substances, conditions of bleaching, various kinds of waste paper, and printing and deinking processes are affecting the bleaching response of recycled fibres.

Among the various chemicals used in oxidative bleaching, hydrogen peroxide is the most commonly used for deinked pulp.[13-18] Hydrogen peroxide has many advantages as a bleaching agent, such as low capital costs for bleaching application and high efficiency under alkaline operation conditions. Textbooks dealing with secondary fibre and deinking processes emphasize the wide range of possibilities for the use of peroxide for DIP brightening either in one-step or short bleaching sequences and give details about interactions of chemical charges ($H_2O_2$, NaOH, sodium silicate), stabilizers, and bleaching conditions.[4,6,9] At the same time, these references remind us that "more chemicals" does not mean necessarily higher brightness gain; beyond a certain point, brightness gains get smaller and chemical usage and losses of yield increase.[2] An important role is played by sodium silicate – it stabilizes the peroxide, maintains alkalinity, disperses ink particles, and protects fibres from redeposition of contaminants. The optimal silicate charge ranges from 1.00 to 3.00% on pulp where brightness gain is maximum, but without scaling problems and effluents. Also, hydrogen peroxide and sodium hydroxide charges have to be properly selected. Although NaOH activates hydrogen peroxide, too high an alkalinity dissolves lignin fragments producing coloured substances and reducing brightness. Higher temperatures (60–70 °C) enhance bleaching, but may cause the breakdown of peroxide and yellowing. The typical reaction time is in the range of 1–3 hours, when most brightness is attained in 1–2 hours. Consistency medium (10.00–12.00%) is optimal for efficient chemical interaction and mixing, and very low or high consistencies decrease the effectiveness of the process. The addition of peroxide leads to increases in brightness, but when more than 3.00–4.00% is used, the effect decreases, whereas the consumption of chemicals and loss of yield increases.

The optical effects of bleaching may be analyzed through the framework of Kubelka–Munk model, which links the diffuse reflectance of light with the scattering coefficient (s) and absorption coefficient (k). The scattering coefficient depends on the properties of the fibres themselves and their surface areas; higher values indicate that the pulp is whiter. The absorption coefficient is a measure of the presence of chromophore molecules; the lower the value, the whiter the pulp. Usually, hydrogen peroxide reduces the absorption coefficient (k) through destruction of chromophores, whereas variations in the scattering coefficient (s) arise from cleaning the fibre surface, the redistribution of fines and residual ink particles, and alterations in sheet structure. The combined effect of these two coefficients governs the resulting brightness and overall visual quality of the sheet.[4]

The effects of different bleaching chemicals on the brightness and other optical characteristics of mechanical pulps[19-22] and recycled fibres[5-7,14,15,23-34] have already been investigated. Hydrogen peroxide was considered as a bleaching agent for old corrugated container pulp.[14] Also, it has been shown that other additives, like sodium silicate and calcium carbonate, increase the efficiency of peroxide bleaching, particularly when working with deinked old magazine pulp, which increases residual peroxide concentration and brightness.[35] Peroxide alone has poor ability to remove dyes from recycled fibres during deinking pulp bleaching process.[24,34,36] However, single-stage peroxide bleaching was shown to be efficient for newsprint and magazine-grades of recycled fibres.[37] For instance, according to a study, ~58.00% ISO brightness at ~92.00% yield was achieved for deinked ONP via a single P stage, and yield losses were due to alkaline extraction of hemicelluloses/fines and structural changes in cellulose.[25] Literature reports demonstrate that single-stage peroxide treatment can easily meet all DIP brightness requirements; however, if higher brightness is required, staged or hybrid processes (*e.g.*, oxidative/reductive) can provide good results, without the use of chlorinated compounds.[26,38]

Despite intensive investigation of hydrogen peroxide bleaching processes, their chemistry still needs to be clarified in relation to positive and negative reactions involved. In accordance with previous studies, an optimum peroxide load is within 1.50–2.00% based on pulp, while a further increase in dosage does not produce any significant results. Optimization in such a case should include tuning of peroxide, NaOH, silicate, and other process parameters. Sustainability-wise, hydrogen peroxide allows for the increased usage of fibre recycling and does not involve AOX chemistry. Literature shows that a properly controlled one-step bleaching by hydrogen peroxide allows achieving a targeted DIP brightness of 58.00–65.00% ISO with appropriate yields, while higher brightness will require multi-stage or oxidation–reduction process.

The goal of the present research is to investigate the impact of process variables such as peroxide charge, sodium hydroxide, sodium silicate, temperature, reaction time, and pulp consistency on the performance of hydrogen peroxide bleaching of deinked pulp. Special attention is paid to brightness gain, yield, residual peroxide, and optical characteristics through Kubelka–Munk analysis.

## EXPERIMENTAL

The experimental programme was designed to isolate the effect of each major bleaching variable in turn, while holding the remaining conditions constant, so that the individual and combined contributions of chemical dosage and process conditions to brightness development could be resolved. Five sequential series of trials were carried out: (i) hydrogen peroxide dosage (1.00–4.00%), (ii) sodium hydroxide dosage (1.00–3.00%), (iii) temperature (50–90 °C) combined with retention time (1–4 h), (iv) pulp consistency (6.00–12.00%) at varying peroxide dosage, and (v) sodium silicate dosage (0.00–3.00%). The overall workflow, from raw deinked pulp to the optical and yield measurements reported in the Results and Discussion, is summarized in Figure 1.

### Equipment

Chemical dosages and oven-dry pulp charges were weighed on an analytical balance (0.01 g resolution). Bleaching was carried out in heat-sealed low-density polyethylene bags immersed in a thermostatically controlled water bath (±1 °C) capable of maintaining set-point temperatures between 50 °C and 90 °C. Filtration after bleaching was performed using a Büchner funnel connected to a vacuum flask and a laboratory vacuum pump. Oven-dry weight and moisture content were determined using a laboratory convection oven maintained at 105±2 °C. Handsheets were formed on a standard British sheet former, and their optical properties were measured with a reflectance spectrophotometer meeting TAPPI T452 specifications, fitted with an 85.00% ISO brightness backing and a black cavity for the two-backing reflectance measurements required for Kubelka–Munk analysis. A digital timer was used to control mixing intervals and total retention time throughout the bleaching trials.

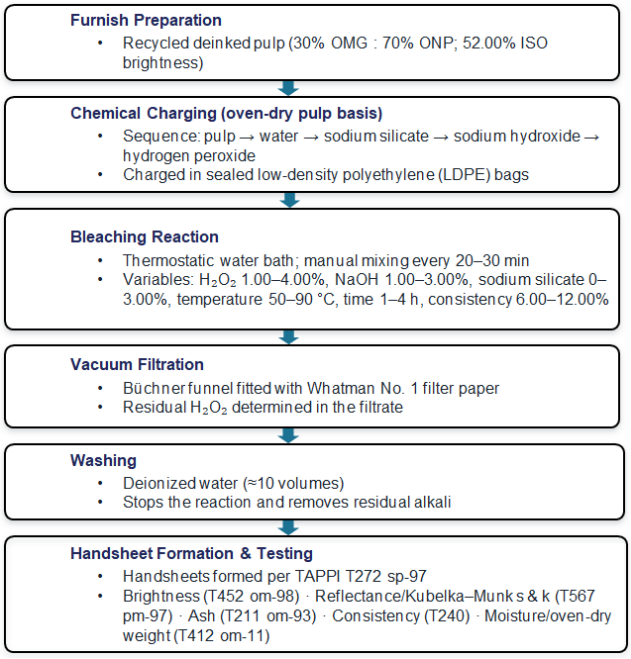


Figure 1: Overview of the experimental workflow for single-stage hydrogen peroxide bleaching of recycled deinked pulp, including the five investigated process variables and the analytical methods applied to bleached pulp

**Recycled pulp**

The deinked pulp used in this study was obtained from an industrial recycling plant. It was prepared from a furnish containing 30.00% old magazines (OMG) and 70.00% old newspapers (ONP), and had an initial brightness of 52.00% ISO, scattering coefficient (s) of 47.0 $m^2$/kg, and absorption coefficient (k) of 10.1 $m^2$/kg. The pulp ash content was 1.82%. Before bleaching, the pulp consistency was increased to 24.50% determined gravimetrically according to TAPPI T240 and the thickened pulp was stored at 4 °C until needed.

**Chemicals**

A 35.00% hydrogen peroxide solution from Asia Pacific Specialty Chemicals Ltd. was used as the bleaching chemical. Its exact concentration was verified by titration with potassium permanganate (0.25 N, 0.05 mol/L) in the presence of sulfuric acid (5 N, 2.5 mol/L) following Degussa analytical method WM 09/WM 11, and the measured value was 33.50%. Other chemicals obtained locally included sodium hydroxide (60.00% solution) and sodium silicate containing 14.00% NaOH and 27.00% $SiO_2$.

**Pulp bleaching**

Bleaching was performed with hydrogen peroxide inside sealed low-density polyethylene bags, each charged with 60 g of pulp on an oven-dry basis, which were placed in a thermostatically controlled water bath described above. The arrangement was employed for investigating the effect of various charges of peroxide, as well as the effect of the amount of sodium hydroxide and sodium silicate on the bleaching process, as well as the effect of temperature, retention time, and pulp consistency. In the bleaching tests, the chemicals were added to the pulp in the following order: deinked pulp, water, sodium silicate, sodium hydroxide, and hydrogen peroxide. All chemical dosages were calculated as percentages based on oven-dry pulp, determined gravimetrically following TAPPI T412 om-11. Unless specifically varied as an experimental parameter, all bleaching trials were carried out at a standard pulp consistency of 10.00%, determined according to TAPPI T240. Before chemical addition, the pulp slurry and the required water were pre-warmed to within ±2 °C of the target bleaching temperature (50–90 °C, depending on the trial); the sealed bags were then immersed in the water bath at the target temperature for the specified retention time, and during bleaching process the pulp was mixed manually every 20–30 minutes. Bleaching trials did not follow a single prescribed international test method, as bench-scale peroxide bleaching is a process operation rather than a standardized analytical determination; however, the chemical charging sequence, mixing regime, and reaction protocol followed established secondary-fibre bleaching practice as described in the literature,[3,4,9] ensuring reproducibility and comparability with previously published DIP bleaching studies.

After bleaching, when the retention time was over, the plastic bag was taken out and the pulp was first filtered using a Büchner funnel fitted with Whatman No. 1 qualitative filter paper to make a wet fibre cake. The liquid that passed through was recycled once through the cake to retain fine material. Residual peroxide in the filtrate was then measured. To terminate the bleaching reaction and remove excess alkali that could cause yellowing, the fibres were then washed well with deionized water (around ten volumes). After washing, the pulp consistency was raised to around 20.00% solids and made ready for evaluation of its optical properties and yield. The moisture content of the pulp was determined following TAPPI T412 om-11 and pulp yield was measured by the gravimetric method, using the oven-dry weight of the pulp as the basis.

**Handsheet making and paper testing**

Handsheets were prepared from the pulp slurry following TAPPI method T272 sp-97. The brightness of these sheets was determined at 457 nm under directional reflectance, in accordance with TAPPI method T452 om-98. The reflectance of the sheets was measured according to TAPPI standard method T567 pm-97. Measurements were taken with the sheet placed over an 85.00% ISO brightness backing and over a black cavity. The scattering coefficient (s) and absorption coefficient (k) were calculated using the Kubelka–Munk equations. Tappi standard method T211 om-93 was used for paper ash determination.

## RESULTS AND DISCUSSION

The brightening effect of alkaline hydrogen peroxide on deinked pulp is well established, and its underlying chemistry – formation of the perhydroxyl anion, chromophore oxidation, and the competing decomposition and alkaline-darkening reactions – has been studied for several decades, as summarized in the Introduction. The contribution of the present work is not the discovery of a new bleaching mechanism, but a systematic, single-furnish dataset in which all major process variables (peroxide charge, sodium hydroxide, sodium silicate, temperature, retention time, and consistency) were varied individually under otherwise identical conditions, and interpreted jointly through brightness, yield, Kubelka–Munk scattering/absorption coefficients, bleaching efficiency, and k/s ratio. This combined dataset is benchmarked below against more than a dozen previously published single-stage peroxide bleaching studies on comparable recycled furnishes, allowing the present optimum operating windows to be assessed directly against the wider literature rather than in isolation.

The effect of different peroxide charges, sodium hydroxide and sodium silicate levels, as well as the influence of temperature, retention time, and pulp consistency is described on optical properties, *i.e*., brightness, scattering coefficient, absorption coefficient, as well as pulp yield as mentioned below. The scattering coefficient (s) measures how much light is scattered by the pulp fibres. The 's' value is influenced by fibre structure, internal surface area, fines, and fillers. Materials with higher scattering coefficients appear whiter because light is more widely scattered in a less dense structure. The absorption coefficient (k) measures how much light is absorbed by the pulp, mainly due to chromophores, such as lignin residues, dyes, and inks. The 'k' value represents the fraction of light absorbed by the sheet and is used as an indicator of the presence of coloured substances. Together, scattering and absorption values contribute to the definition of the diffuse reflectance that finally determines the visual perception of the material.

**Effects of hydrogen peroxide dosage during bleaching**

The hydrogen peroxide concentration was changed from 1.00% to 4.00%, while other conditions were kept constant at 1.50% NaOH, 3.00% sodium silicate, 70 °C temperature, 3 h retention time and 10.00% consistency. Figure 2 clearly shows the effect of single stage hydrogen peroxide bleaching of recycled deinked pulp. Recycled deinked pulp showed the initial brightness value of 52.34% ISO, scattering coefficient – 42.50 m²/kg and absorption coefficient – 10.10 m²/kg. With increasing hydrogen peroxide application, there appeared a noticeable improvement of brightness and optical properties, although the decrease in the pulp yield became observable too.

In the first stage (1.00% $H_2O_2$), brightness increased to 55.99% ISO, which gave a 3.65 points increment. At this stage, there was a noticeable increase in the scattering coefficient (to 47.49 m²/kg) and a significant decrease in the absorption coefficient (to 8.08 m²/kg), which point out the removal or passivation of light absorbing chromophores. The pulp yield decreased only up to 96.90%.

The increase of peroxide charge to 2% resulted in a noticeable brightness increase of 61.95% ISO, which is equal to 9.61 points compared to the starting value. The scattering coefficient increased up to 52.20 m²/kg, and the absorption coefficient decreased to 6.11 m²/kg. A consistent increase in scattering proves better reflectance of light owing to the cleanliness of fibres from the ink particles, while the decrease in absorption indicates the destruction of chromophores. The pulp yield was high – 96.40%, which means that moderate amounts of peroxide were able to improve optical characteristics without much fibre loss.

With 3.00% charge, brightness became 63.77% ISO, while the scattering increased to 56.04 m²/kg and the absorption decreased to 5.75 m²/kg. This result shows high efficiency of the peroxide bleaching process, especially in the case of deinked pulp, where there are plenty of ink particles and chromophores in the lignin. Pulp yield decreased to 95.7%.

In addition, the maximum value of brightness was recorded in the highest dosage (4.00% $H_2O_2$). It amounted to 65.00% ISO, with an overall increase of 12.66 points. The scattering coefficient also increased to 59.94 m²/kg, whereas the absorption coefficient reduced to 5.55 m²/kg. The pulp yield was 95.20%, which is still acceptable considering the significant increase in brightness. From these results, it can be deduced that further increase in dosage above 3.00% does not provide much benefit, since the increase in brightness between 3.00% to 4.00% dosages amounts only 1.23 points. This underscores the need to optimize peroxide dosage for cost-effective operation.

As depicted in the figures, brightness rises in an approximately linear fashion with increasing peroxide dosage up to the 3.00% level, after which the response levels off and further gains become marginal. In a comparable manner, the scattering coefficient increases progressively, indicating greater light diffusion through the sheet structure, whereas the absorption coefficient falls off steeply during the initial dosage range before reaching a stable plateau. Collectively, the results confirm that peroxide bleaching effectively improves optical properties of recycled deinked pulp, with the most cost-effective balance between brightness gain and yield preservation occurring at around 2.00–3.00% dosage.

Bleaching efficiency is a measure of how effectively a bleaching chemical improves pulp brightness relative to the amount of chemical consumed.[7,39] A higher bleaching efficiency means more brightness is achieved per unit of chemical used. It also indicates whether the chemical dosage is being used productively or wasted in side reactions (*e.g*., peroxide decomposition, alkaline darkening). It also helps in optimizing bleaching

processes for cost-effectiveness and environmental sustainability. The k/s ratio relates the absorption coefficient (k) to the scattering coefficient (s) of pulp fibres. A lower k/s ratio indicates reduced light absorption relative to scattering, reflecting effective chromophore removal and improved brightness. The effects of varying doses of hydrogen peroxide on bleaching efficiency and k/s ratio are presented in Table 1.

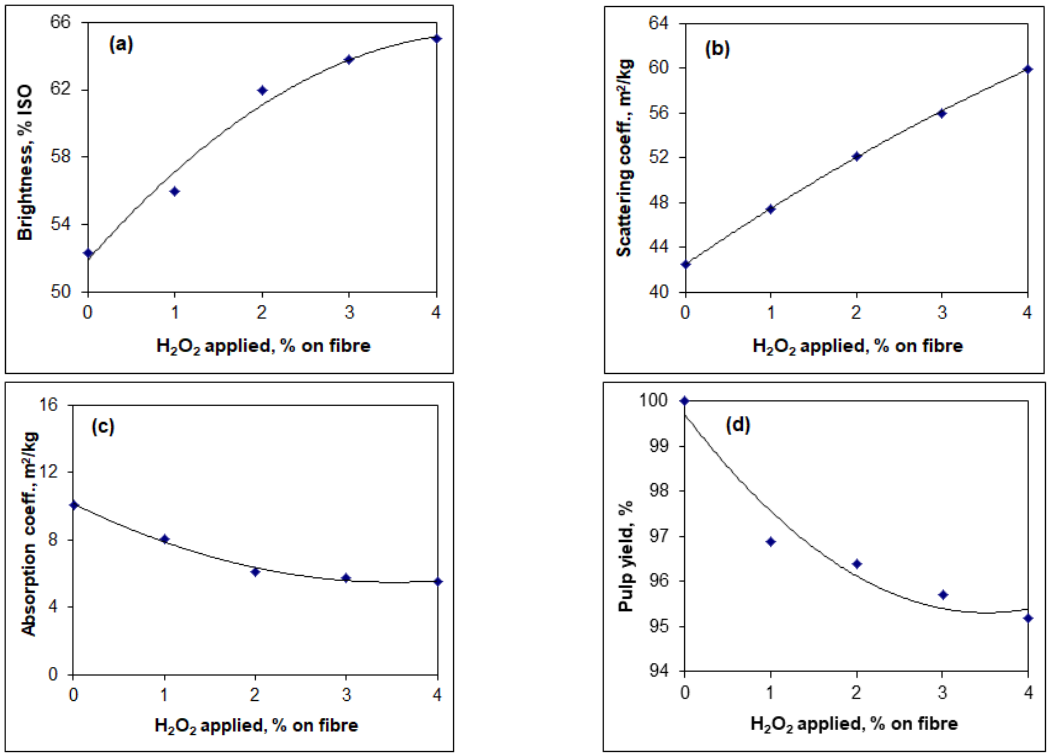


Figure 2: Effects of hydrogen peroxide dosage during bleaching on optical properties and pulp yield

Table 1
Effects of hydrogen peroxide dosage on bleaching efficiency and k/s ratio

| $H_2O_2$ applied, % | Bleaching efficiency | k/s ratio |
|---|---|---|
| 0.00 | - | 0.238 |
| 1.00 | 4.45 | 0.170 |
| 2.00 | 5.59 | 0.117 |
| 3.00 | 4.41 | 0.103 |
| 4.00 | 3.62 | 0.093 |

Constant conditions: 1.50% NaOH, 3.00% sodium silicate, 10.00% consistency, 70 °C temperature, 3 h retention time

Increasing hydrogen peroxide from 1.00% to 2.00% significantly improved bleaching efficiency (from 4.45 to 5.59) and reduced the k/s ratio (0.170 to 0.117). Beyond 2.00%, efficiency declined, and the k/s ratio stabilized around 0.093–0.103. This indicates an optimal peroxide dosage at 2.00% under the studied conditions for maximum brightness and minimal light absorption (Table 1). The ratio of k/s decreases with increasing dose of hydrogen peroxide used. This is predicted by the increase of s and decrease of k when concentration of hydrogen peroxide increases. From this set of results, it can be seen that hydrogen peroxide concentration has a positive effect on the improvement of brightness.

The present results align well with earlier studies on single-stage peroxide bleaching of recycled deinked pulp. Brightness gains of 10–13 points at moderate peroxide dosages have been widely reported. For example, peroxide bleaching enhanced brightness primarily through oxidative removal of residual lignin chromophores and ink

contaminants.[1,2] Deinked pulp from a paper mill, prepared from 90.00% old newspapers and 10.00% old magazines, was bleached in a single peroxide stage under the conditions of 2.00% peroxide, 0.50% sodium hydroxide, 1.20% sodium silicate, 85 °C, 10.00% consistency, and 90 minutes reaction time. The treatment significantly improved brightness, raising it by about 10 points –from 45.70% ISO to 55.00% ISO.[28] Yun and He[7] investigated peroxide bleaching of a mixed mill deinked pulp made from U.S. wastepaper PS#8, European wastepaper A9, Hong Kong wastepaper, and Dowling paper in a 70:10:10:10 ratio. The unbleached pulp had an initial brightness of 45.70% ISO. Under the conditions of 3.00% peroxide, 2.00% NaOH, 0.50% EDTA, 2.00% sodium silicate, 80 °C, 10.00% consistency, and 120 minutes retention time, the pulp achieved an 11.3-point brightness improvement.[7] In one experiment, deinked pulp was treated with hydrogen peroxide dosages of 0.50–2.50% (on oven-dry pulp) along with 0.20% chelating agent. Bleaching was carried out in sealed glass vessels at 80 °C, 10.00% consistency, and 90 minutes reaction time. Both high-brightness (69.80% ISO) and low-brightness (57.70% ISO) pulps were tested. Brightness increased as peroxide dosage rose, but improvements became negligible above 1.50%. At 1.50% peroxide, high-brightness DIP reached 75.50% ISO (a gain of 5.7 points), while low-brightness DIP reached 62.10% ISO (a gain of 4.4 points).[26] Another laboratory study examined the use of hydrogen peroxide for bleaching different recycled deinked pulps, including old newsprint, magazines, notebooks, and imported yellow pages. The bleaching conditions were 10.00% consistency, 65 °C, 1.25% sodium silicate, and 90 minutes retention time, with peroxide dosages ranging from 0.50% to 1.50%. At 0.50% peroxide, recycled fibres showed a brightness improvement of about 3.7–4.2 points. Increasing the dose to 1.00% gave an additional 2.0–3.2 points gain, while raising it further to 1.50% resulted in only a small increase of 1.6–2 points. Among the pulps tested, imported yellow pages from the USA had the lowest starting brightness (44.30%), but showed the highest improvement, with about 14 points gain, which was greater than that of the other pulps.[30]

Old newspaper pulp obtained from a mill was deinked in the laboratory, giving a starting brightness of 52.5% ISO. When bleached with hydrogen peroxide (1.00–4.00%) under the conditions of 1.50% NaOH, 0.05% magnesium sulfate, 5.00% sodium silicate, 70 °C, 10.00% consistency, and 60 minutes retention, brightness improved by 2.60–5.50% ISO compared to the unbleached control. However, pulp yield dropped steadily as the peroxide dose increased.[25] Deinked newsprint pulp (51.75% ISO brightness) was bleached with hydrogen peroxide at dosages ranging from 0.50% to 2.00% under different conditions of pulp consistency (15.00 and 20.00%), temperature (60, 70, and 80 °C), and reaction time (20, 40, and 60 minutes) to determine the optimum bleaching parameters. Other chemicals added were 1.00% NaOH, 5.00% sodium silicate, and 0.05% magnesium sulfate, based on oven-dry pulp. Results showed that a single-stage peroxide treatment increased pulp brightness to 64.05% ISO at 2.00% $H_2O_2$, 20.00% consistency, 80 °C, and 60 minutes. Brightness gain ranged from 2.30% to 11.30% over the deinked pulp (51.70% ISO), depending on peroxide dosage and consistency, mainly due to delignification.[40] A furnish made from 70.00% deinked ledger and 30.00% coloured broke was bleached in a single peroxide stage at 10.00% consistency, 60 °C, and 120 minutes. Using 1.50% hydrogen peroxide along with 1.30% sodium hydroxide, 0.05% magnesium sulfate, and 0.20% DTPA, the pulp brightness increased from 64.60% to 76.60% ISO.[34] Alkaline hydrogen peroxide bleaching was carried out on mixed office waste paper pulp made up of 65.00% sorted high-quality office paper with high laser print content, 20.00% coloured/offset print, 10.00% newsprint, and 5.00% magazines. The pulp had a kappa number of about 5 and an ash content of 11.00%. The bleaching conditions were: 2.00% hydrogen peroxide (on oven-dry pulp), 0.80% sodium hydroxide, 3.00% sodium silicate, 0.05% magnesium sulfate, 15.00% consistency, 75–80 °C, and 1 hour reaction time. Pulp repulped with only water and surfactant showed the lowest brightness of 57.80%. Conventional chemical deinking with 0.50% hydrogen peroxide and stabilizers gave 61.50% brightness, while single-stage peroxide bleaching achieved 68.70% ISO brightness.[32] In another case, curb side wastepaper with higher newsprint and glossy coloured content (kappa ~42, 8.00% ash) was bleached in a single peroxide stage using 2.00% peroxide. Brightness improved from 47.50% ISO to 52.30% ISO.[32]

Overall, the results validate that single-stage peroxide bleaching remains an efficient, environmentally compatible method for upgrading

deinked pulp quality, with optimal dosages typically in the 2.00–3.00% range.

Having identified 2.00–3.00% hydrogen peroxide as the most cost-effective dosage range, the next series of trials examined how sodium hydroxide charge – the alkali required to activate peroxide into its bleaching-active perhydroxyl form – affects brightness development at a fixed 2.00% peroxide charge.

**Effects of sodium hydroxide dosage during bleaching**

The sodium hydroxide dosage was varied from 1.00% to 3.00% to examine how it influences pulp yield, brightness, scattering, and absorption coefficients, while other conditions were kept constant at 2.00% $H_2O_2$, 3.00% sodium silicate, 70 °C temperature, 3 h retention time and 10.00% consistency. These results, as shown in Figure 3, show the effect of dosage of sodium hydroxide (NaOH) on the effectiveness of bleaching of recycled deinked pulps.

At 1.00% NaOH dosage, the brightness of pulp was 58.58% ISO, and the scattering coefficient was 49.73 m²/kg and the absorption coefficient was 7.28 m²/kg. As the NaOH dosage was increased to 1.50%, there was considerable improvement in brightness, which reached 61.94% ISO, which is the optimum case in this set of data. The corresponding scattering coefficient also increased to 52.20 m²/kg, whereas the absorption coefficient decreased to 6.11 m²/kg. This behaviour points to moderate alkaline conditions favouring both peroxide activation and chromophore degradation, which together enhance the sheet's optical characteristics.

In the case of a higher dose of sodium hydroxide solution at 2.00%, the value of brightness was a little bit lower (61.60% ISO), while the value of the scattering coefficient amounted to 51.82 m²/kg. This is related to a considerable increment in absorption coefficient, which reached the value of 6.23 m²/kg, which indicated the beginning of side reactions producing coloured lignin derivatives. It is a known phenomenon described as alkaline darkening. Even though the decrement in brightness was quite small, it proved the fine balance between the peroxide activation and its degradation in alkaline environment. It is well established that alkaline darkening compromises peroxide bleaching outcomes by reducing the pulp's final brightness level.[41,42]

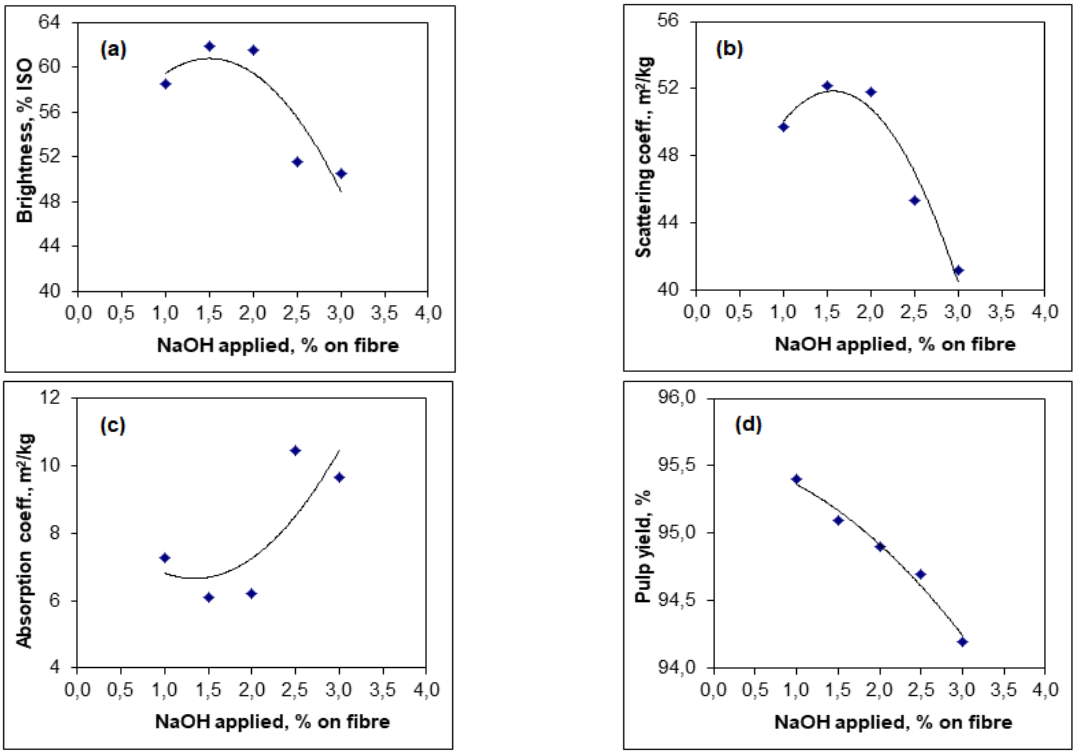


Figure 3: Effects of sodium hydroxide dosage during bleaching on optical properties and pulp yield

Table 2
Effects of sodium hydroxide dosage on bleaching efficiency and k/s ratio

| NaOH applied, % | Bleaching efficiency | k/s ratio |
|---|---|---|
| 1.00 | 3.98 | 0.146 |
| 1.50 | 5.55 | 0.117 |
| 2.00 | 5.55 | 0.120 |
| 2.50 | -0.45 | 0.231 |
| 3.00 | -0.99 | 0.235 |

Constant conditions: 2.00% $H_2O_2$, 3.00% sodium silicate, 10.00% consistency, 70 °C temperature, 3 h retention time

In addition, when increasing the amount of sodium hydroxide beyond this optimum level, a significant decrease in optical properties occurred. At 2.5% NaOH, the value of brightness dropped significantly to 51.57% ISO, with the scattering coefficient of 45.34 m²/kg and the absorption coefficient of 10.47 m²/kg. In the case of the highest level of alkaline solution at 3.00% NaOH, brightness was even more reduced, reaching the value of 50.57% ISO, while the scattering coefficient was lower than before, 41.20 m²/kg, and the absorption coefficient remained at high levels, 9.67 m²/kg. According to these results, high alkalinity impairs bleaching in two ways — by speeding up peroxide decomposition and lowering its efficiency, by favouring the generation of chromophores that cause the pulp to yellow.

However, pulping efficiency in the NaOH series was relatively low with pulp yields varying from 95.40% at 1.00% NaOH to 94.20% at 3.00% NaOH. Although there were little variations, this is due to the fact that alkaline solubilization of fines and hemicelluloses occurred. The figures further show these relationships: brightness peaks at 1.50% NaOH and then decreases sharply, whereas the absorption coefficient displays an inverse trend, findings that underscore the pronounced sensitivity of peroxide bleaching performance to alkali charge.

It should be noted that the most efficient peroxide bleaching process occurred at about 1.50% NaOH concentration, where the highest increase in brightness occurred and scattering was favourable and absorptions were minimum. The overcharge of the caustic soda has a negative influence on peroxide bleaching efficiency.

The effectiveness of bleaching was progressively increased by the increase in sodium hydroxide content till 1.50–2.00% (≈5.55). On further increasing the content of sodium hydroxide from 2.50 to 3.00%, there was a drastic reduction in effectiveness, even reaching negative figures, while the value of k/s ratio increased (0.231–0.235). This shows that excess alkali promotes alkaline darkening and reduces brightness, confirming the importance of optimizing NaOH levels to balance peroxide activation and minimize yield loss (Table 2).

The results obtained from this study are in agreement with past studies on peroxide bleaching of recycled deinked pulp. Several studies emphasize that the hydrogen peroxide bleaching system requires a carefully controlled $H_2O_2$/NaOH ratio, as both under- and over-dosing of caustic soda can reduce brightness. For instance, McKinney reported that brightness increased with NaOH addition up to an optimum point, beyond which excessive alkalinity promoted colour reversion and reduced brightness.[43] Göttsching and Pakarinen similarly concluded that peroxide bleaching efficiency is maximized at moderate alkali levels, with higher NaOH leading to alkaline darkening and non-productive peroxide consumption.[3] Chen *et al*. demonstrated in deinked ONP pulp that yield remained above 92.00% under moderate peroxide and caustic charges, but higher alkali promoted hemicellulose dissolution and reduced screened yield.[25]

Laboratory deinked old newspaper pulp (brightness of 52.50% ISO) received from a mill was bleached using different sodium hydroxide dosages (0.50–2.00%) with 2.00% peroxide following the conditions of 0.05% magnesium sulfate, 5.00% sodium silicate, 70 °C, 10.00% consistency, and 60 minutes retention. Brightness rose sharply with increasing alkali charge up to an optimum level, after which further alkali addition reduced the gain. For instance, with 2.00% peroxide and 1.50% NaOH, brightness reached 57.30% ISO, but only 55.00% ISO at 2.00% NaOH. A decreased yield was seen with increasing levels of alkali content.[25] The removal of chromophores in alkali-peroxide bleaching is due to lignin modifications and solubilization.[1] Pan

also found that hemicelluloses dissolution in alkaline environment plays a significant role in yield loss as well.[44]

On the whole, it can be concluded that NaOH dosage has a major impact on the efficiency of peroxide bleaching, it is estimated to be between 1.50–2.00% in 2.00% $H_2O_2$. This finding is supported by past studies that agree on the significance of alkali addition in peroxide bleaching. With 1.50–2.00% NaOH established as the optimum alkali range at a fixed 2.00% peroxide charge, attention turned to the process conditions under which this chemical system was applied, namely temperature and retention time, since both govern the rate of perhydroxyl formation and its competing decomposition.

**Bleaching effects of temperature and retention time**

Retention time was changed from 1 to 4 hours for each temperature varied from 50 to 90 °C, while all other parameters were kept constant at 2.00% $H_2O_2$, 1.50% NaOH, 3.00% sodium silicate, and 10.00% consistency. As shown in Figure 4, the effects of temperature and retention time during hydrogen peroxide bleaching of deinked recycled pulp have been highlighted. Three temperatures (50 °C, 70 °C, and 90 °C) give unique bleaching performance when the retention times vary from 1 to 4 hours.

For example, at 50 °C, peroxide consumption was high (92.50–96.30%) because of the relatively stable bleaching conditions at this moderate alkalinity level. As the reaction time increases, the brightness changes gradually increasing from 56.06% ISO after 1 hour to 61.12% ISO after 4 hours. The scattering coefficient increased from 52.68 to 58.45 m²/kg, whereas the absorption coefficient decreased slightly from 9.11 to about 8.15 m²/kg. The pulp yield decreased from 96.10% to 92.10%. This is probably due to a loss of fines and hemicelluloses during bleaching. This suggests that lower operating temperatures demand prolonged retention to secure substantial brightness improvement, though this comes with a slight incremental loss in yield.

At 70 °C, an increase in bleaching effectiveness was noticeable. The increase in brightness was steeper, from 57.74% ISO after 1 hour to 61.80% ISO after 4 hours. It should be noted that the absorption coefficients dropped considerably (8.74 → 6.38 m²/kg), proving effective destruction of chromophores. At this temperature, the pulp yield reduced slightly (from 98.40% to 95.30%), but still remained higher than at 50 °C, owing to increased effectiveness of the reactions and low degradation of fibres. Brightness increment was more significant within 3 hours; after that, the increase stopped, showing the benefit of high temperature in decreasing the necessary reaction time.

The results obtained for 90 °C demonstrated a negative effect on the stability of bleaching. So, at first, the brightness rose to 59.15% ISO after 1 hour, then it decreased and reached 52.75% ISO after 4 hours. The absorption coefficients grow after 2 hours (up to 10.92 m²/kg), which means that there was much chromophore formation caused by peroxide destruction and alkaline darkening. The scattering coefficient fluctuated considerably, which means changes in the structure of fibres. Pulp yield showed only a modest decline (97.60% to 95.10%); however, the more significant issue was brightness reversal, which demonstrates that excessively high temperatures hasten the breakdown of peroxide and consequently diminish bleaching efficiency.

In general, the best conditions were achieved at 70 °C for 3 h retention time, when brightness exceeded 62.00% ISO, absorption was reduced, and yield loss remained at a minimum. Thus, this research proved the necessity of taking into consideration both parameters, because low temperature means that the process will take more time, whereas high temperature results in peroxide decomposition and reduction in brightness.

At 50 °C, efficiency rose continuously over time, reaching a maximum of 4.62 after 4 h. In the case of 70 °C, efficiency was maximal (5.39) in 3 h, having minimal k/s ratio (0.117) and therefore providing an optimal bleaching process. At 90 °C, efficiency dropped quickly after 1 h, having high k/s ratios, which means peroxide decomposition and decrease in brightness (Table 3). These findings are supported by other research on peroxide bleaching of deinked pulp done in one stage, which underscores the importance of moderate temperatures and durations of reaction. For example, according to Dence and Reeve, peroxide bleaching is most efficient between 60–70 °C because maximum perhydroxyl anion activity is achieved while minimizing the degradation of peroxide decomposition.[2] In addition, McKinney showed that bleaching duration of more than 2 to 3 hours yields no further benefits, but causes losses of yield.[43] Furthermore, according to Göttsching and Pakarinen, peroxide bleaching becomes inefficient at temperatures above 80 °C because of rapid peroxide degradation

and darkening due to alkalinity, just as it happens in this study at 90 °C.[3]

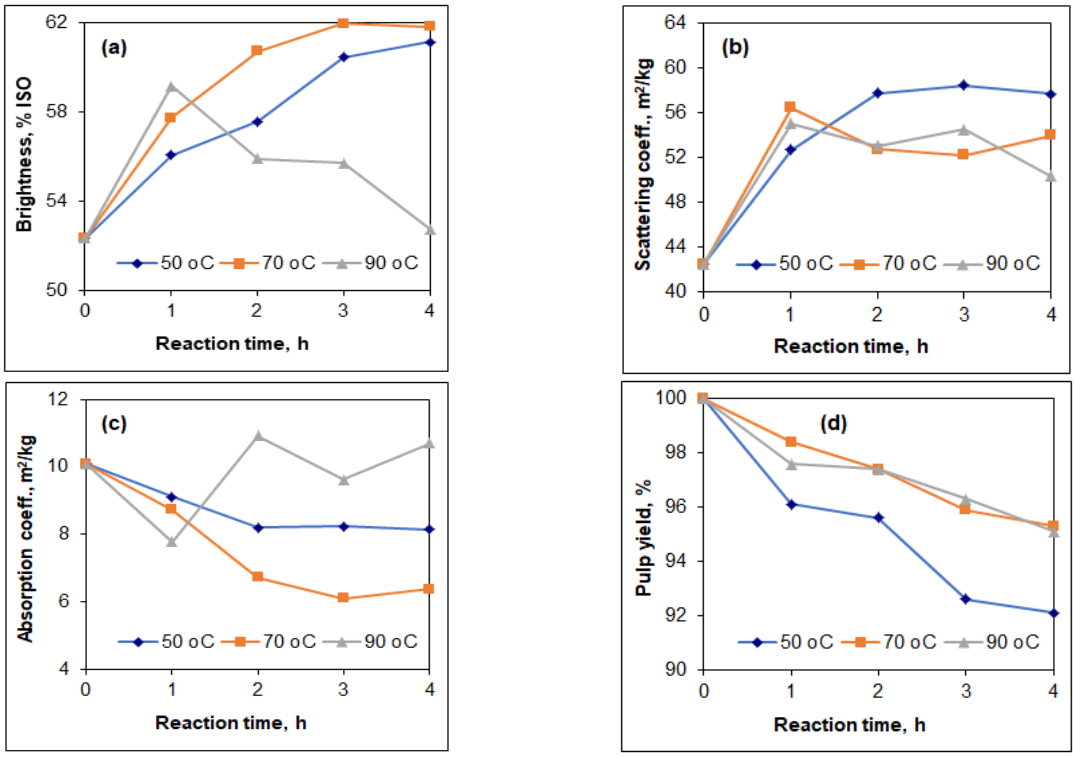


Figure 4: Effects of temperature and reaction time during bleaching on optical properties and pulp yield

Table 3
Effects of temperature and reaction time on bleaching efficiency and k/s ratio

| Temperature, °C | Retention time, h | Bleaching efficiency | k/s ratio |
|---|---|---|---|
| 50 | 1 | 2.01 | 0.173 |
| | 2 | 2.72 | 0.142 |
| | 3 | 4.33 | 0.141 |
| | 4 | 4.62 | 0.141 |
| 70 | 1 | 3.05 | 0.155 |
| | 2 | 4.71 | 0.128 |
| | 3 | 5.39 | 0.117 |
| | 4 | 5.30 | 0.118 |
| 90 | 1 | 3.75 | 0.141 |
| | 2 | 1.92 | 0.173 |
| | 3 | 1.79 | 0.177 |
| | 4 | 0.22 | 0.213 |

Constant conditions: 2.00% $H_2O_2$, 1.50% NaOH, 3.00% sodium silicate; 10.00% consistency

In an experimental study on a wastepaper pulp mixture of 50.00% old corrugated cartons, 30.00% newsprint, and 20.00% kraft paper, bleaching experiments were done at various temperatures (30, 40, 50, 60, and 66 °C). The other conditions remained constant: 2.00% hydrogen peroxide, 0.10% sodium hydroxide, 1.50% sodium silicate, 8.00% consistency, and 60 minutes retention. The pulp brightness obtained was 49.10, 50.10, 50.93, 51.63, and 51.70% ISO, respectively. From the results, it is evident that the brightness increased as the temperature was raised and its optimum reached at 60 °C. Temperatures below 60 °C had an inadequate bleaching effect, while those above 60 °C resulted in rapid decomposition of peroxide, thus low efficiency. As seen from the negligible

increase in brightness at temperatures above 60 °C (less than 0.10%), 60 °C was the most efficient temperature for bleaching.[45] In another experiment, bleaching of wastepaper pulp with peroxide was done with 2.00% hydrogen peroxide, 0.10% sodium hydroxide, 1.50% sodium silicate, 50 °C, 8.00% consistency, and retention times of 50–90 minutes. The brightness values obtained were 50.02, 50.93, 51.17, 51.26, and 51.33% ISO, respectively. It was observed that bleaching time is directly proportional to brightness; however, after 70 minutes of bleaching, the increase is minimal. This is due to the low availability of chromophores that can be removed and the decrease in peroxide over time, which results in slowing down of the bleaching process. So, 70 minutes was taken as optimum bleaching time because after that there is no significant difference.[5] Newsprint deinked pulp with a brightness of 51.75% ISO was bleached using hydrogen peroxide at 0.50–2.00%. The bleaching was done at different consistencies of pulps (15.00–20.00%), different temperatures (60–80 °C), and reaction times (20–60 minutes). The chemical formulation for bleaching consisted of 1.00% sodium hydroxide, 5.00% sodium silicate, and 0.05% magnesium sulfate based on oven-dry weight of pulp. The increase in temperature from 60 °C to 80 °C increased the bleaching efficiency, giving increased brightness at both consistencies.[17,40,46] The reaction time had a smaller, but positive influence, with the best results achieved after 60 minutes.[40,47]

Together, these studies support the conclusion that 70 °C for 2–3 hours represents an optimum condition for DIP peroxide bleaching, balancing brightness improvement, chemical efficiency, and pulp yield. Having established 70 °C and 3 h retention as the optimum temperature–time combination, the effect of pulp consistency during bleaching was examined next, using the same 2.00% peroxide charge together with the previously optimized alkali and silicate levels, to determine how the concentration of the fibre suspension influences chemical contact and mixing efficiency.

**Effects of peroxide dosage on bleaching at different consistencies**

The consistency was varied from 6.00% to 12.00%, while all other parameters were kept constant at 2.00% $H_2O_2$, 3.00% sodium silicate, 1.50% NaOH, temperature of 70 °C, and retention time of 3 h. The data presented in Figure 5 show how peroxide dose and pulp consistency interact to produce bleaching effects. At a consistency of 6.00%, there was a regular rise in brightness when peroxide dose increased from 1.00% (53.23% ISO) to 4.00% (64.89% ISO). There was a substantial decrease in the absorption coefficient (from 11.00 to 4.70 m²/kg), which confirmed an effective removal of chromophores. However, pulp yield became much lower (from 97.80% to 91.80%), which is typical of stronger chemical action at higher peroxide doses.

At a consistency of 10.00%, the same effect was observed with somewhat better results: brightness increased from 55.99% ISO (at 1.00%) to 65.02% ISO (at 4.00%). The increase in the scattering coefficients (from 47.49 to 59.94 m²/kg) and the decrease in the absorption coefficient (from 8.08 to 5.55 m²/kg) showed an improvement in optical characteristics in comparison with lower consistency pulp. Pulp yield losses remained relatively small (from 96.90% to 95.20%), which means medium consistency provides a favourable balance between brightness improvement and preservation of pulp yield.

Where peroxide consumption was the highest (>92.00%) at 12.00% consistency, brightness increase was lower. At 4.00% peroxide, the maximum brightness reached ~58.60% ISO with high absorption coefficient (from 7.52 to 8.91 m²/kg). Pulp yields were still high (>97.00%), indicating low fibre degradation, but also low efficiency of peroxide treatment. Optimum results were obtained at 10.00% consistency with 3.00–4.00% peroxide, where brightness was >65.00% ISO with good scattering capacity and moderate pulp yield reduction.

The findings are consistent with the literature reporting that the best bleaching efficiency of DIP is observed at medium consistencies (8.00–12.00%). As reported by Göttsching and Pakarinen, high consistency could limit chemical penetration, thereby reducing brightness increase, despite high peroxide consumption.[3] Additionally, according to Fišerová *et al*., over-dosage resulted in high chemical consumption with poor brightness increase.[26] These findings align with the present results, confirming that 10.00% consistency at moderate peroxide charges offers the best efficiency. However, deinked newsprint pulp (51.75% ISO brightness) was bleached with hydrogen peroxide (0.50–2.00%) under varying conditions of consistency (15.00–20.00%), temperature (60–80 °C), and reaction time (20–60 min). The bleaching mixture also contained 1.00% NaOH, 5.00% sodium silicate, and 0.05%

magnesium sulfate, based on oven-dry pulp. At higher consistency, brightness improved further because bleaching chemicals were more concentrated and in closer contact with fibres, although mixing issues arise above 20.00%.[40,47]

With 10.00% consistency confirmed as the most favourable operating point, the final series of trials examined sodium silicate dosage, the stabilizer responsible for buffering alkalinity, dispersing residual ink, and protecting peroxide from metal-catalyzed decomposition throughout the preceding series of trials.

**Effects of sodium silicate dosage during bleaching**

The sodium silicate dose was varied from 1.00% to 3.00%, while the other conditions were maintained constant at 2.00% $H_2O_2$, 1.50% NaOH, 70 °C temperature, 3 h retention time and 10.00% consistency. The results in Figure 6 show the effect of sodium silicate dosage on peroxide bleaching of recycled deinked pulp. At 0.00% silicate, brightness was 56.49% ISO with a scattering coefficient of 47.58 m²/kg and an absorption coefficient of 10.28 m²/kg. Pulp yield was highest (99.24%), but peroxide consumption was lower, reflecting peroxide instability and reduced bleaching efficiency without stabilization.

There was increase in brightness of 58.32% ISO, scattering coefficient increased to 51.63 m²/kg, while absorption coefficient decreased to 8.91 m²/kg in the presence of 1.00% silicate. There is slight reduction in pulp yield, which stands at 98.76%, showing that there is some solubilization of fines in the stabilized condition. In the presence of 2.00% silicate, there was an increase in brightness of 60.10% ISO, the absorption coefficient decreased to 6.55 m²/kg.

The maximum effect was obtained from the use of 3.00% silicate, when there was an increase in brightness of 61.95% ISO, and the absorption coefficient was minimum (6.11 m²/kg). The slight reduction in pulp yield was 97.99%, but the presence of high peroxide utilization (94.49%), together with good optical properties, indicate the importance of sodium silicate in the stabilization of peroxide. Bleaching effectiveness increased progressively with increasing sodium silicate from 2.29 at 0.00% to 5.17 at 3.00%, while the k/s value fell from 0.216 to 0.117, meaning that peroxide was stabilized and less light was absorbed.

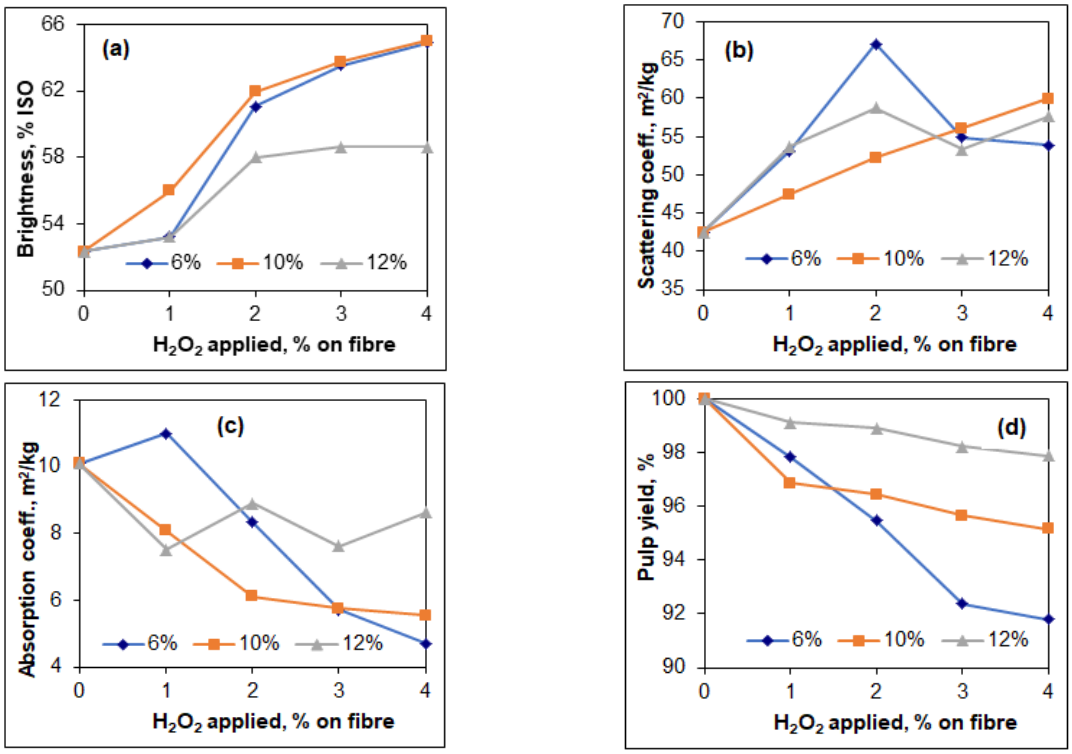


Figure 5: Effects of peroxide dose at varying consistency during bleaching on optical properties and pulp yield

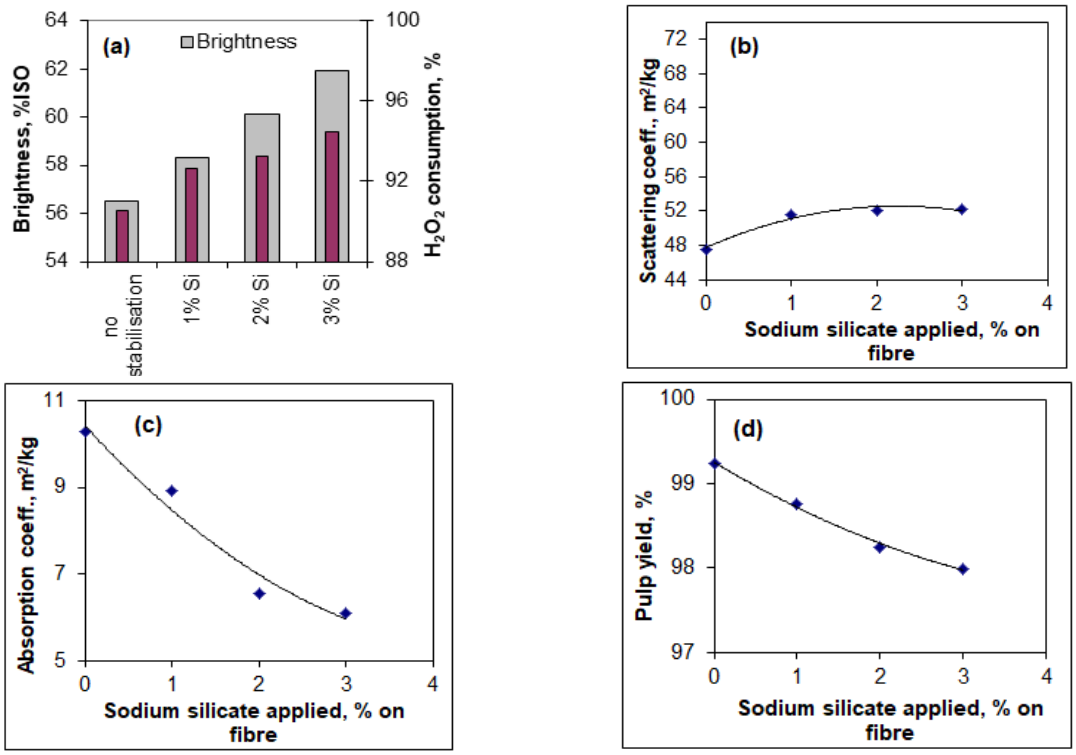


Figure 6: Effects of sodium silicate dosage during bleaching on optical properties and pulp yield

Table 4
Effects of sodium silicate dosage on bleaching efficiency and k/s ratio

| Sodium silicate applied, % | Bleaching efficiency | k/s ratio |
|---|---|---|
| 0.00 | 2.29 | 0.216 |
| 1.00 | 3.23 | 0.173 |
| 2.00 | 4.16 | 0.126 |
| 3.00 | 5.17 | 0.117 |

Constant conditions: 2.00% $H_2O_2$, 1.50% NaOH, 70 °C temperature, 10.00% consistency, 3 h retention time

Consequently, sodium silicate is very important for the stabilization of peroxide bleaching reaction, prevention of reversion, and optimization of brightness in about 3.00% dosage (Table 4). These results are consistent with other works on the role of silicate in peroxide bleaching of recycled fibres. Sridhar stated that the addition of sodium silicate not only stabilizes peroxide, but also helps remove ink residues, which leads to increasing brightness and scattering and decreasing absorption.[30] Göttsching and Pakarinen have indicated that the addition of silicate in the amount of 1.00–3.00% o.d. pulp gives the best result, while higher doses result either in reduced effect or in problems such as scaling.[3] The results of more recent research by Hämäläinen *et al*. and Liu *et al.* proved that silicate acts not only as a stabilizer, but also improves optical properties through better removal of ink.[8,11] In general, the current results prove that the optimal dose of sodium silicate is 3.00%.

## CONCLUSION

The results showed that the bleaching effect of hydrogen peroxide on the recycled deinked pulp was significantly affected by the dose of chemicals, process conditions, and pulp consistency. The increase in the dose of hydrogen peroxide resulted in an improvement in brightness and decrease in absorption, although the effectiveness of bleaching reduced when the dose exceeded 3.00–4.00%, since higher doses resulted in yield losses due to increased solubility of fibres. The dose of sodium hydroxide was one of the key factors for activating the peroxide. Optimal results were observed at 1.50–2.00% NaOH, where maximum brightness and minimum absorption were observed. Excess alkali resulted in the

decomposition of peroxide and a darkening effect, thus decreasing the efficiency of bleaching. The effects of temperature and retention time on bleaching efficiency showed that the most effective parameters were 70 °C with 2–3 h retention time, which provided high brightness and yield without much losses. Lower temperatures required higher retention times, and higher temperatures resulted in rapid decomposition of hydrogen peroxide and brightness reversal. The effect of pulp consistency indicated that medium consistency (10.00%) was optimal in terms of brightness gain, scattering, and pulp yield; at low consistency, peroxide demand increased; conversely, at high consistency, poor distribution of chemicals throughout the pulp limited bleaching effectiveness. Finally, the addition of sodium silicate at 2.00–3.00% stabilized peroxide, improved ink dispersion, and enhanced scattering, leading to higher brightness compared to silicate-free systems. Overall, optimal bleaching performance was achieved under carefully balanced chemical and process conditions.

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