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Development of Semi-Transparent Paper for Tamper-Proof Sustainable E-Commerce Packaging

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Abstract: *The growing environmental issues related to plastic packaging made from petroleum-based materials have increased the need for sustainable and biodegradable packaging materials. Cellulose-based semi-transparent papers have become more popular due to their recyclable nature, renewability, lightweight, and applicability for circular economy. However, conventional processes for manufacturing transparent papers involve significant fibrillation, production of nanocellulose, use of synthetic polymers for coating, and other energy-demanding processes that limit their commercial viability. In this study, semi-transparent functional papers of 50 gsm (hand-sheets) were developed from softwood pulp by refining to 20°SR using a carrier-assisted impregnation approach, for sustainable packaging purposes. Different levels of concentration of functionalizing agent (10-40%) were applied to determine its influence on the optical, barrier, surface, and mechanical properties of the produced handsheets. The obtained sheets demonstrated a significant improvement in transparency, from 40.18% to 61.65% at different concentrations as compared to untreated hand-sheet, indicating decreased internal light scattering inside the paper substrate. Cobb value was reduced from 28.50 to 19.87 g/m², denoting better barrier towards water absorption. Gloss levels showed very little improvement, increasing from 4.40 to 4.85 G.U., implying that the treatment had modified the internal structure more than the surface. Tensile index and burst factor were reduced from 54.76 to 37.23 Nm/g and 53.80 to 35.56, respectively, because of the weakening of the inter-fiber bonding effect due to increased concentration of treatment loadings. Tear strength index increased initially from 9.84 to 13.02 mNm²/g and then decreased to 8.83 mNm²/g with the maximum loading amount. Semi-transparent paper obtained through the process displayed good optical clarity and barrier characteristics while retaining acceptable mechanical integrity for advanced sustainable packaging applications.*

Keywords: *Semi-transparent paper, Functional cellulose paper, Barrier properties, Transparency, Oil-based formulation.*

Introduction

The swift growth of the global e-commerce industry has increased the need for light, eco-friendly, and tamper-proof packaging material that can substitute petroleum-based plastic film and laminates (1, 2). Conventional plastic-based courier envelopes and flexible packaging materials is environmentally burdensome due to poor biodegradability and recycling. As a result, the pulp and paper industry has begun shifting its focus towards developing sustainable fiber-based packaging materials (3, 4).

The development of transparent and semi-transparent papers made from cellulose has been recognized as an attractive option for flexible packaging because of their biodegradable nature, renewability, recyclability, and excellent functional versatility (5). According to Fang et al., transparent paper products exhibit great potential in packaging and functional purposes due to their improved optical properties and renewable cellulose structure (5). Furthermore, transparent paper systems have received considerable interest for use in product visibility packaging, electronic substrates, and specialty barrier applications (6, 7).

Recent studies have demonstrated that transparency in cellulose-based materials can be achieved by reducing light scattering inside the material using methods such as fibrillation, pore-filling, or refractive index matching in the fiber network (8). Transparent films and papers made from nanocelluloses have shown better optical properties; however, most of these require repeated homogenization, polymer impregnation, or energy-intensive nanofibrillation processes (9). Such treatments increase the cost of production and reduce scalability in industry. Furthermore, many researchers have reported that optical and barrier properties in microfibrillated and nanofibrillated cellulose-based materials are better but require complicated and energy-intensive processing (10, 11).

Additionally, over-fibrillation and harsh chemical modification often result in poor bulk structure of the paper matrix which negatively affect mechanical strength. Papers made from highly purified nanocellulose system are also found to have poor tearing strength and limited flexibility, making them unsuitable for use in packaging (12). Moreover, many of the transparent packaging materials rely on coating of synthetic polymers and multi-layered structures, thus becoming unsustainable (13). Studies have shown that maintaining a balance between transparency, barrier properties, and mechanical properties poses considerable problems in the development of environmentally friendly cellulose-based packaging systems (14).

In view of the above-mentioned problem, the current work is focused on the development of semi-transparent functional paper using relatively low refined softwood pulp in a carrier-assisted impregnation approach. The developed semi-transparent paper would be used in sustainable tamper-evident e-commerce packaging, where optical transparency, good barrier properties, a light weight, and adequate mechanical integrity are required.

2. Materials and Methods

2.1 Materials

Softwood bales sourced from Kuantum Papers Ltd (India) were utilized to produce handsheets in the laboratory. Before the hand-sheet formation, the pulp was refined to 20 °SR. Food-grade mineral oil served as the functional phase and was obtained from a commercial supplier in India. Additionally, alkyl ketene dimer (AKD) was procured from Raghav Industrial Products (India) to enhance the hydrophobicity of the handsheets.

2.2 Preparation of Handsheets

The laboratory handsheets, with a basis weight of 50 gsm, were prepared using 20° SR softwood pulp in a standard sheet former. Additionally, 2% AKD was incorporated into the pulp prior to sheet formation. The handsheets prepared thus were then pressed, dried, and conditioned under standard laboratory conditions before further treatment.

2.3 Preparation of Functional Formulation

A variable quantity of functional oil corresponding to 10, 20, 30, and 40% concentration of the functionalizing agent was added to a fixed total formulation volume using a carrier-assisted process. The concentration of the functionalizing agent refers to the volumetric proportion of functional oil present in the total impregnation formulation prior to application. A carrier medium, specifically a polar aprotic solvent, was employed to facilitate the dispersion and penetration of the functional component within the porous structure of the paper. The amount of carrier composition used remained constant throughout the investigation period to ensure comparable treatment conditions for all samples. The concentration of functionalizing agent and corresponding sample codes used in the present study are presented in Table 1.

Table 1: Sample coding corresponding to different concentrations of functionalizing agent

Sample Code	Concentration of Functionalizing Agent (%)
S0	0
S10	10
S20	20
S30	30
S40	40

2.4 Treatment of Hand-sheets

The developed handsheets were uniformly impregnated through prepared formulations. Following impregnation, a laboratory bar coater was used to remove excess formulation from the sheet surface and ensure a uniform distribution of the functional phase throughout the paper structure, while minimizing surface accumulation. The excess formulation removed during the coating process was collected separately. The treated handsheets were oven dried at 105 °C to allow evaporation of the carrier phase and retention of the functional component in the matrix of the handsheets.

2.5 Characterization

The prepared hand-sheets were analyzed for their transparency, gloss, Cobb, tensile index, burst factor, and tear strength index using standard testing methods. For measuring tensile properties, ISO 1924-2:2009-05 was adopted, and the measurement of tear index and burst factor was carried out following ISO 1974:2012-09 and ISO 2758:2011-03, respectively. The water absorptivity test was done using Cobb45 according to ISO 535:2014. The gloss determination was done using the ISO 8254-1 standard method. The optical transparency was measured using the opacity measurement method per ISO 2471:2008, with transparency determined as 100 minus the opacity. The evaluated properties were used to determine the effect of the concentration of functionalizing agent on the optical, barrier, surface, and mechanical properties of the developed semi-transparent handsheets.

3. Results and Discussion

3.1 Mechanical Properties

The mechanical, optical, and water absorption properties of the developed semi-transparent paper at different concentration of functionalizing agent are presented in Table 2. The mechanical properties of the produced semi-transparent paper are greatly influenced by the concentration of the functionalizing agent. The tensile strength shows a clear decline, from 54.76 Nm/g for the untreated sample to 37.23 Nm/g at the highest functionalization agent concentration. Similar trends can be seen when considering the burst factor; the value falls from 53.80 for the control to 35.56 as the concentration of the functionalizing agent increases. This decrease in tensile strength and burst factor is a result of the increased penetration of the functionalizing agent in the inter-fiber bonding region of the cellulose matrix. However, increased incorporation of hydrophobic material partially restricted direct fiber-fiber hydrogen bonding, which reduces the efficiency of stress transfer and structural cohesion within paper matrix. On the other hand, the tear resistance index showed a first increase in value to 13.02 mNm^2/g from 9.84 mNm^2/g with a moderate treatment loading, but it dropped subsequently to 8.83 mNm^2/g with the highest treatment loading. The initial increase in tear resistance could be due to enhanced flexibility and controlled fiber pull-out during crack propagation. The moderate addition of the functional phase could reduce the rigidity of the fiber matrix and thus improved energy absorption during tearing. However, excessive treatment loading weakened inter-fiber cohesion and facilitated easier crack propagation, resulting in lower tear resistance at higher concentration. Figure 1 presents influence of the concentration of functionalizing agent on tensile index, tear index, and burst factor of the developed semi-transparent paper with increasing concentration of functionalizing agent.

Similar results have been obtained in modified cellulose and microfibrillated cellulose systems in which the addition of hydrophobic or barrier forming material improves flexibility at low levels of treatment but reduces tensile strength and bursting strength at high levels due to degradation of the bonding of cellulose (10, 11). It has been found in recent research that sustainable functional paper materials need to be developed by balancing barrier enhancement with retaining sufficient mechanical strength (6, 7). Therefore, based on mechanical property results, moderate concentration of functionalizing agent provides an optimum balance between flexibility, toughness, and structural integrity of the developed semi-transparent paper system.

Table 2: Properties of developed semi-transparent papers at different concentrations of functionalizing agent

Sample	Transparency (%)	Gloss (G.U)	Cobb45 (g/m^2)	Tensile Index (Nm/g)	Burst Factor	Tear strength index (mNm^2/g)
S0	40.18±0.18	4.40±0.08	28.50±0.49	54.76±1.22	53.80±4.09	9.84±0.63
S10	45.95±0.53	4.43±0.12	25.35±0.67	48.24±1.69	51.11±1.28	11.53±0.83
S20	50.76±1.16	4.53±0.12	22.31±0.27	45.43±1.40	46.67±2.97	12.76±0.51
S30	54.63±1.15	4.64±0.14	20.36±0.52	42.99±1.33	40.83±2.15	13.02±0.27
S40	61.65±0.89	4.85±0.37	19.87±0.58	37.23±3.33	35.56±2.14	8.83±0.41

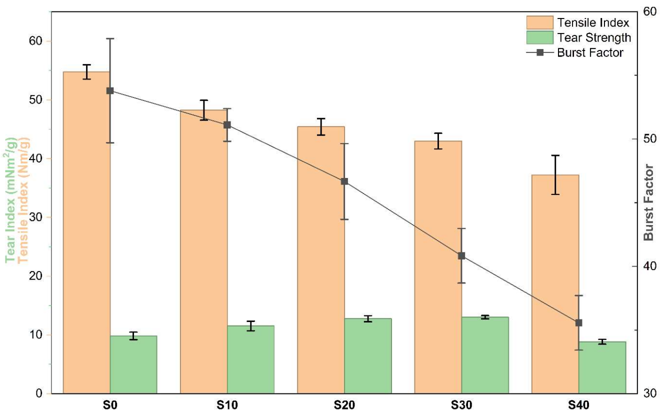

Fig 1: Effect of concentration of functionalizing agent on physical properties of developed semi-transparent paper

3.2 Water Absorption Properties

The water absorption behavior of the developed semi-transparent paper was evaluated through Cobb45 testing, which is presented in Figure 2. The Cobb value of the untreated paper was 28.50 g/m² and it decreased progressively from 25.35 to 22.31, 20.36, and finally to 19.87 g/m² as the concentration of the functionalizing agent increased. This reduction in the Cobb value can be explained by the fact that due to partial filling of inter-fiber pores and reduction of capillary pathways within the paper structure due to increase in concentration of functional phase. Furthermore, the developed treatment reduced the accessibility of water molecules to the cellulose network, thereby limiting liquid penetration within the sheet structure. The obtained Cobb values indicate significant improvement in water resistance behavior of the developed semi-transparent paper. The progressive improvement in optical transparency with increasing concentration of functionalizing agent is visually illustrated in Figure 3.

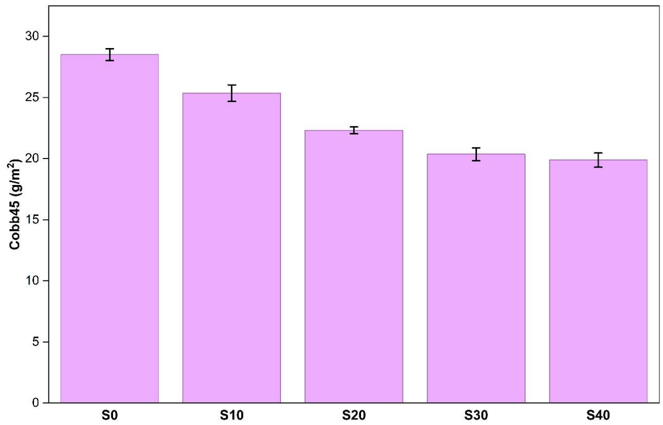

Fig 2: Effect of the concentration of functionalizing agent on Cobb45 of developed semi-transparent papers

3.3 Optical Properties

The optical properties of the developed semi-transparent paper were determined by analyzing transparency and gloss parameters. Transparency demonstrated an increasing trend from 40.18% in the untreated sample up to 61.65% in the case of maximal concentration of functionalizing agent, which implies that there was a significant decrease in the amount of light scattering inside the paper. The improved transparency could be associated with partial filling of inter-fiber voids and reduction in refractive index mismatch between cellulose fibers and entrapped air within the porous network. Increased incorporation of the functional phase facilitated greater light transmission through the sheet structure.

On the other hand, there was a slight rise in gloss values, from 4.40 to 4.85 G.U., with an increase in the concentration of functionalizing agent. From the slight variance in gloss measurements, it can be seen that the treatment mainly affected the internal pores of the material and did not form a highly glossy surface coat. The slight increase in gloss readings could be attributed to improved surface smoothness and reduction in diffuse light reflection.

Fig 3: Effect of concentration on optical transparency of developed semi-transparent papers

3.4 Practical Applicability Assessment

To demonstrate the practical applicability of the developed semi-transparent paper, QR codes were printed on the developed hand sheets and successfully scanned using a mobile device through the paper structure. The semi-transparent nature of the developed paper enabled visibility of the enclosed product while maintaining scannability of the printed QR code from the external surface. This feature may provide additional potential for tamper-evident and product-authentication packaging applications in which product authentication is possible by using a QR code that is accessible without being able to physically access the inside of the package. Representative images of the developed semi-transparent paper and QR code scanning demonstration are presented in Figure 4.

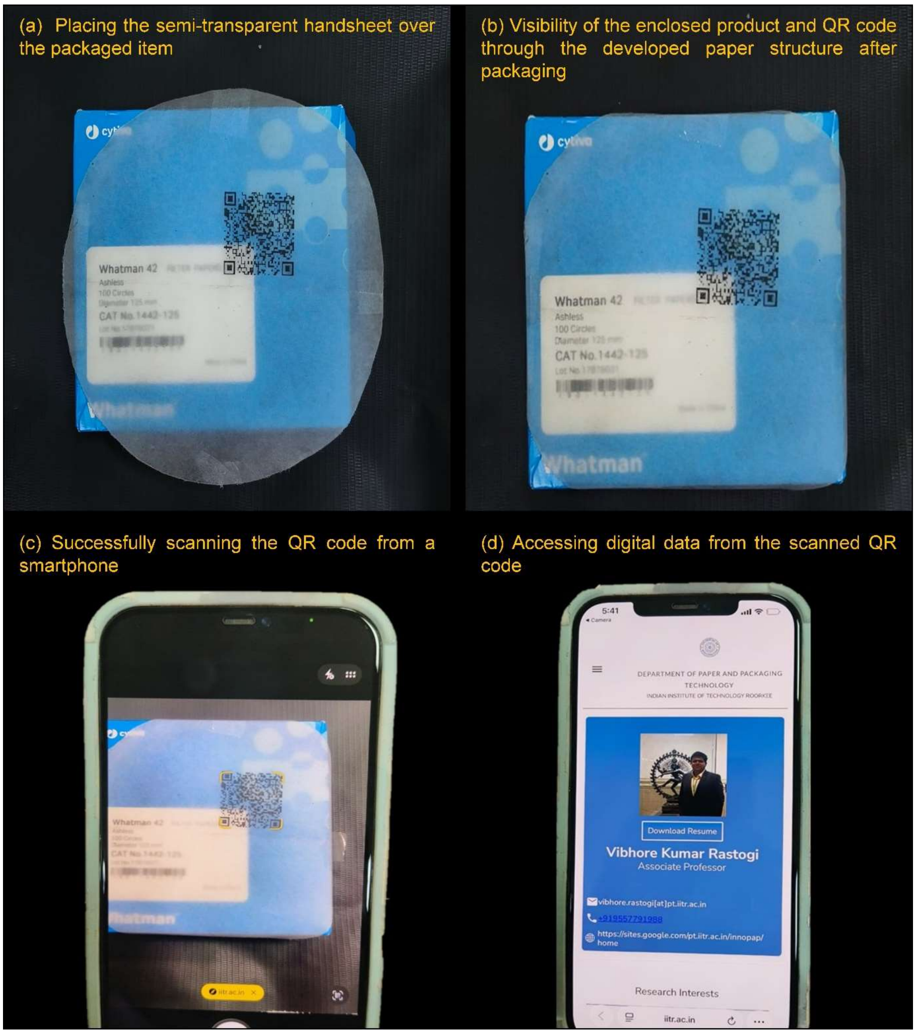

Fig 4: Practical applicability assessment of the developed semi-transparent papers.

Conclusion

The present study has demonstrated the capability to generate semi-transparent paper with excellent optical and hydrophobic properties by modifying the structure of low-refined softwood fiber networks in a controlled manner. The treatment with functionalizing agent effectively altered the porous morphology of the cellulose matrix resulted in the increase in transparency while significant reduction in Cobb45 value. The continuous decrease in Cobb45 values with increasing concentration of functionalizing agent proves that the capillary movement was limited within the fiber network.

Mechanical properties of the paper after modification showed significant dependence on concentration of functionalizing agent. The gradual decrease in the tensile index and burst factor under high concentrations suggests the partial disruption of inter-fiber hydrogen bonding and decreased stress-transfer efficiency within the cellulose network. In turn, the tear factor increased at moderate concentration, which implies better flexibility and more controlled fiber pull-out during crack formation. The comparatively limited variation in gloss values further suggested that the developed modification approach mainly influenced the internal porous structure of the paper rather than forming a dense surface coating layer.

Moreover, the practical evaluation of applicability showed that reliable reading of QR codes is possible on such semi-transparent paper materials using mobile for scanning, thereby demonstrating the capability of the developed material to combine product visibility with functional tamper-proof characteristics. Overall, the semi-transparent paper shows a good balance between transparency, hydrophobicity, and mechanical strength, demonstrating significant promise as an eco-friendly replacement for plastics in flexible packages.

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