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Enhancing Film Quality and Uniformity in Pearlescent Bi-axially Oriented Polypropylene Films: A Study of Manufacturing Process

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Abstract

Polypropylene (PP) is essential granules in the plastics industry for packaging purposes. This study investigates the manufacturing process of pearlescent biaxially oriented polypropylene (BOPP) films, focusing on quality parameters and surface uniformity. ASTM methods were used to evaluate the physical, optical, mechanical, and thermal characteristics. On the basis of experimental work, the results were analyzed using statistical paired two-sample t-tests and scanning electron microscopy (SEM) analysis were employed to assess density variation and surface non-uniformity respectively. Most quality parameters fell within typical ranges observed in commercial films. Significant density variations were found between Sample 1 (M = 0.714 g/cc) and Sample 2 (M = 0.763 g/cc) of P-BOPP A ($p < 0.001$, $t(4) = -17.89$), while no significant differences were observed for P-BOPP B and P-BOPP C. SEM analysis revealed rough patches on film surfaces, possibly attributed to substances like calcium carbonate or dirt. Controlling parameters such as thickness, unit weight, and surface uniformity is crucial to achieve consistent and high-quality pearlescent BOPP films. Further research on process optimization and control strategies is recommended to minimize density variations and enhance film performance.

Keywords: BOPP Films, Pearlescent Films, Quality Parameters, Surface Uniformity, Scanning Electron Microscopy.

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1. Introduction

Plastic films play a pivotal role in the industrial packaging sector, providing unparalleled protection for sterilized equipment, lightweight packaging, and prolonged product shelf life [1]. The versatility and wide-ranging applicability of single-use polypropylene (PP) packaging, particularly in the form of flexible film, have rendered it indispensable in sectors including agriculture, food storage, construction, and healthcare. Consequently, the global packaging film market is projected to surpass \$166 billion by 2027, with the PP market alone estimated to grow from \$111.3 billion in 2020 to \$174 billion by 2027 [2]. To realize the full potential of packaged goods, it is imperative to have effective and reliable packaging solutions that safeguard products from external influences and maintain their quality and safety throughout storage, transportation, post-processing, and sales [3-4]. Within the family of synthetic resins, PP stands out as an important member alongside polyethylene, polystyrene, polyvinyl chloride, and acrylonitrile butadiene styrene plastic [5]. PP can be classified into two categories based on composition: homo-polymer polypropylene and copolymer polypropylene [6]. Moreover, it can be further categorized into three types based on structural differences: isotactic polypropylene, anisotropic polypropylene, and atactic polypropylene [7].

A notable variant of PP films is bi-axially oriented propylene (BOPP) films, which undergo stretching in both transverse and machine directions [8-9]. This stretching process imparts desirable mechanical and barrier properties, dimensional stability, and processability to the films [10-11]. Furthermore, the optical properties and pearl-like aesthetic appearance of BOPP films have been enhanced by incorporating fillers and such as calcium carbonate, pigment, and talc, resulting in a structure known as cavitated and pearlescent structure. During the orientation process, small cavities are formed within the polymer, as the particle interface undergoes biaxial stretching [12-13]. Notably, pearlescent BOPP films find extensive use in the food packaging industry [14]. To further enhance their performance, various coatings are commonly applied to control gas and moisture permeability, thereby prolonging the shelf life of food products [15].

While Numerous studies have examined various aspects of biaxially oriented polypropylene (BOPP) films, including degradation mechanisms, breakdown characteristics, and other electrical related phenomena [16-19]. There appears to be a gap in the literature regarding the specific focus of this study over the last decade. Therefore, the objective of this study is to address the research gap by examining the manufacturing process of commercial pearlescent BOPP films and evaluating their quality parameters and surface uniformity. By gaining insights into these aspects, the study aims to optimize the production process and develop control strategies that minimize density variations, improve film performance, and ensure consistent and high-quality pearlescent BOPP films.

2. Materials and methods

2.1. Materials

The Film samples referred as P-BOPP A, P-BOPP B, and P-BOPP C were collected from the packaging industry located in Karachi. The films were supplied in form of A4 sized sheets with 25µ, 30µ, and 38µ thickness, respectively.

2.2. Methodology

2.2.1. The analysis of quality parameters of pearlescent BOPP film

The methodology of this study involved conducting various physical, optical, mechanical, and thermal tests to assess the quality parameters of the films. First, the physical tests were performed, including measurements of thickness, unit weight, coefficient of friction (C.O.F), yield, and treatment of the surface. The thickness of the films was measured using a digital thickness gauge following ASTM standard D-6988. The unit weight determination was conducted using a precision balance, adhering to ASTM standard D-646. The coefficient of friction was evaluated using a friction tester, in accordance with ASTM standard D-1894. The yield of the films was calculated based on ASTM standard D-4321. The surface treatment evaluation was carried out using a surface energy analyzer, following ASTM standard D-2578. Optical tests were conducted to assess the gloss measurements at 60°C using a gloss meter according to ASTM standard D-2457, opacity using an opacity meter, following ASTM standard D-589, haze measurements using a haze meter in accordance with ASTM standard D-1003. Following the optical tests, mechanical properties of the films were evaluated. Tensile strength at break was determined using a universal testing machine, adhering to ASTM standard D-882. The elongation at break was measured as per ASTM standard D-882. Lastly, thermal tests were performed to analyze the dimensional stability, heat seal temperature range, and heat seal strength of the films. The dimensional stability was assessed using a precision measuring tool, following ASTM standard D-1204. The heat seal temperature ranges and heat seal strength at 130°C were evaluated using a heat sealer. The density of each sample was then calculated with several measurements of thickness and unit weight for P-BOPP A, P-BOPP B, and P-BOPP C by below mentioned formula.

$$Density\ (\rho) = \frac{Unit\ Weight}{Thickness}$$

Microsoft Excel was utilized as a tool for data analysis, where the calculated densities, were organized in spreadsheets. Paired two-sample t-tests for means were conducted using Excel's statistical functions and formulas to compare the mean densities between Sample 1 and Sample 2 for each film. The significance level (α=0.05) was chosen to determine statistical significance. The calculated t-values and p-values were examined to assess the differences in densities. The results were analyzed to determine whether the observed differences in densities were statistically significant or attributable to random variation.

2.2.2. The analysis of surface non uniformity of pearlescent BOPP film

The non-uniformity of the film's surface was investigated using scanning electron microscopy (SEM) micrographs of the cross-section of P-BOPP A. The SEM analysis was performed with a JSM-6380A Jeol Japan scanning electron microscope. The objective of this analysis was to examine the surface characteristics of the film and identify any irregularities or rough patches present. To prepare the sample for SEM analysis, a representative portion of P-BOPP A was carefully cut and mounted on a sample stub using a conductive adhesive. The mounted sample was then sputter-coated with a thin layer of gold to enhance its conductivity and improve the imaging quality during SEM observation. After the preparation process, the sample was inserted into the SEM chamber, and micrographs of the cross-section was captured at specific magnification. During the SEM analysis, the minimum and maximum sizes of the observed rough patches on the film's surface were also investigated. This provided valuable information regarding the extent and distribution of the non-uniformities present. By examining the micrographs, the morphology and topography of the rough patches were assessed, allowing for a comprehensive understanding of the surface characteristics and their potential impact on the film's overall quality and performance. In addition to SEM analysis, Table 1 presents the multilayer structure of the pearlescent BOPP films under study. It provides details on the composition of each layer, including the skin layer, inner layer, core layer, and outer layer. The thicknesses of the layers and the additives used, such as the antiblock agent and calcium carbonate ($CaCO_3$) based additive, vary among the different films. This table provides essential information for understanding the film's construction and aids in linking the surface non-uniformities observed in the SEM analysis to the specific layers and additives present in the film structure.

3. Results and Discussions

3.1. The analysis of quality parameters of pearlescent BOPP film

The analysis of the quality parameters was conducted, and the results indicated that the majority of the parameters fell within the typical range observed for commercial pearlescent BOPP films. Table 2 present the findings for films with thicknesses of 25µ, 30µ, and 38µ, respectively. These tables provide an overview of the measured values for each parameter and demonstrate their adherence to established standards. However, the analysis of the quality parameters of pearlescent BOPP films revealed that the manufacturing process complexity resulted in variations in the thickness and unit weight, which in turn affected the density of the films. Specifically, the density ranged from a typical value of 0.714 g/ccto an abnormal value of 0.763 g/ccin in P-BOPP A. This was further investigated using Microsoft Excel Data Analysis, and the results are presented in the following tables. The mean densities of P-BOPP A Sample 1 and P-BOPP A Sample 2 were compared using a paired two-sample t-test in Table 3.

Table 1: The structure of multilayer pearlescent BOPP films under study

Layer	P-BOPP A (25µ)	P-BOPP B (30µ)	P-BOPP C (38µ)
Skin Layer	Copolymer + 2% Master batch (0.9µ)	Copolymer + 2% Master batch (0.9µ)	Copolymer + 2% Master batch (1.2µ)
Inner Layer	Homopolymer (µ)	Homopolymer (µ)	Homopolymer (1.6µ)
Core Layer	Homopolymer + 1.2% Antiblock + 10% CaCo3 based additive	Homopolymer + 1.2% Antiblock + 9% CaCo3 based additive	Homopolymer + 1.2% Antiblock + 7% CaCo3 based additive
Inner Layer	Homopolymer (µ)	Homopolymer (µ)	Homopolymer (1.6µ)
Outer Layer	Copolymer + 2% Masterbatch (1.1µ)	Copolymer + 2% Masterbatch (1.1µ)	Copolymer + 2% Masterbatch (1.2µ)

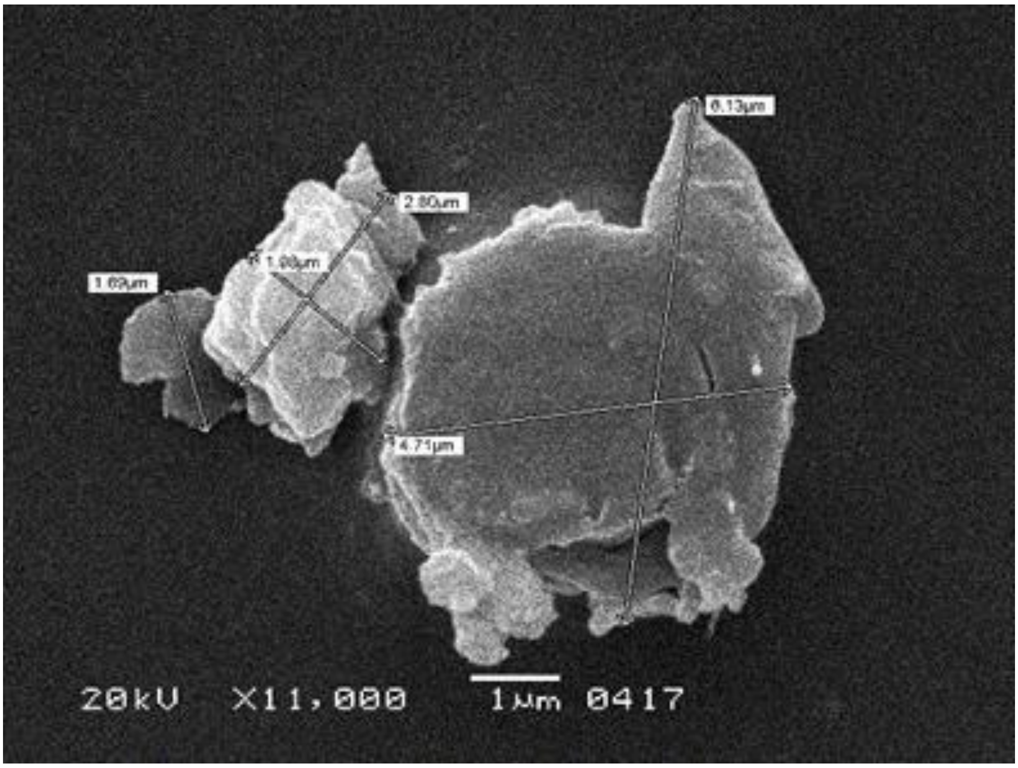

Figure 1: SEM micrograph of P-BOPP A showing rough patches on the surface.

Table 2: Summary of analyzed quality parameters of P-BOPP A, B and C.

Tests	Units	Typical Values		
		P-BOPP A	**P-BOPP B**	**P-BOPP C**
Thickness Measurement	micron	25	30	38
Unit Weight Determination	g/m2	18	22	27
Density	g/cc	0.714 0.763*	0.728 0.7272	0.728 0.7201
Yield Calculation	m2/kg	55.6	46.3	36.5
Surface Treatment Evaluation	dynes/cm	≥38	≥38	≥38
Gloss Measurement (at 60oC)	%	75	75	75
Opacity	%	70	70	70
Coefficient of Friction (C.O.F)	F*M	0.3	0.3	0.3
Tensile Strength at Break	MD (Kgf/mm2) TD (Kgf/mm2)	≥ 8 ≥ 14	≥ 8 ≥ 14	≥ 8 ≥ 14
Elongation at Break	MD (%) TD (%)	≤ 130 ≤ 60	≤ 130 ≤ 60	≤ 130 ≤ 60
Dimensional Stability	120°C, 15 min MD (%) TD (%)	 4 2	 4 2	 4 2
Heat Seal Temperature Range	°C	115-140	115-140	115-140
Heat Seal Strength at 130oC	g/cm	≥ 150	≥ 150	≥ 150
Haze Measurement	%	93	95	97

Note: *) Indicates the deviated value

Table 3: Paired two-sample t-tests for means densities of P-BOPP A.

	P-BOPP A Sample 1	**P-BOPP A Sample 2**
Mean	0.714	0.763
t Stat	-17.89227021	
P(T<=t) one-tail	2.86727E-05	
t Critical one-tail	2.131846786	

Note: *) P≤0.05; **) P≤0.01

Table 4: Paired two-sample t-tests for means densities of P-BOPP B.

	P-BOPP B Sample 1	**P-BOPP B Sample 2**
Mean	0.728	0.7272
t Stat	0.245255736	
P(T<=t) one-tail	0.409163708	
t Critical one-tail	2.131846786	

Note: *) P≤0.05; **) P≤0.01

Table 5: Paired two-sample t-tests for means densities of P-BOPP C.

	P-BOPP C Sample 1	**P-BOPP C Sample 2**
Mean	0.726	0.72013796
t Stat	1.605039168	
P(T<=t) one-tail	0.091877624	
t Critical one-tail	2.131846786	

Note: *) P≤0.05; **) P≤0.01

The mean density of P-BOPP A Sample 1 was M = 0.714 g/cc(SD = 0, N = 5), while P-BOPP A Sample 2 had a mean density of M = 0.763 g/cc(SD = 0, N = 5). With a t-statistic of t(4) = -17.89, with a corresponding p-value of 2.87E-05 which is significantly lower than the chosen significance level. The calculated t-value exceeded the critical t-value (t_critical = 2.13), providing strong evidence for rejecting the null hypothesis. Therefore, it can be concluded that the observed density variation is unlikely to have occurred by chance and there is a substantial variation in densities between P-BOPP A Sample 1 and P-BOPP A Sample 2.

Table 4 presents the results of a paired two-sample t-test for means comparing P-BOPP B Sample 1 and P-BOPP B Sample 2. P-BOPP B Sample 1 had a mean density of 0.728 g/cc, while P-BOPP B Sample 2 had a slightly lower mean density of 0.7272 g/cc. The calculated t-statistic was 0.245, with a corresponding p-value of 0.409. These results suggest no significant difference in the means of the two film samples, indicating that the observed density variation could potentially occur by chance. Table 5 presents the findings of a paired two-sample t-test for means comparing P-BOPP C Sample 1 and P-BOPP C Sample 2. P-BOPP C Sample 1 exhibited a mean density of 0.726 g/cc, while P-BOPP C Sample 2 had a slightly lower mean density of 0.72013796 g/cc. The calculated t-statistic was 1.605039168, with corresponding p-values of 0.091877624 for a one-tailed test. These results suggest that there may be a slight difference in the means of the two film samples, but it is not statistically significant. Thus, the observed difference in densities could potentially be attributed to chance or other factors not captured by the test.

3.2. The analysis of surface non uniformity of pearlescent BOPP film

The analysis of surface non-uniformity in pearlescent BOPP film was conducted, focusing on the examination of morphology and the presence of impurities. SEM micrograph revealed the existence of rough patches on the film surface as shown in **Figure 1**, indicating the presence of irregularities that could potentially contribute to the observed variation in film density. These rough patches were attributed to the presence of substances such as CaCO3 or dirt, which could have a significant impact on the film's density distribution. The SEM analysis provided valuable insights into the microstructural features of the film's surface and shed light on possible factors contributing to its non-uniformity. Maximum and minimum particle sizes of these patches were also identified.

4. Conclusions

In conclusion, the analysis of quality parameters and surface non-uniformity of pearlescent BOPP films yielded several noteworthy findings. The majority of the quality parameters examined aligned with typical ranges observed in commercial films, indicating adherence to established standards. However, variations in thickness and unit weight were observed, resulting in density variations within the films. Statistical analyses using paired two-sample t-tests revealed a significant difference in density between P-BOPP A Sample 1 and P-BOPP A Sample 2 from the typical value of 0.714 g/cc to an abnormal value of 0.763 g/cm³., indicating substantial density variation. Conversely, no significant differences were observed in the mean densities of P-BOPP B and P-BOPP C samples. The presence of rough patches on the film surface, as revealed by SEM, suggested the existence of irregularities that could contribute to density variations. These rough patches were attributed to substances such as CaCO3 or dirt, potentially influencing the film's density distribution. To ensure consistent and high-quality pearlescent BOPP films, it is crucial to monitor and control parameters like thickness, unit weight, and surface uniformity. Further investigations into process optimization and control strategies are recommended to mitigate density variations and enhance film performance.

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Authors' Contributions

Muhammad Khizar performed the experimental work, conducted the experimentations, collected the data, and wrote the laboratory reports. Additionally, Muhammad Khizar conducted the data analysis and interpreted the results. Shagufta Ishtiaque provided supervision and guidance throughout the entire experimentation process. Shagufta Ishtiaque reviewed and provided valuable feedback on the manuscript, ensuring the scientific rigor and accuracy of the study. Junaid Hashmi provided data, invaluable mentorship and guidance throughout the research process. He reviewed the manuscript and ensured scientific rigor. Mahwish Mobeen Khan contributed to the manuscript by compiling and organizing the research findings, ensuring proper formatting and coherence in the manuscript.

Conflicts of Interest Statement

The authors have no conflicts of interest to declare.

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Data Availability Statement

The author confirms that the data supporting the findings of this study are available within the article.

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