# Evaluating Paper's Optical Properties after Separate and Combined Use of Nanofibrillated Cellulose with Cationic Starch and Cationic Polyacrylamide

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Nanofibrillated cellulose (NFC) and its combined usage with cationic starch and a cationic copolymer of acrylamide were studied in relation to the properties of paper. Independent pulp treatments using additives separately included 0%, 5%, 10%, and 15% refined long fiber pulp, 3 and 6% NFC, 0.75 and 1.5% cationic starch and 0.07% and 0.15% cationic polyacrylamide and combined treatments. Handsheets were made of the above treatments, and finally their optical and microscopic properties were evaluated. Increasing the NFC content to 6% increased the brightness and yellowness of the white liner by 13% and 21%, respectively. The liner opacity was also reduced by 1%. Additionally, increasing NFC by 6% compared to imported long fibers, the brightness and yellowness of the white liner increased 5.44% and 6.3%, respectively. The liner opacity was also reduced by 1%. A 1.5% cationic starch addition to NFC increased the brightness of the white liner by 4.4%, its whiteness increased 1.5%, and its yellowness increased 2.1%. The opacity of the liner was also reduced by 7.1%. The use of NFC and cationic starch can improve the optical properties of the white liner, while imported long fibers may be problematic.

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## INTRODUCTION

Waste paper recycling is a crucial industry globally and in Iran, offers environmental and human advantages. It enables the reuse of resources, reduces costs, and expands applications. By recycling waste paper, it is possible to conserve natural resources, to mitigate deforestation and groundwater depletion, and to minimize air, water, and soil pollution. The energy and water-efficient recycling process contributes to a sustainable and eco-friendly paper production cycle. Waste paper recycling offers substantial economic benefits by reducing production costs and generating employment opportunities in paper collection, recycling, and production sectors.

The recycling of small paper pieces is crucial, necessitating the development of suitable collection programs and systems. Overall, waste paper recycling has environmental, economic, and societal benefits, and its advancement should be prioritized. However, the recycling process may lead to a reduction in the quality and strength properties of the product, particularly in packaging paper, which relies heavily on waste paper and recycled fibers as raw materials (Vaysi and Vaghari 2021).

Unfortunately, in the paper recycling process, the initial properties and quality of waste paper may be inferior, and this can have a negative impact on the properties of the final product. For example, the optical properties of the paper, such as the brightness and transparency, can be low, and the strength of the paper relative to stress and tearing may fail to meet grade requirements.

However, quality improvement methods can be used to solve these problems. Selecting high-quality recycled materials, improving recycling processes, optimizing formulations, and using advanced technologies can be helpful. Further, in the packaging industry, the use of additives and strengthening methods can significantly improve the strength and quality of recycled paper.

Finally, paying attention to the research and development of new technologies in the field of paper recycling and improving production processes can help minimize the problems of reducing the quality and properties of recycled products and increase the use of recycled paper in the packaging industry.

In numerous studies, cationic starch is commonly utilized due to its beneficial effects and cost-effectiveness. Cationic starch functions by binding to fibers through electrostatic forces, thereby enhancing the cohesion among negatively charged fibers. Additionally, cationic starch forms hydrogen bonds with the fibers. As a result, the combination of electrostatic interactions and hydrogen bonding facilitated by cationic starch improves the adhesion between fibers and overall material properties. This renders cationic starch a valuable and cost-effective additive for various applications that require enhanced fiber bonding and strength (Wang *et al*. 2018).

Currently, the paper industry uses commercially available dry strength agents, such as cationic starch and polyacrylamide, to improve the strength properties of paper (Glittenberg and Tippett 2005). Heermann *et al*. (2006) stated that cationic starch acts as an adhesive and establishes bonds between the parts in the paper structure. The study results of Vaysi and Vaghari (2021) showed that increasing the strength of each unit of bonding surface by cationic starch improves physical properties, especially paper strength. Moreover, when these fibers are combined with recycled fibers, product quality is improved in the paper recycling process (Vaysi and Vaghari 2021). Various studies have been conducted in the field of using cationic materials along with nanoparticles (Svedberg 2007; Khosravani 2009).

Recent studies have shown that the use of cationic materials in the paper industry can significantly improve the strength properties and quality of paper. These materials cause the structural bonding of paper and strengthen the physical strength of paper. The addition of recycled fibers to cationic materials can improve the quality of recycled paper. Meanwhile, the use of nanoparticles in this process provides the possibility of improving the final properties of the paper. In short, the use of cationic materials and nanoparticles in the paper industry can lead to a significant improvement in the strength properties and quality of paper, which can improve the paper recycling process and promote the use of recycled resources (Hosseini *et al*. 2022).

Polyacrylamide, as a class of the water-soluble polymers and copolymers with high molecular mass, is used in the paper industry as a dry strength resin. Through forming more hydrogen bonds between fibers, in the final part of the process, this resin improves the durability of fibers, softeners, fillers, and fine particles, and as a result, it can increase the strength of the resulting paper. Additionally, the use of this resin can help prevent waste of materials and reduce paper production costs (Ebrahimpour Kasmani *et al*. 2022).

Recently, nanocellulose preparations have also been considered as environmentally friendly additives for various uses, including paper and cardboard industries (Najideh *et al*. 2021). Because of its anionic nature and high specific surface area, nanofibrillated cellulose (NFC) has shown a positive effect in combination with biopolymers, such as starch and chitosan, on fiber suspensions. NFC, due to the increase in the specific surface area, increase the possibility of bonding with the surfaces of ordinary fibers, and are usually used as reinforcements of the physical and mechanical properties of paper for the production of paper and cardboard (Mamizadeh and Ebrahimpour Kasmani 2018).

The nanomaterials, especially NFC, as well as new research methods and approaches, are being used to improve the properties of paper. This trend has included the usage of a high molecular weight cationic acrylamide copolymer as a dry strength resin. This resin, in the final part of the process, by forming more hydrogen bonds between the fibers, can contribute to the improvement of the durability of the fibers, softeners, fillers, and fine particles. Thus it can increase the strength properties of pulp. Further, the use of this resin can prevent waste of materials and reduce production costs. However, the use of NFC on a commercial scale faces challenges, including high costs, low dispersibility, low durability, possible adverse interactions, and lack of sufficient knowledge in the field of optimal use of these nanomaterials (Ebrahimpour Kasmani *et al*. 2021).

The appearance of paper can be characterized by its opacity, brightness, color, fluorescent properties, gloss, and other factors related to its uniformity. The optical properties of paper, particularly its ability to scatter and absorb visible light, are closely tied to the paper's structure and chemical composition. These factors play a significant role in determining how light interacts with the paper and contribute to its overall visual properties (Hubbe *et al*. 2008).

To improve the contact between the fibers and increase the strength properties of the products, various methods are used, including higher refining, addition of virgin fibers, and the use of cationic additives to improve the strength and optical and physical properties of paper (Ghasemian and Khalili 2011).

The cardboard recycling industry plays an important role in developing paper-related industries from an environmental and economic point of view, due to the lack of primary wood sources and the increase in demand for paper and cardboard products. However, paper recycling is associated with a reduction in optical properties. In addition, importing pulp containing long fibers due to the lack of commercial coniferous forests in Iran should be considered.

According to the above, it is expected that using NFC separately or in combination with cationic starch and polyacrylamide, in addition to reducing the use of long fibers, can simultaneously improve the desired and required optical properties. Therefore, the objective of this study was to investigate understanding an NFC implementation to paper product for its selective properties.

## EXPERIMENTAL

### Materials

*Pulp*

To supply white pulp, 10 kg of pulp with at least 78% brightness and 45% glossiness was prepared at the Atrak paper factory. Chemical pulp containing long fibers of kraft softwood pulp imported from Russia with 89% brightness was prepared and transported to the laboratory. The prepared pulp was dewatered to a concentration of 10% to 15% and then packed in plastic bags.

## Nanofibrillated Cellulose

In this study, NFC was produced from unadulterated commercial cellulose fibers obtained from softwood. The starting cellulose material was sourced from Nano Novin Polymer Co in Gorgan, Iran. Three different levels of NFC were used: 0%, 3%, and 6% based on the dry weight of the pulp and paper.

To obtain the NFC, long fiber α-cellulose material underwent a super-grinding method. The process involved rinsing the α-cellulose material with distilled water, followed by treatment in a 5% potassium hydroxide (KOH) solution under mechanical mixing at 80 °C for 1 hour. Subsequently, a 1% consistency α-cellulose suspension was prepared and subjected to multiple passes through a super-grinding disk machine (MKCA6-3; Masuko Sangyo Co., Ltd., Kawaguchi, Japan). The super-grinding disk machine consisted of a static and rotating processor disc, with a SiC grinding stone of 6 inches in diameter. The grinding process occurred at a speed of 1800 rpm, with a grinding throughput of 40 g/hour. The energy consumption of the processor was 25 kWh/kg. The resulting NFC was obtained in the form of a hydrogel.

## Cationic Starch

Cationic starch was prepared from potato starch produced by Lyckeby Amylex Company (Slovakia). The cationic starch used had the following properties: pH of approximately 6, degree of substitution (DS) of approximately 0.035 mol/mol, protein content of 1.5%, nitrogen content of 0.25%, and moisture content of 10% based on fresh weight. To prepare starch solution at a concentration of 0.5 g, the required amount of impure starch was determined by considering moisture content. The desired amount was placed in an Erlenmeyer flask and its volume was made up to 100 mL using distilled water. During stirring, the temperature inside the Erlenmeyer flask was monitored using a thermometer, and a sheet of foil was placed on the Erlenmeyer lid to prevent water evaporation. The Erlenmeyer flask was placed on the heater and the temperature slowly increased to 90 °C for 30 min and then kept at this temperature for 30 min. Fresh starch solution was prepared and used every day to avoid changes in viscosity and concentration caused by environmental effects.

## Polyacrylamide

Cationic polyacrylamide (Farinret K325) was purchased from Degussa (Germany). The product is used in the paper industry. This polyelectrolyte is based on acrylic polymers and has a high molecular weight and medium cationic charge. Given the proprietary nature of the product, the manufacturing company has provided limited information on molecular weight and ionic charge, limiting itself to terms such as low, medium, and high. A 1% solution based on the percentage purity of cationic polyacrylamide was prepared using distilled water. Then, 1.0 mL of this solution was added to a 100-mL flask of distilled water and mixed using a magnetic stirrer for 3 h. Then, the reaction content was placed in the refrigerator for 24 h. Next, the volume of the solution was increased 100 mL using distilled water and stirred again for 20 min at a concentration of 0.1%.

### Preparation of Handsheets

After the initial preparation of white pulp, long fiber pulp, and additives as described above, handsheets corresponding to 14 treatment conditions were prepared according to Table 1.

**Table 1.** Composition of the Treatments and the Amounts of Lignocellulosic Nanofibers, and Cationic Starch and Polyacrylamide

| No. | Code | White liner | Long Fiber Pulp | Cellulose Nanofibers | Cationic Polyacryl-amide | Cationic Starch |
|---|---|---|---|---|---|---|
| 1 | 0LF | 100 | 0 | 0 | 0 | 0 |
| 2 | 5LF | 95 | 5 | 0 | 0 | 0 |
| 3 | 10LF | 90 | 10 | 0 | 0 | 0 |
| 4 | 15LF | 85 | 15 | 0 | 0 | 0 |
| 5 | 0.75CS | 99.25 | 0 | 0 | 0 | 0.75 |
| 6 | 1.5CS | 98.5 | 0 | 0 | 0 | 1.5 |
| 7 | 3NC | 97 | 0 | 3 | 0 | 0 |
| 8 | 6NC | 94 | 0 | 6 | 0 | 0 |
| 9 | 3NC+1.5CS | 95.5 | 0 | 3 | 0 | 1.5 |
| 10 | 6NC+1.5CS | 92.5 | 0 | 6 | 0 | 1.5 |
| 11 | 0.07CPAM | 99.93 | 0 | 0 | 0.07 | 0 |
| 12 | 0.15CPAM | 99.85 | 0 | 0 | 0.15 | 0 |
| 13 | 3NC +0.15CPAM | 96.85 | 0 | 3 | 0.15 | 0 |
| 14 | 6NC +0.15CPAM | 93.85 | 0 | 6 | 0.15 | 0 |

Handsheets with a basis weight of 127 g/m$^2$ were made according to the SCAN C-26:67 using a KCL handsheet maker, INDIA, DELHI. Ten handsheets were made from each treatment.

### Measurement of Paper Properties

A spectrophotometer was used to measure the optical properties of paper products. The colors were expressed using the CIELab system. The performance is based on diffuse reflection from the studied surface. Optical properties including $L^*$, $a^*$, and $b^*$, light absorption coefficient ($K$), and light scattering coefficient ($S$) were determined according to INSO 20747-4. The wavelength of light was at 457 nm. The brightness, whiteness, and opacity were determined according to ASTM D- 2244.

### Microscopic Studies

The surfaces of the produced papers were examined with the field emission electron microscope MIRA3TESCAN-XMU (Czech Republic) in the Razi Metallurgical Research Institute.

### Statistical Analysis

A completely randomized experimental design was used for the statistical analysis of the data. The one-way analysis of variance (ANOVA) was used for the analysis. To statistically group the mean values, Duncan's test was used at a statistical confidence level of 95% using SPSS.

## RESULTS AND DISCUSSION

According to the data provided, Table 2 shows a significant difference between the properties of handsheets. At the 95% confidence level, the effect of additives on lightness, whiteness, opacity, *K*, *S*, *L**, *a**, and *b** was significant. It can be said that the additives used to produce handsheets had a significant effect on the optical and color properties of the papers. These differences were shown to be significant in the results of ANOVA.

**Table 2.** Analysis of Variance (F Value and Significance Level) of the Effect of Treatments on the Properties of Handsheets

| Properties of Paper | Brightness (%) | Whiteness (CIE) | Opacity (%) | Light Absorption Coefficient ($m^2/g$) | Light Scattering Coefficient ($m^2/g$) | *L** | *a** | *b** |
|---|---|---|---|---|---|---|---|---|
| F value | 3.15* | 1273.23* | 89.28* | 224.29* | 19.88* | 5239806.46* | 84198268.84* | 11081646.46* |

*Significant at the 95% confidence level
ns not significant at the 95% confidence level

### Effects of Paper Production Variables on the Handsheets Brightness

Figure 1 shows the trend of changes in the paper samples. The mean brightness was divided into 4 separate groups based on Duncan's grouping. The highest brightness (96.6%) was related to samples containing 3% NFC and 1.5% cationic starch. These samples were in Group D. The lowest brightness (85.9%) was related to the samples containing 1.5% cationic starch and 10% long fibers. These samples were in Group A. According to the results, paper variables, such as fiber type and amount of cationic starch, had a significant effect on the brightness of handsheets.

Using NFC in papers can improve their optical properties (Mirshokraei 2007). However, the extent of these changes depends on the structure of the paper, the size, and surface of the filler. Such variables can affect the amount of light scattering.

The brightness of the paper depends on the brightness of pulp raw materials, the pH of pulp, the type, and amount of additives (Afra *et al*. 2015). The results of brightness tests showed that increasing the amount of cationic starch and long fibers did not cause a significant change in brightness. However, by increasing the amount of NFC and polyacrylamide, the brightness increased somewhat. In short, the use of these materials led to the change and improvement of the optical properties of paper (Hosseini *et al*. 2017).

Through adding NFC to the paper network and changing its structure, the intercellular spaces became filled and the contact between the fibers was increased, which led to an increase in light transmission through the paper. In general, the presence of NFC in the paper structure led to the development and improvement of inter-fiber contact, the reduction in pores, and the reduction of surface roughness. These effects tend to reduce light scattering, which decreases the brightness of the paper (Pourkarim Dodangeh *et al*.

2021). Increasing the presence of NFC in the structure of the paper leads to the development of the bond surface. Also, the high brightness of the NFC is another reason for increasing the brightness of paper (Hosseini *et al*. 2017).

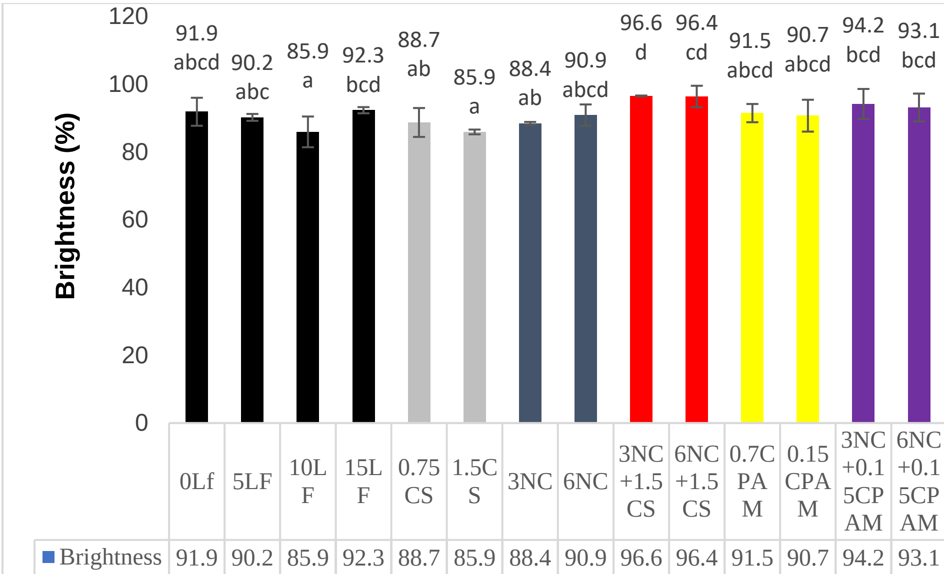



**Fig. 1.** Mean comparison of brightness of handsheets and their grouping

## Effects of Paper Production Variables on the Whiteness of Handsheets

Figure 2 shows the trend of changes in the whiteness of paper samples. The mean whiteness was divided into 12 separate groups based on Duncan's grouping. The highest whiteness (159.6%) was related to the samples containing 0.15% polyacrylamide. These samples are in Group l. The lowest whiteness (85.6%) was related to the samples containing 0.07% cationic polyacrylamide. These samples are in Group A. According to the results, paper variables, such as the type and amount of polyacrylamide had a significant effect on the whiteness of handsheets.

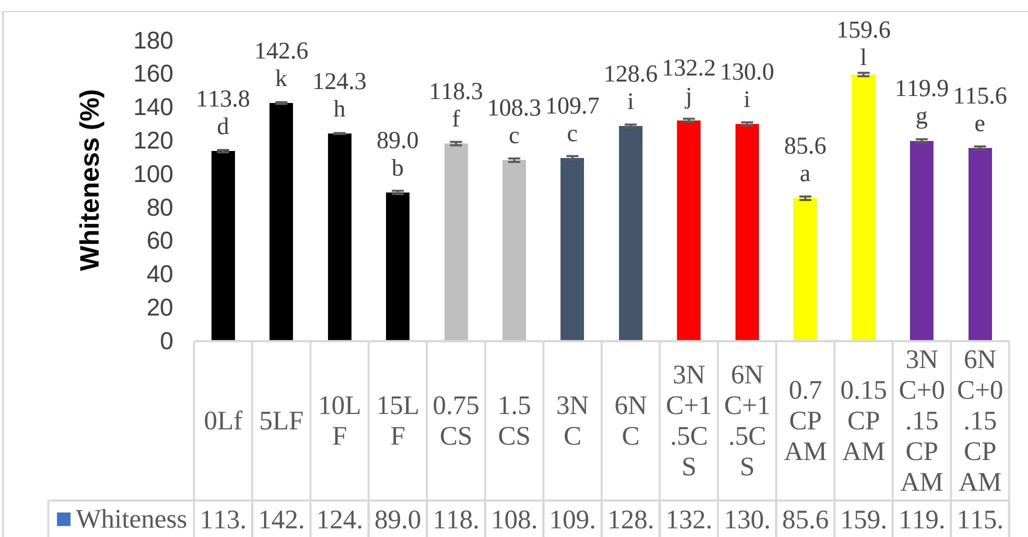



**Fig. 2.** Mean comparison of whiteness of handsheets and their grouping

The whiteness of the paper is caused by the reflection at all wavelengths, but the total reflection depends on various factors. Studies have shown that the amount of diffuse reflection depends on the light scattering coefficient in the base paper and the structure of the materials used. Other factors, such as particle size, particle size distribution, and particle morphology, also affect this. Adding cationic polyacrylamide and cationic starch to the composition of NFC leads to an increase in the whiteness of paper.

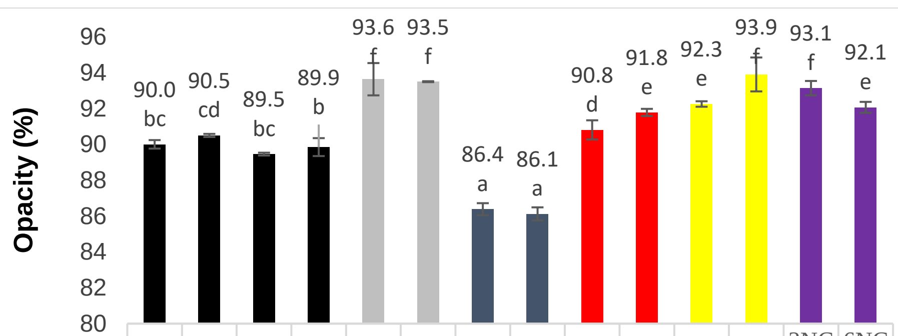
## Effects of Paper Production Variables on the Opacity of Handsheets

Figure 3 shows the trend of changes in opacity of paper samples. The mean opacity was divided into 6 separate groups based on Duncan's grouping. The highest opacity (93.9%) was related to the samples containing 0.15% polyacrylamide. These samples were in Group F. The lowest opacity (86.1%) was related to samples containing 6% NFC. These samples were in Group A. According to the results, paper variables, such as the type of additives like polyacrylamide and cellulose nanofibers, had a significant effect on the opacity of handsheets.

Studies have shown that adding NFC to the composition reduces the opacity of the paper. The factors affecting the opacity include fiber spacing, paper structure, fiber type, amount of fine and short fibers, and amount of filler. The opacity of paper depends on the transmission of light. The smaller the area of close contact between the fibers, the more surface area is in contact with air, and this unbonded surface causes higher light scattering coefficient.

Through adding NFC to the paper network, the opacity is reduced due to the increase in the contact between the fibers. When the optical contact surface is increased, the light passes through the paper with less refraction, which results in a reduction in the opacity of the paper.

The opacity is one of the most important properties of paper, which directly depends on the bulk value and the light scattering coefficient (Sodeifi *et al*. 2019). The light scattering coefficient also depends on the structure, especially the micro-spaces on the surface of the coating layer. The opacity of paper is a property of paper that prevents light from passing through it and depends on factors, such as base weight, light absorption coefficient, and light scattering coefficient of paper (Afra *et al*. 2015).




| | 0Lf | 5LF | 10LF | 15LF | 0.75CS | 1.5CS | 3NC | 6NC | 3NC+1.5CS | 6NC+1.5CS | 0.7CPAM | 0.15CPAM | 3NC+0.15CPAM | 6NC+0.15CPAM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Opacity | 90.0 | 90.5 | 89.5 | 89.9 | 93.6 | 93.5 | 86.4 | 86.1 | 90.8 | 91.8 | 92.3 | 93.9 | 93.1 | 92.1 |

**Fig. 3.** Mean comparison of opacity of handsheets and their grouping

## Effects of Paper Production Variables on Light Absorption Coefficient of Handsheets

Figure 4 shows the trend of changes in light absorption coefficient of paper samples. The mean light absorption coefficient was divided into 7 separate groups based on Duncan's grouping. The highest light absorption coefficient (2.17) was related to samples containing 0.15% polyacrylamide. These samples were in Group G. The lowest light absorption coefficient (0.76) was related to the samples containing 6% cellulose nanofibers. These samples were in Group A. According to the results, paper production variables, such as additives like polyacrylamide and NFC had a significant effect on light absorption coefficient of handsheets.

In this study, adding cationic starch and polyacrylamide led to an increase in the light scattering coefficient of paper and significantly increased the opacity of the paper. Further, addition of NFC to the paper network, reduced the opacity of the samples compared to the control paper, which was also due to the increase in the contact between the fibers. Hence, papers in combination with cationic cellulose-polyacrylamide nanofibers or cellulose-starch nanofibers acheived higher opacity, and the positive effect of polyacrylamide and cationic starch on increasing this property was observed.

The light absorption coefficient of paper depends on the chemical composition of pulp and especially color compounds such as lignin and dyes. Moreover, filler materials affect the light absorption coefficient of paper according to their light absorption coefficient. In general, the increase in the light absorption coefficient of papers containing cationic polyacrylamide may be due to the increase in light absorbing groups such as the oxidation of coloring groups (Afra *et al*. 2015).

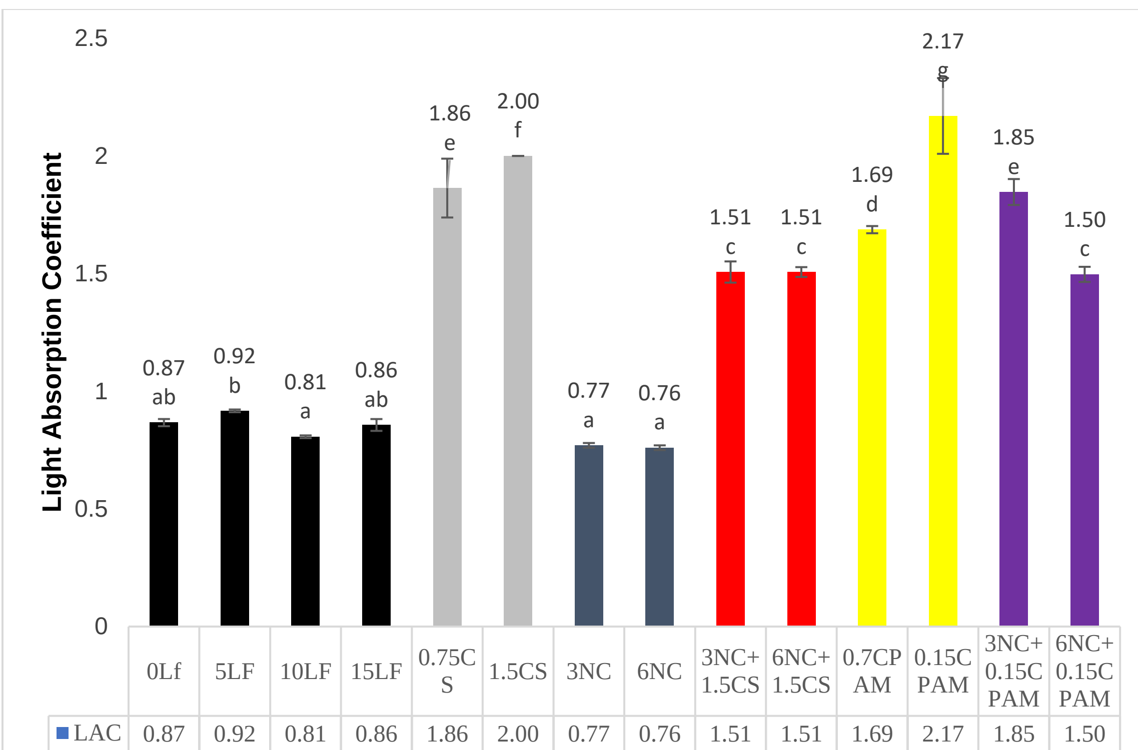



**Fig. 4.** Mean comparison of light absorption coefficient of handsheets and their grouping

## Effects of Paper Production Variables on Light Scattering Coefficient of Handsheets

Figure 5 shows the trend of light scattering coefficient changes for paper samples. Averages of light scattering coefficient are divided into 6 separate groups based on Duncan's grouping. The highest light scattering coefficient (65.5%) was related to samples containing 0.75% of cationic starch. These samples were in Group F. The lowest light scattering coefficient (49.2%) was related to the samples containing 6% of NFC. These samples were in Group A.

The light scattering coefficient depends on several factors, including the contact surface between fibers, softness of fibers and filler materials, and fibers per unit weight. However, the greatest effect is the relative contact surface between fibers. In other words, when the contact between the fibers increases, due to the relative reduction in the surface area of the fibers, the light scattering coefficient also reduces. Excessive use of NFC leads to an increase in the contact between the fibers and as a result the relative reduction in the unbonded surface of the fibers, which reduces the light scattering coefficient.

The light scattering coefficient depends on the non-connected surface of fibers and/or paper bulk. In contrast, the light absorption coefficient directly depends on the concentration of light-absorbing coloring groups or the types and amounts of residual lignin. The reason for the reduction in the light absorption coefficient may be due to the reduction in the light absorbing groups such as the oxidation of the coloring groups (Kajforush and Resalati 2012). Additionally, the reduction in the *a** and *b** may be due to partial destruction of attached carbonyl groups and quinoid structures, respectively (Chen *et al*. 2012).

Furthermore, adding nano particles to paper can fill the gap between the fibers and thus reduce the light scattering coefficient of handsheets (Wu *et al*. 2021).

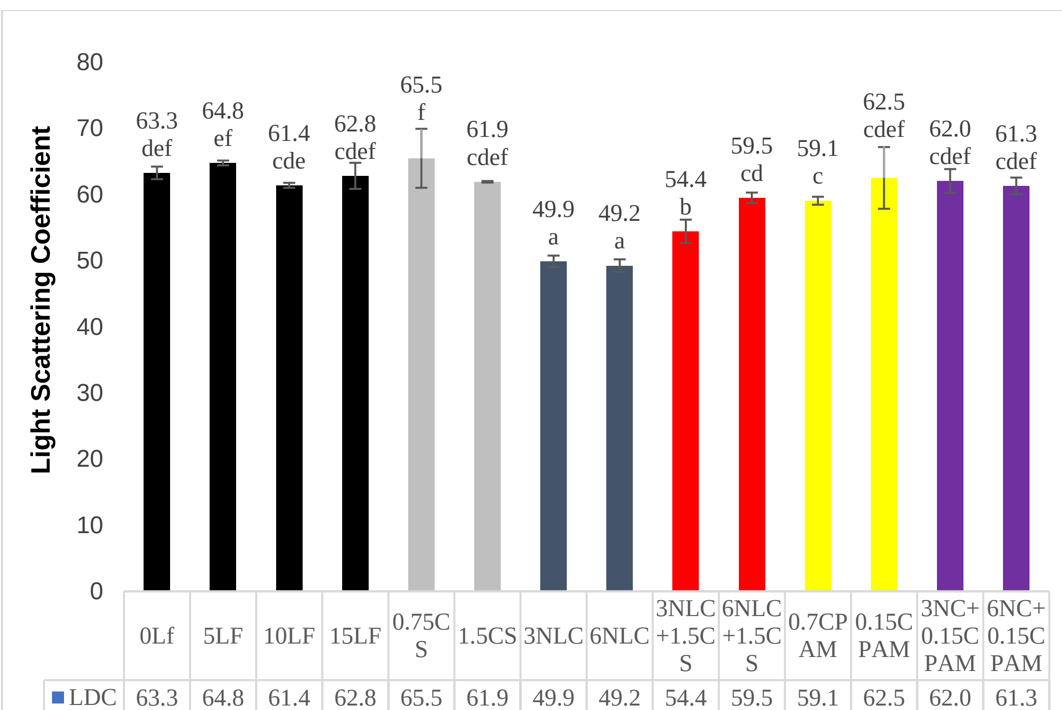



**Fig. 5.** Mean comparison of light scattering coefficient of handsheets and their grouping

Table 3 shows the results of measuring the color components *L**, *a**, and *b** for paper samples. The CIE system was used for the measurement of color.

Table 3 shows the differences of the effective components for measuring the color of the samples. Adding additives increases the opacity and tendency to redness in some samples, such as samples containing 0.15% cationic polyacrylamide, 6% NFC and 6% NFC + 1.5% cationic starch. A tendency to yellowness was observed in samples containing 6% NFC and 1.5% cationic starch, and a tendency to greenness in samples containing 10 and 15% imported long fibers and 0.07% cationic polyacrylamide. Blue color tendency was also observed in samples containing 5% of imported long fibers and 0.15% of cationic polyacrylamide.

**Table 3.** Changes in Optical Components of Paper Samples

| Sample | $L^*$ | $a^*$ | $b^*$ | $\Delta L$ | $\Delta a$ | $\Delta b$ | $\Delta E^*$ |
|---|---|---|---|---|---|---|---|
| Control | 92.05 | -2.9 | -7.1 | - | - | - | - |
| 5LF | 89.17 | 2.3 | -14.4 | -2.88 | 5.20 | -7.34 | 9.45 |
| 10LF | 92.45 | -13.1 | -9.0 | 0.40 | -10.25 | -1.91 | 10.43 |
| 15LF | 92.34 | -15.6 | -1.6 | 0.29 | -12.72 | 5.43 | 13.83 |
| 0.75CS | 91.29 | -8.1 | -8.3 | -0.76 | -5.21 | -1.19 | 5.40 |
| 1.5CS | 89.96 | -2.2 | -6.7 | -2.09 | 0.70 | 0.34 | 2.23 |
| 3NLC | 92.10 | -10.5 | -6.1 | 0.05 | -7.61 | 0.98 | 7.67 |
| 6NLC | 86.27 | 16.2 | -12.6 | -5.78 | 19.10 | -5.53 | 20.71 |
| 3NLC+1.5CS | 87.89 | 3.9 | -12.6 | -4.16 | 6.76 | -5.52 | 9.67 |
| 6NLC+1.5CS | 86.15 | 13.3 | -12.9 | -5.90 | 16.14 | -5.80 | 18.14 |
| 0.07CPAM | 89.57 | -15.2 | -2.1 | -2.48 | -12.26 | 4.95 | 13.45 |
| 0.15CPAM | 79.78 | 35.3 | -21.3 | -12.27 | 38.20 | -14.26 | 42.58 |
| 3NC+0.15CPAM | 90.67 | -3.7 | -8.9 | -1.38 | -0.81 | -1.83 | 2.43 |
| 6NC+0.15CPAM | 92.43 | -7.5 | -7.2 | 0.38 | -4.63 | -0.16 | 4.65 |

An increase in the *L** means that the sample is brighter. The positive $\Delta a$ means red color change and negative $\Delta a$ means green color change. A positive $\Delta b$ means yellow color change and negative $\Delta b$ means blue color change.

## CONCLUSIONS

In this study, the effects of nanofibrillated cellulose (NFC), cationic polyacrylamide, cationic starch, and imported long fibers on the optical properties of white liner made of recycled fibers were investigated. The results were as follows:

1. Increasing the amount of NFC up to 6% significantly increased the brightness of the white liner (by 13%) compared to the control sample. Its yellowness significantly increased 21%. The opacity white liner was significantly reduced by 1%.

2. Increasing the amount of NFC 6% compared to the sample containing 15% imported long fibers, the brightness of the white liner increased significantly 5.4% and its yellowness also increased significantly 3.6%. The opacity of the liner was significantly reduced (by 1%).

3. Increasing the amount of NFC 6% along with 1.5% cationic starch compared to the sample containing 15% imported long fibers, significantly increased the brightness of the white liner (by 4.4%), significantly increased its whiteness (by 1.46%), and also

significantly increased its yellowness (by 1.2%). The opacity of the liner was reduced significantly (by 1.7%).

4. Increasing the amount of cationic starch 1.5% compared to the control sample, significantly increased the opacity of the liner (by 9.3%), significantly reduced its brightness (by 7%), and its whiteness was reduced significantly (by 1.5%) and its yellowness also reduced significantly (by 8.8%).

In general, the results showed that the use of NFC and cationic starch can improve the optical properties of white liner, while imported long fibers may be problematic. Through increasing NFC, the brightness improved, and opacity of white liner was reduced. Further, the addition of cationic starch along with NFC had a positive effect on the brightness, whiteness, and yellowness of the white liner. However, the addition of cationic starch by 1.5% increased the opacity and reduced the brightness, whiteness, and yellowness of the white liner.

The results further showed that various combinations of NFC, cationic polyacrylamide and starch, and imported long fibers can be used as effective methods to improve the optical properties of white liner.

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