Improving Physical Properties and Printability of Fruit Packaging Kraft Liner with Mineral and Nanographene Coatings

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Biological nanomaterials such as nanographene and fluorite have garnered the attention for the production of diverse products, particularly food packaging, owing to their biocompatibility and biodegradability. The objective of this study was to prepare a coated paperboard sheet utilizing nanomaterials and mineral compounds to enhance the physical characteristics and printability of the brown kraft liner paper. In this investigation, a 120 g/m^2 brown kraft liner was employed, in conjunction with varying quantities of nanographene, zein protein, and fluorite, combined with internal resin for the coating process. The physical properties were examined. The samples were treated in standard conditions of 20 °C and 65% relative humidity. The results revealed that the coating led to an increase in yellowness, opacity, glossiness, optical density, and resistance to air permeation compared to the control sample. Notably, the air resistance of the graphene-coated sample was about 5350 seconds. The roughness increased by 9.7 μm with the use of fluorite. Furthermore, a noticeable increase in opacity and glossiness was observed in the coated samples. The adhesion of the coated layer and flexo ink was also excellent, so that it remained intact on the paper surface.

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INTRODUCTION

The pulp and paper industry is one of the oldest and most diverse industries globally, focused on the production and processing of wood and paper products. The consumption of paper, as an economic and cultural indicator, reflects the development of a society. In recent years, with evolving consumption patterns and urbanization, the demand for wood and paper products in Iran has significantly increased, accompanied by a rise in the production of cardboard and packaging paper. In response to societal needs and the imperative to enhance packaging quality, nanotechnology has emerged as an effective solution for preserving food safety. Active packaging with antibacterial properties can help mitigate microbial growth. Alongside this, traditional polymeric materials such as polyethylene are commonly utilized in packaging due to their specific characteristics; however, their non-biodegradability leads to environmental pollution. With growing concerns about the environmental impacts of these materials, efforts are underway to identify sustainable and renewable alternatives, prompting industries to shift towards the use of natural and renewable packaging.

Fruit packaging must meet specific requirements, including moisture retention, breathability, and mechanical strength, to protect the fruit from external factors while allowing for adequate respiration. Traditional polymeric materials, such as polyethylene, are commonly used for this purpose; however, their non-biodegradability poses significant environmental challenges. As consumers become more environmentally conscious, there is a pressing need for sustainable and renewable alternatives.

Nanographene is recognized as an innovative material in the paper industry, having the potential to significantly enhance the mechanical and thermal properties of paper (Liu *et al*. 2022). The application of nanographene in paper production leads to increased strength, reduced weight, and improved resistance to water and fire (Gadakh *et al*. 2019).

Zein, the main protein found in corn kernels, accounts for approximately 50 to 60 percent of the total proteins in corn (Abiose Sumbo and Victor 2014). Due to its unique properties, zein is increasingly utilized in the paper industry. This natural additive contributes to improving the strength and durability of paper, potentially reducing the reliance on synthetic chemicals in the paper manufacturing process (Corradini *et al*. 2014).

Although unmodified CaF_2 behaves as a typical ionic compound when in contact with water, certain processed forms of fluorite or surfaces modified with fluoride ions have been shown to exhibit significant hydrophobic behaviour (Chevalier 2017). Moreover, molecular-level studies of the CaF_2/water interface indicate the formation of a structured water layer and weak hydrogen-bonding interactions at the surface, implying reduced wettability under specific conditions (Khatib *et al*. 2016). Therefore, when incorporated into paper coating formulations, CaF_2 particles can potentially enhance water resistance and surface durability, which are critical for improving the physical performance and printability of fruit packaging kraft liners.

Printing on packaging has become a crucial component of product marketing, and the creation of attractive and suitable packaging is an inevitable necessity for businesses. The smoothness, high brightness, high optical density, good adhesion, and opacity of paper surfaces are essential for optimal printing. Research in this area contributes to the enhancement of the final properties of paper and cardboard.

Recent research in the field of protein coatings and coated papers has been conducted with the aim of improving the mechanical and barrier properties of these materials. Kianirad *et al*. (2021) studied the mechanical properties of soybean protein films coated with zein corn and demonstrated that the zein-coated, bilayer films exhibited greater tensile strength compared to the uncoated samples. Hamdani *et al*. (2023) also examined the barrier properties and resistance to water vapor and oil of zein-coated papers, finding that the zein coating significantly reduced the water vapor transmission rate and fat permeability. Hamzeh *et al*. (2008) investigated the sizing of rosin under neutral-alkaline papermaking conditions and concluded that the optimal ratios for the compounds used were 1:1 for polyaluminum chloride to rosin and 1:1.5 for alum to rosin**.** Zhu *et al*. (2019) investigated the effect of silicon on coated base paper and analyzed the conditions for water and vapor transfer through the paper fibers and the coated samples. This study indicated that the deformation of fiber cavities during the paper-making process affects the rate of water and vapor transfer, and the Young's modulus of the fibers reflects their mechanical properties. Schuman *et al*. (2005) investigated the print quality on kraft linerboard using one and two coatings, finding that an increase in coating led to an improvement in flexographic print quality. Vaswani *et al*. (2005) modified paper and cellulose surfaces with fluorocarbon layers using plasma deposition, which contributed to improving the hydrophobic and barrier properties of these materials.

Rhim *et al*. (2006) studied the mechanical properties and water resistance of paperboard coated with alginate and soy protein. They found that these coatings resulted in a smooth and homogeneous surface, significantly increasing the tensile strength of the paper. Preston *et al*. (2007) demonstrated that increasing the coating weight led to a smoother layer, which reduced the percentage of unprinted areas. Machotová *et al*. (2008) prepared acrylic microgels that enhanced surface hydrophobicity, although they exhibited a low glass transition temperature.

Tihminlioglu *et al*. (2010) investigated the barrier properties of polypropylene films coated with zein corn and found that the zein coating improved barrier to oxygen and water vapor. Yu *et al*. (2017) investigated the hydrophobic properties of paper made from hemp fibers using rosin sizing agents, demonstrating that combining rosin with alum and MCC suspension resulted in a hydrophobicity of 92.46%. Mujtaba *et al*. (2022) examined the impact of biodegradable polymer coating, such as polyhydroxybutyrate (PHB) and polylactic acid (PLA), discovering that these coatings provided better barrier properties compared to uncoated papers.

Aloui *et al*. (2011) analyzed the impact of glycerol and coating weight on the properties of paper coated with chitosan and sodium caseinate, showing that coating weight significantly affects water vapor permeability. Bedane *et al*. (2012) studied the transmission of water vapor, carbon dioxide, and oxygen in papers modified with PLA and zein, finding that permeability is dependent on temperature and relative humidity. Khwaldia *et al*. (2014) demonstrated that layered coating of chitosan and caseinate reduce water vapor permeability in packaging papers.

Wolf *et al*. (2018) investigated the barrier properties of paper using aluminum and glass fillers, finding that these compounds significantly enhance barrier properties. Ozcan and Zelzele (2017) examined the effect of pigments and binder types in coated paper, showing that modifications in binders improve mechanical properties and permeability. Chen *et al*. (2024) utilized calcium sulfate for coating base paper. They concluded that this material enhances optical properties while reducing water and gas permeability. Tambe *et al*. (2016) produced a moisture-resistant coating from soy oil, resulting in reduced water absorption and improved mechanical properties. Kunam *et al*. (2024) examined the effect of bio-based coatings on packaging paper, demonstrating significant improvements in barrier performance against water, oil, and gases.

Cardboard is primarily used for packaging due to its availability, low desnity, relatively low cost, and, most importantly, renewability. Generally, printing on cardboard is also of higher quality and clarity; for this reason, cardboard is preferred over other materials. However, one of the major challenges in the paper recycling industry in Iran is the low printability quality of cardboard and its uneven surface. One of the most important packaging cardboard manufacturing companies is Mazandaran Wood and Paper Company, which faces such challenges. Also, various types of binding agents used in the formulation of coating compositions are primarily made from non-biodegradable materials and petroleum derivatives.

Although there have been numerous studies on protein coatings and similar materials, none have specifically investigated the use of mineral coatings and nanographene on liner kraft paper for fruit packaging. Therefore, the main objective of this study is to enhance the surface properties and printability of paper by employing biodegradable binding agents, specifically focusing on the application of nanographene and mineral coatings. Additionally, this research aims to investigate the impact of various coating compositions, including zein and fluorinated compounds, on critical quality parameters paper and cardboard utilized in the fruit packaging industry.

EXPERIMENTAL

Materials

Main materials

The brown liner paper used was sourced from Mazandaran Wood and Paper Company (Iran) and is composed of 30% mixed species, 10% poplar, and 60% waste paper, with a basis weight of 120 g/m^2.

Functional additives

The AO-4 type nanographene was obtained from Graphene Supermarket in the United States. Zein protein (corn protein) was sourced from Sigma Aldrich. Fluorite was obtained from the production group of Mine Kavann.

Supplementary components

Acrylamide-based resin (model SH-305) was supplied by Simab Resin Co. (Iran). styrene-butadiene latex was supplied by Persepolis Petrochemical Co. (Iran). Cationic starch was sourced from Lyckeby Amylex, Slovakia, from potato. Specifications for nanographene, zein protein, fluorite, and acrylamide-based resin are presented in Table 1.

Table 1. Characteristics of Nanographene, Zein Protein, Fluorite, and Acrylamide Resin

Feature	Nanographene	Zein	Fluorite (Calcium Fluoride)	Acrylic Resin (SH-305)
Specific Surface Area (m²/g)	More than 15	-	-	-
Color	Black	Yellow	-	Milky
Purity (%)	99.5	-	-	-
Average Thickness (nm)	60	-	-	-
Particle Diameter (nm)	3-18	-	-	-
Surface Area (m²/g)	300	-	-	-
Appearance Status	-	-	-	Liquid
Crude Protein (%)	-	55	-	-
Crude Fiber (%)	-	10	-	-
Ash (%)	-	3	-	-
Urea Content (mg/kg)	-	Negative	-	-
CaF_2 (%)	-	-	96.17	-
Density (g/cm^3)	-	-	3.18	-
Molar mass (g/mol)	-	-	78.07	-
Melting point (^{o}C)	-	-	1418	-
Type	-	-	-	Self-crosslink
Emulsifying Property	-	-	-	Anionic
Solid Content (%)	-	-	-	50
pH	-	-	-	6-8

Coating of Base Paper

Protein-based coatings

Zein was weighed and mixed in specified weight percentages with distilled water at 50 °C. The mixture was blended for 30 minutes to ensure a homogeneous solution. Cationic starch was added as a retention aid to enhance coating uniformity.

Mineral coatings

Fluorite was similarly prepared and mixed under the same conditions as zein. This coating aims to improve the hydrophobic properties of the paper.

Nanographene coatings

Nanographene was weighed and treated in conjunction with other coating materials to assess its impact on the mechanical and thermal properties of the paper.

Composite coatings

Each of the coating materials (nanographene, zein, and fluorite) was mixed individually and in combinations. A mixture of 2.5 g of styrene-butadiene latex and 0.5 g of dispersant D200 was added to enhance the adhesion and performance of the coatings.

Application process

The final coating mixtures were applied to the paper sheets using an Auto Bar Coater (GBC-A4, GIST Co., Ltd, Taejon, Korea). A volume of 27 mL was evenly distributed across one side of the paper at a speed of 25 mm/s. The coated sheets were air-dried for 24 hours at room temperature and conditioned at 27 °C with 65% relative humidity for a minimum of 24 hours.

Summary of coating compositions

The specific codes and percentages of the compositions used in the coatings and treatments are summarized in Table 2.

Table 2. Combination of Codes and Treatment Conditions

Treatment Number	Treatment Code	Descriptions
1	CBL	Control Brown Liner
2	BLG	Brown Liner Coated with Nanographene
3	BLZ	Brown Liner Coated with Zein
4	BLF	Brown Liner Coated with Fluorite
5	BLZG	Brown Liner Coated with Nanographene and Zein
6	BLFG	Brown Liner Coated with Nanographene and Fluorite
7	BLFZ	Brown Liner Coated with Fluorite and Zein
8	BLZFG	Brown Liner Coated with Nanographene, Zein, and Fluorite

Measurement of Paper Properties

To determine the physical and optical properties of the papers, a minimum of 10 repetitions for each sample was conducted in accordance with the following standard guidelines. This repetition ensures the accuracy and reliability of the results obtained.

The physical properties measured included caliper (T411 om-21), ash content (T413 om-22), roughness (T555 om-22), and air permeability (T460 om-21). The optical properties measured included brightness, opacity, and yellowness (T452 om-18), and adhesion (ASTM D-4541).

To measure glossiness, a gloss meter of the type Ihara S900, manufactured by Xrite Pantone I1 BYK Gardner Micro TRI Gloss in Carlstadt, United States, was used. It should be noted that to assess the level of glossiness, a film with a thickness of 6 µm of flexographic ink was first applied to the papers, and then the glossiness of the samples was measured using the gloss meter.

To measure optical density, a spectrodensitometer (X-Rite 530, X-Rite, Inc., Grandville, USA) was used. The print test was conducted by pulling a flexographic ink film on a solution applied by an applicator with a number 8 blade at the Research Institute of Color Science and Technology. The flexographic ink used in this study was S Flexography ink in violet color, prepared from isopropanol and ethyl acetate mixtures at ratios of 1:2 to 1:3 from Behroofan Company (Tehran, Iran). This solvent mixture was chosen for its effectiveness in our research conducted at the Color Technology Research Center.

The experimental design used in this research was completely random, and to process the results obtained from the measurements, the statistical package for social science software (SPSS) software (Version 23) was utilized. For data analysis, one-way analysis of variance (ANOVA) was used, and Duncan's test was employed to compare the means at a confidence level of 95%.

The caliper of the paper, paperboard, and combined board was measured according to Test Method TAPPI/ANSI T 411 om-21.

RESULTS AND DISCUSSION

The relevant properties are presented in Table 3.

Table 3. Analysis of Variance (F-Value and Significance Level) for the Effects of Structural Variables on Properties

Property	Variables
Air Permeability (S)	46627.637*
Roughness (µm)	36.189*
Opacity (%)	21208.929*
Whiteness (%)	2599391.483*
Brightness (%)	71231.518*
Yellowness (%)	104772.643*
Glossiness (%)	865794.643*
Optical Density (g/m^2)	22.929*
*Significance Level: * 95%, ns: Not Significant	

Air Permeability

The one-way ANOVA indicated that there was a significant difference at the 5% significance level in the air permeability values among the 8 types of paper tested. The air permeability values were categorized into seven groups. Figure 1 shows resistance the average variations in air permeability for these eight types of paper. The highest air permeability was associated with the brown liner paper coated with nanographene, while the lowest was observed in the control sample. The use of nanographene, both individually and in combination with zein and fluorite, resulted in a significant increase in air permeability resistance. This increase is attributed to the interconnection between the nanographene particles and the reactive groups on the fiber surfaces, as well as the mechanical interlocking between the polymers and the cellulose fibers. The addition of nanographene enhances the possibility of hydrogen bond formation between the coating compounds and the nanographene, resulting in increased air permeability resistance (Molaei *et al*. 2015).

The air permeability test of the papers showed that with coating, this resistance significantly increased, to the extent that in some cases, the measured values were beyond the range that the measuring device could record. This improved property may influence the print quality and dimensional stability of the paper. The increased flexibility of the fibers allows for greater penetration of nanomaterials into the paper structure, resulting in enhanced air permeability resistance (Molaei *et al*. 2015).

Additionally, the hydrogen bonds between the hydroxyl groups of the paper and the nanomaterials can also enhance the intermolecular bonding between the paper and the coating compounds (Marvizadeh *et al*. 2017). Furthermore, nanographene fills the extracellular spaces, bringing the cellulose fibers closer together, which results in an increased barrier property of the final paper (Jamshidi Kaljokah *et al*. 2014). The increase in air permeability resistance in the graphene-coated sample was approximately 7360% compared to the control sample.

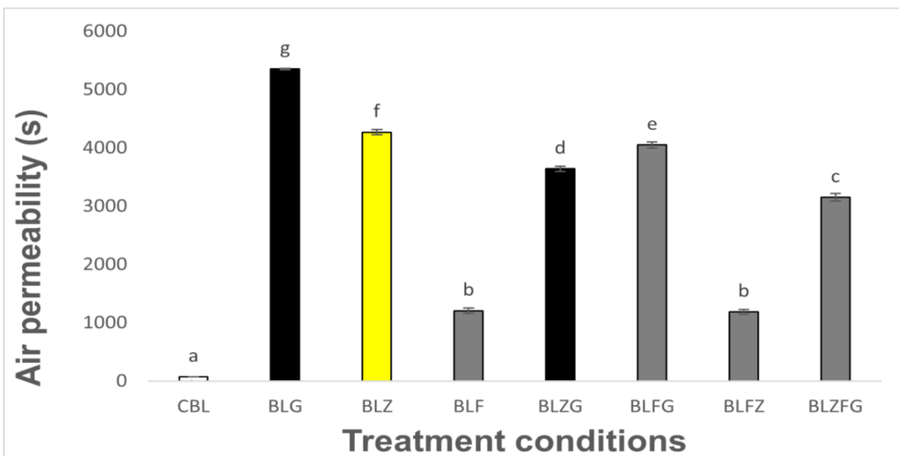

Fig. 1. Comparison of the average air permeability of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Roughness

There was a significant difference at the 5% significance level in the roughness values in ANOVA among the 8 types of paper tested. The roughness values were categorized into four distinct groups. Figure 2 shows the average variations in roughness for these eight types of paper. The lowest roughness value was observed in the brown liner paper coated with nanographene and zein, while the highest roughness value was associated with the brown liner paper coated with fluorite. Although the use of coating materials has resulted in changes in the roughness of the papers, these changes were not drastic and could be further addressed through calendering processes (Ebrahimpour Kasmani *et al*. 2014).

In the treatments that utilized fluorite, the roughness increased, which may be attributed to the uneven dispersion of this material on the surface of the paper. The significant difference in the roughness of the papers is notable as one of the indicators of printability. The use of fluorite resulted in maximum roughness, while the lowest roughness was observed in the uncoated sample. This is a natural occurrence and will improve with surface finishing operations on the coated papers (Asadi Khansari 2013).

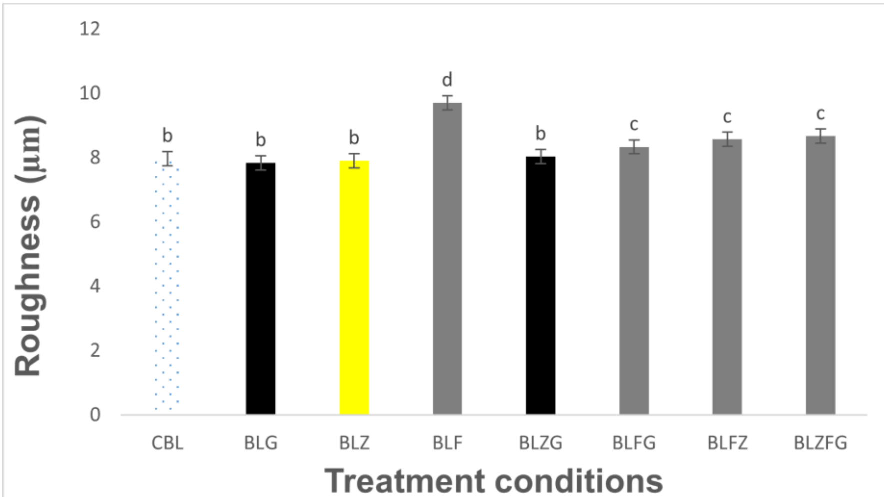

Fig. 2. Comparison of the average roughness of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Opacity

A significant difference at the 5% significance level in the opacity values was observed in ANOVA among the 8 types of paper tested. The opacity values were categorized into five groups. Figure 3 showed the average variations in opacity for these eight types of paper. The lowest opacity value was observed in the uncoated brown liner paper, whereas the highest opacity value was associated with the brown liner paper coated with fluorite, zein, and nanographene. The Contrast Ratio, as a percentage, was introduced as a measure of the degree of opacity of the coating, and this index was measured using a spectrophotometer (Technibrite Micro TB-1C, New Albany, Indiana, USA) with a geometry of 45 to 0 degrees.

Factors affecting the opacity of paper include basis weight, absorption coefficient, and light scattering coefficient, and the relationship between opacity and these factors is direct; meaning that with the increase or decrease of any of these factors, the level of opacity also changes (Afra and Narchin 2016). The extent of changes in the optical properties of the coated paper is related to the type and amount of coating components. The coating process, by filling the cavities and empty spaces between the fibers—especially when using protein-based materials like zein—leads to an increase in the opacity of the paper surface (Ebrahimpour Kasmani *et al*. 2014).

In most cases, particularly in treatments that utilized a combination of coating materials, the opacity of the paper increased. This can be attributed to the enhanced light scattering coefficient following the coating process. Furthermore, nanographene increases the opacity of the coated samples (Sodeifi *et al*. 2019).

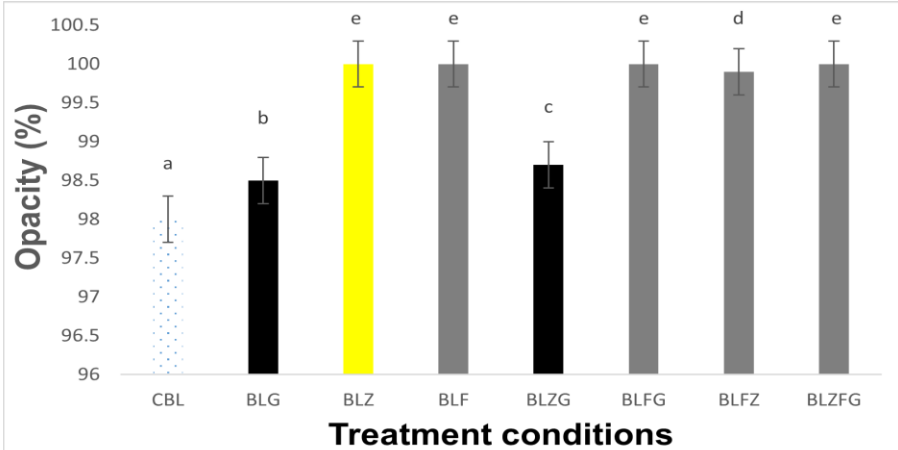

Fig. 3. Comparison of the average opacity of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Whiteness

One-way ANOVA showed that there were significant differences in the whiteness values of the 8 types of papers tested at the 5% significance level. The whiteness values were categorized into eight groups. Figure 4 showed the average variations in whiteness for these 8 types of paper. The lowest whiteness value was associated with the brown liner paper coated with fluorite and zein, while the highest whiteness value belonged to the control brown liner paper. The sample coated with zein and fluorite showed a 7.23% reduction in whiteness compared to the control sample. Factors such as particle size, particle size distribution, and particle morphology have a significant impact on the reduction of whiteness in coated papers.

Handsheet filled with coating materials tend to have lower whiteness due to the presence of impurities and the reduced specific surface area of the particles. The use of white pigment is not the only factor affecting the whiteness of papers; other factors such as particle size, particle size distribution, and their morphology also play a significant role in this regard (Hosseini *et al*. 2017).

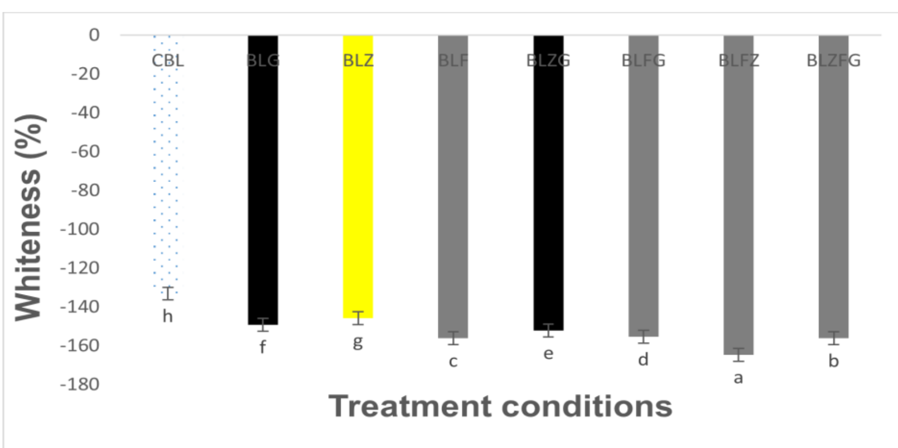

Fig. 4. Comparison of the average whiteness of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Brightness

Significant differences in brightness values among the 8 types of papers tested at the 5% significance level were observed in one-way ANOVA. The brightness values were categorized into eight groups. Figure 5 showed the average variations in brightness for these 8 types of paper samples. The lowest brightness value was associated with the brown liner paper coated with fluorite and nanographene, while the highest brightness value was associated with the control samples of brown liner paper. The brightness of the sample coated with fluorite and nanographene exhibited a 9.81% reduction compared to the control sample. The most important property of pigments that affects the characteristics of paper was brightness.

In general, smaller particles have a higher light reflection index, light scattering coefficient, and brightness. Due to the higher initial brightness and specific surface area of the fillers compared to the fibers, adding them to the paper results in an increase in brightness. Therefore, the reduction in brightness percentage may be related to the particle size, refractive index, and greater specific surface area of the particles used (Perng *et al*. 2015). The examination of the optical properties of paper indicates that the combination of coating materials had a significant impact on the reduction of the brightness degree of the paper. The use of mineral fillers can lead to changes and reductions in brightness in various types of paper, and the extent of these changes is influenced by the structure of the paper, as well as the size and specific surface area of the fillers.

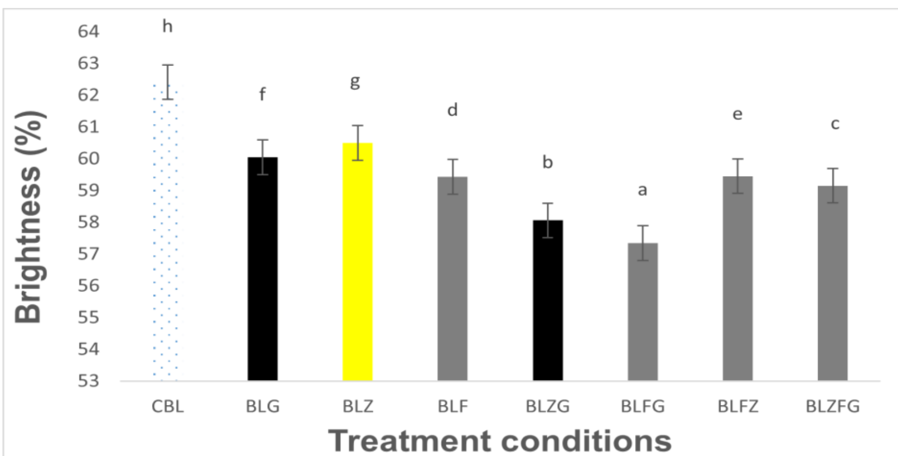

Fig. 5. Comparison of the average brightness of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Yellowness

One-way ANOVA indicated that there were significant differences in the yellowness values among the 8 types of papers tested at the 5% significance level. The yellowness values were categorized into eight groups. Figure 6 shows the average variations in yellowness in the machine direction for these 8 types of papers. The lowest yellowness value was associated with the control brown liner paper, while the highest yellowness value was for the brown liner paper coated with fluorite and zein. The level of yellowness is a very important factor from the perspective of consumers of coated papers. In the papers produced by the Mazandaran Wood and Paper Company, the phenomenon of yellowing occurred after a while due to the presence of modified lignin. Therefore, if the paper coating can help improve this property and act as a barrier against the effects of light on the yellowing of the paper. Then the coating process will be considered effective. The results indicated that the use of coating led to an increase in the yellowness of the paper, with the sample coated with fluorite and zein showing a 3.3% increase in yellowness compared to the control sample.

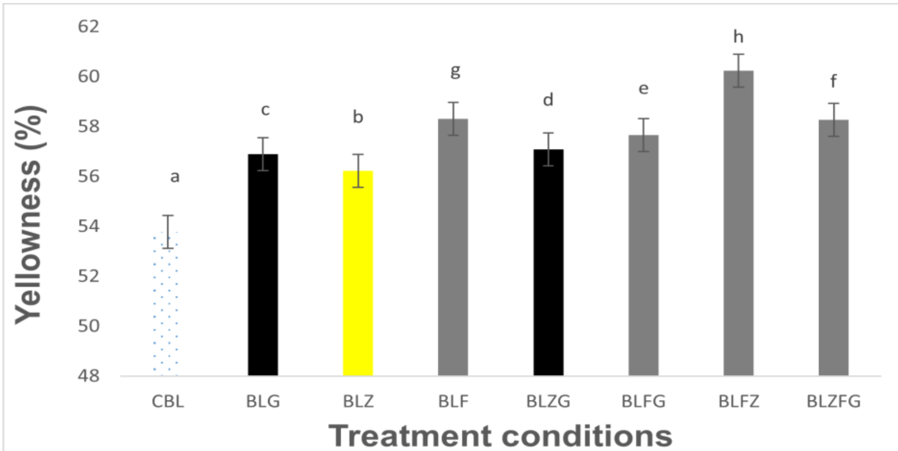

Fig. 6. Comparison of the average yellowness of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Glossiness

One-way ANOVA revealed that there were significant differences in the glossiness values among the 8 types of papers tested at the 5% significance level. The glossiness values were categorized into eight groups. Figure 7 shows the average variations in glossiness for these 8 types of papers. The highest glossiness value was for the brown liner paper coated with fluorite, zein, and nanographene, while the lowest glossiness value was for the control samples of brown liner paper. The glossiness of the samples, or light reflection, was assessed at an angle of 85º. The higher the reported value, the greater the glossiness. According to ASTM D523-08 standards, glossiness was measured at a 60º angle and is categorized into three criteria: matte, semi-matte, and glossy.

If the glossiness value is less than 10, indicating a matte finish of the coating, the measurement is performed at an angle of 85º. The sample coated with zein, fluorite, and nanographene showed a 321% increase in glossiness compared to the control sample. The level of glossiness depends on the structure and surface porosity of the paper, and the increase in glossiness of the coated papers indicates an improvement in their printability. The glossiness of a film reaches its maximum when the angle of incidence equals the angle of reflection. It appears that coating materials act as plasticizers in the ink, filling in voids and resulting in greater adhesion. After the ink is applied to the paper, the evaporation of water allows the molecules of the coating materials to fill in the voids, creating a smooth and non-porous surface. In contrast, ink without coating materials cures quickly, and the resulting sheen does not achieve the smoothness of the surface provided by the coating materials. This explains the difference in glossiness between the coated papers and the uncoated control samples.

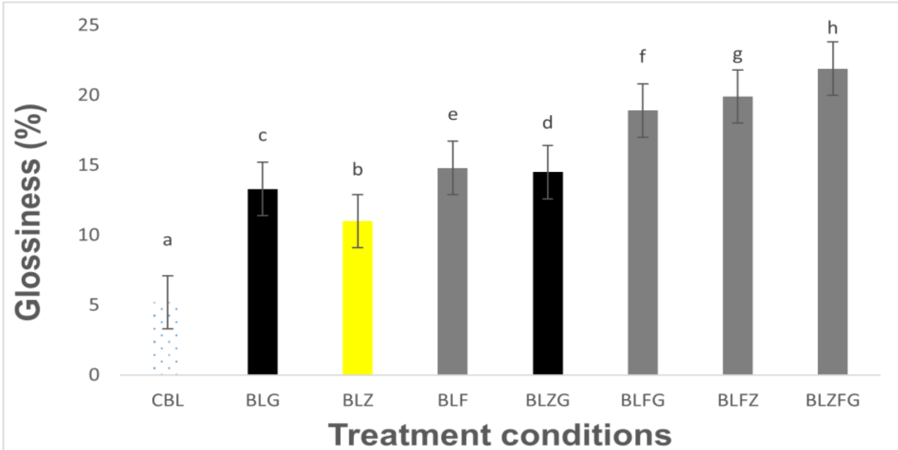

Fig. 7. Comparison of the average glossiness of different papers

Optical Density

One-way ANOVA indicated that there were significant differences in the optical density values among the 8 types of papers tested at the 5% significance level. The optical density values were categorized into five groups. Figure 8 shows the average variations in optical density for these 8 types of paper. The highest optical density value was associated with the brown liner paper coated with fluorite and zein, while the lowest optical density value belonged to the control samples of brown liner paper. Optical density is recognized as a measure of the pigment concentration in the printed film or its thickness. This metric numerically reports the intensity of color perceived by the eye and is based on the principles of light reflection and absorption. The results indicated that in coatings that utilized a combination of materials for coating, a higher optical density was observed. This increase in optical density signifies improved clarity and print quality, which was readily observable. In general, the higher the optical density value, the greater the light absorption, and the better the color quality perceived by the eye. In all treatments, the optical density along with the clarity and print quality increased significantly.

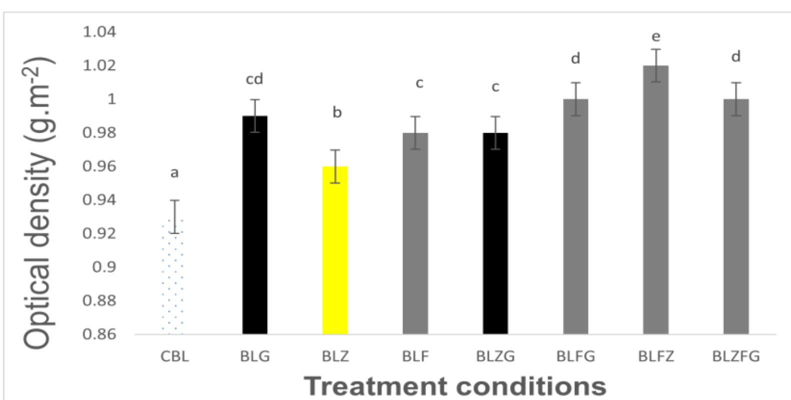

Fig. 8. Comparison of the average optical density of different papers (lowercase letters indicate Duncan ranking of averages at 5% confidence interval)

Adhesion

The adhesion test was conducted to evaluate the quality of the coated layers and flexo inks. In this test, 3 to 5 cm of the desired adhesive was applied to the surface of the flexo-printed film and was quickly removed from the film's surface after 5 seconds. The results indicate that the adhesion of the coated layer and the applied flexo ink was excellent, as both layers were fully removed along with the surface of the paper (substrate) by the adhesive. In comparison, in the uncoated samples, the amount of paper substrate that was removed was significantly less. This result indicates the superior performance of the coatings in creating adhesion and achieving higher print quality.

CONCLUSIONS

This study highlights the critical role of packaging materials in product quality and safety. Traditional plastic packaging contributes to environmental issues, while biodegradable or recyclable options provide a sustainable alternative. Advancements in coating technologies improve paper properties like printability and glossiness, meeting the demand for high-quality packaging. Overall, these findings support the shift towards eco-friendly packaging solutions.

This research demonstrated that the use of nanomaterials and biodegradable mineral and protein materials that can assist in improving the printability characteristics of coated papers. The following results were obtained:

1. The highest air permeability resistance was with the brown liner paper coated with nanographene, while the lowest air permeability resistance was observed with the control sample.
2. The lowest roughness was associated with the brown liner paper coated with nanographene and zein, while the highest roughness was found in the case of the brown liner paper coated with fluorite.
3. The lowest level of opacity was found for the brown liner paper coated with nanographene, while the highest level of opacity was for the brown liner paper coated with fluorite, zein, and nanographene.
4. The lowest whiteness value was with the brown liner paper coated with fluorite and zein, while the highest whiteness value was with the control brown liner paper.
5. The lowest brightness value was with the brown liner paper coated with fluorite and nanographene, while the highest brightness value was found for the control samples of brown liner paper.
6. The lowest yellowness value was observed for the control brown liner paper, while the highest yellowness value was shown with the brown liner paper samples coated with fluorite and zein.
7. The highest glossiness value was associated with the brown liner paper coated with fluorite, zein, and nanographene, while the lowest glossiness value belonged to the control samples of brown liner paper.

8. The highest optical density value was with the brown liner paper coated with fluorite and zein, while the lowest optical density value was for the control samples of brown liner paper.

Based on the results, it was determined that the brown liner papers coated with nanographene, zein, and fluorite exhibited better overall performance.

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