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Inline color measurement and analysis of the influence of machine parameters on the color of injection molded parts

In the injection molding process the optical properties play an important role in product quality. An inline color measurement sensor was chosen for determining the color of injection molded parts. The study involves examining the influence of machine setting parameters (screw rotational speed and back pressure) and the temperature of the part on the color outcomes. This research demonstrates how the selected measurement technique and machine parameters can be integrated inline for color measurement within the injection molding process to measure the color accurately. The selected sensor exhibits promising potential for practical insights, facilitating enhancements in production efficiency and quality control.

Inline-Farbmessung und Analyse des Einflusses von Maschinenparametern auf die Farbe von spritzgegossenen Bauteilen

Beim Spritzgießprozess spielen die optischen Eigenschaften des Bauteils eine zentrale Rolle für die Produktqualität. Ein Inline-Farbmesssensor wurde ausgewählt, um die Farbe von Spritzgussbauteilen zu untersuchen. Die Untersuchungen beinhalten die Analyse des Einflusses von Maschineneinstellparametern (Schneckenumfangsgeschwindigkeit und Staudruck) und auch der Bauteiltemperatur auf die Farbergebnisse. Der ausgewählte Sensor zeigt vielversprechendes Potenzial für praktische Einblicke, die Verbesserungen in der Produktionseffizienz und der Qualitätssicherung. Diese Forschung zeigt, wie die ausgewählte Messmethode und Maschinenparameter inline in den Spritzgießprozess integriert werden können, um die Farbmessung präzise durchzuführen.

1 INTRODUCTION

In 2021, 57.2 Mt of plastics were produced across Europe. While the majority (87.6%) of the annual European plastics production is based on (non-recycled) fossil-based raw materials, only a small proportion is made from post-consumer waste (10.1%) or bio-based materials (2.3%). The largest proportion of the total production, around 39.1%, is used in packaging [1]. For this sector the recycling targets have been set to 50% by 2025 and 55% by 2030 [2]. The current recycling rate for post-consumer packaging plastic waste in Austria is at 38% (status 2022) [1].

There is a clear gap between current recycling rates and the targets announced by the European Parliament [2]. Achieving these goals will require efficient collection strategies and robust processing techniques for all types of plastic waste materials. In general, two recycling routes can be distinguished: chemical and mechanical recycling [3]. In this work, the focus was on the latter. Mechanical recycling involves the recovery of solid plastic waste for subsequent use in the manufacturing of plastic products. The mechanical recycling process involves several key steps, including sorting, cutting or shredding large plastic parts into small flakes, reducing contamination through washing, drying, and extrusion to produce regranulate (see Figure 1). Sorting, washing, and the preparation of plastic solid waste contribute to achieving higher quality of the recycled material [4]. The regranulate can then be converted into a final product by means of processing steps such as injection molding and extrusion [5].

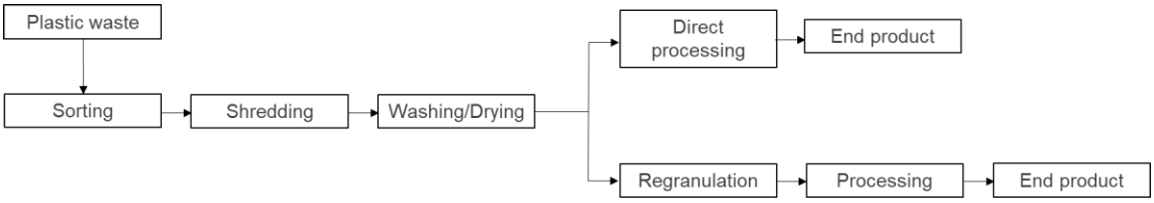


Figure 1: Steps of mechanical recycling

In many cases the pretreated plastic waste is converted in an extrusion line, which offers the advantage of combining several processing steps, such as homogenization and degassing or filtration, within a single process. However, for relatively clean material streams (f. ex. post-industrial waste or post-consumer waste from closed-loop recycling) with low levels of contamination, direct processing of the plastic waste material by an injection molding machine is an economically feasible alternative, as it eliminates the intermediate step of regranulation.

In the direct processing of plastic flakes, pretreatment also plays a significant role in achieving optimal mechanical and optical properties of the final product [6].

Inhomogeneous composition of the input material can, during injection molding of preconditioned plastic waste, give rise to fluctuations in product quality [7]. This can not only lead to inferior mechanical and optical properties, but also to unpleasant odors of the final part [8]. Unless they are detected in time and the process is adapted, optical irregularities (e.g., concerning transparency, surface quality and color [9]) can lead to rejects. Obtaining information about the color of the material processed during manufacturing is therefore key to reducing machine downtime and improving productivity. This is because color plays an important role in the quality assurance process [9]. Offline measurement methods, such as UV/VIS spectrophotometers and digital imaging, are not suitable for the injection molding purpose because they can lead to time delays between sample extraction and measurement [10]. Inline color sensors are better suited to integration into the workflow and allow real-time color analysis and evaluation as the materials are being processed.

In injection molding, inline color measurements can be carried out either directly on the input material, in the melt phase once the material is completely molten or on the final part (see Figure 2).

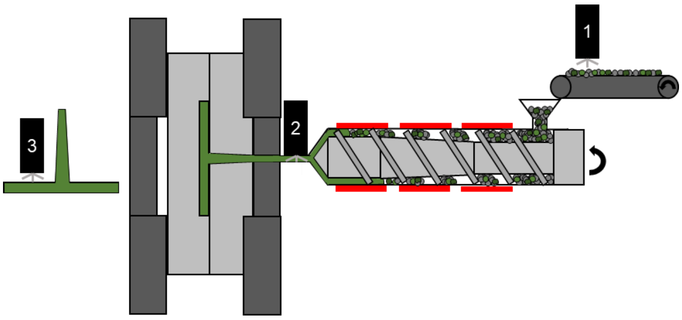


Figure 2: Potential application of inline color measurement sensors in the injection molding machine
Position 1: Color measurement of the input material, Position 2: Color measurement in the polymer melt and Position 3: Color measurement on the final part

The color of the incoming material can be measured inline on the conveyor belt. However, it is essential for the material to be well-distributed on the conveyor belt to accurately generate the color of the plastic material [11]. The preceding washing steps can also impact the color of the plastic flakes, as impurities have the potential to influence the color outcome [12]. Therefore, inline color measurement in the melt is more suitable, as there is already a homogeneous melt, and volatile impurities have ideally been eliminated.

Direct measurement of color within the melt enables immediate intervention in the process, facilitating adjustments through the addition of appropriate additives.

This approach minimizes the rejection of components. To enable color measurement in the polymer melt, specific conditions must be met, and hence implementation is not straightforward [13]. It is preferable to perform color measurements of the polymer melt after the die, where the melt is homogeneous. Since the laminar melt flow consists of various layers, variations in color may arise due to differences in layer speed. At the wall, the flow velocity is zero due to wall adhesion, which may hinder self-cleaning of the sensor head [14]. Further, when measuring in the melt phase, the effects of material temperature and pressure must be considered. It is widely known that temperature can influence the color appearance. This phenomenon – referred to as thermochromism [15, 16] – may occur in textiles, ceramics, paints, and, of course, plastics [17, 18]. Inline color sensors are already used in extrusion because they are sensitive to higher pressures [19, 20]. In extrusion, the pressure is lower within the melt channel than in injection molding. Inline color measurements can also be performed on the final part. In terms of data consistency, this method enables the measurement of the color of each part after demolding. One drawback of the color measurement method in the melt and on the part is that intervention to alter the process is then possible only after a time delay. For measuring the color of an injection molded part, machine setting parameters can have an impact on color and appearance (gloss) of an injection-molded part [21-24]. These effects were therefore examined in detail to demonstrate how to achieve an optimized color by adjusting the machine parameters.

In [25], the utilization of color measurement methods, Portable Spectrophotometer and True Color Sensor, in the injection molding domain was investigated. This comparative analysis facilitated the selection of a sensor for integration and the development of an inline setup for color measurement. This advancement not only enhances inline quality control but also aids in the early detection of deviations, ensuring color consistency across production batches and facilities, supporting sustainability efforts by optimizing recyclate incorporation, and minimizing costs through waste reduction. In this study, investigations are conducted to examine the influence of part temperature on color during the injection molding process, specifically focusing on demolding temperature. An infrared oven is utilized to heat the parts for this purpose. Additionally, inline color measurements were conducted on the parts using the selected sensor from [25] to assess the effects of machine settings parameters, including back pressure and screw rotational speed. These experiments were not only conducted on virgin material, but also focused on recyclates. In the future, the specialized application of color measurement for recyclates will play a key role in both science and industry.

2 THEORETICAL BACKGROUND

2.1 Description of color behavior and color space

Since color is not a physical but a psychophysical and thus subjective quantity, there is no uniform measurement system. Psychophysical measurement methods allow color values to be measured as X, Y, and Z values (i.e., tristimulus values) within the CIE color space. Conversion and representation of color values usually takes place in a defined color space. In industry, the CIELAB (Commission Internationale de l'Eclairage (CIE) 1976 Lab*) model is commonly used because it allows the distance between two points in the color space to be described by a parameter widely known as $\Delta\mathrm{E}$ [26]. This parameter is frequently used in quality control to define the difference between two colors (reference and target color) as a single numeric value.

To determine $\Delta\mathrm{E}$, the L^*, a^* and b^* values must be known. L^* is a metric lightness function, which describes the brightness or luminance within a range from 0 (black) to 100 (white). The parameters a^* and b^* (from -128 to +128), in contrast, are chromaticity coordinates between green and red, and between yellow and blue, respectively. The conversion of XYZ values into the CIELAB space assumes that the use of a standard illumination is used. For the color measurement methods studied, a D65 light source was used which is a standardized light source that closely resembles daylight [27]. The tristimulus (XYZ) values can be translated into the CIELAB Cartesian coordinate system (see Figure 3) by using the following relationships [28]:

$$L^* = 116\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} \quad for \ \left(\frac{Y}{Y_0}\right) > 0.008856 \tag{1}$$

$$otherwise \ L^* = 909.3\left(\frac{Y}{Y_0}\right)$$

$$a^* = 500\left[\left(\frac{X}{X_0}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_0}\right)^{\frac{1}{3}}\right] \tag{2}$$

$$b^* = 200\left[\left(\frac{Y}{Y_0}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_0}\right)^{\frac{1}{3}}\right] \tag{3}$$

where $X_0 = 95.047$, $Y_0 = 100$, $Z_0 = 108.883$ are predefined values that correspond to the D65 white point [28].

The color distance between two points in the CIELAB space can then be obtained by [29]:

$$\Delta E^*_{ab} = [(\Delta a^*)^2 + (\Delta b^*)^2 + (k\Delta L^*)^2]^{1/2} \tag{4}$$

where $k = 1$ for samples close to each other in color space. To categorize the ΔE values calculated, the following classification can be used [30]:

- $0 < \Delta E < 1$: no differences are noticed by the observer;
- $1 < \Delta E < 2$: differences can be noticed only by experienced observers;
- $2 < \Delta E < 5$: differences can be noticed by unexperienced observers;
- $3.5 < \Delta E < 5$: differences are readily apparent;
- $5 < \Delta E$: two different colors can be perceived.

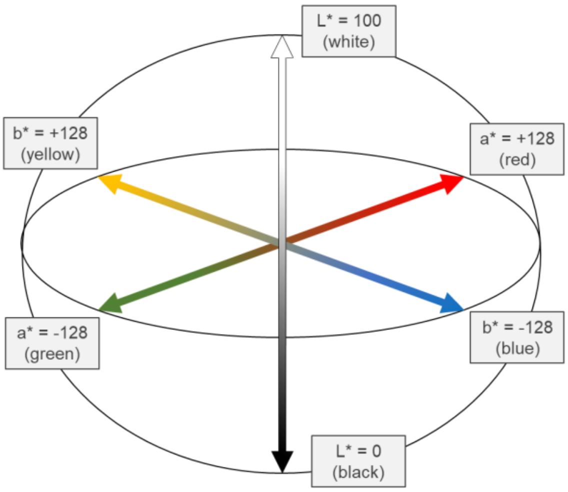


Figure 3: CIELAB color space: L: lightness; a* and b*: chromaticity coordinates*

2.2 Color sensor

In [25] the suitability of two color measurement methods (Portable Spectrophotometer and True Color Sensor) for evaluating the color of injection-molded discs were compared. Therefore, the True Color Sensor (TCS) was selected and have been used for these subsequent experiments. The TCS has three distinct sensors, each of which targets a specific segment of visible light spectrum: long-, intermediate-, and short-wavelengths. These sensors facilitate the acquisition of color data that aligns with the spectral sensitivity defined in the CIE 1931/DIN 50331 standard, which is based on the human color perception [29]. The TCS method also allows tristimulus values (XYZ) corresponding to the color values captured to be determined. Note that the TCS method does not yield detailed spectral information about the sample. Unlike a spectrophotometer, which captures full spectral data [31-33], the TCS focuses on the XYZ tristimulus values, omitting the comprehensive spectral information. A significant advantage of the TCS is its simple sensor construction, which enables cost-effective production.

This simplicity makes the TCS a practical choice for various applications in which accurate color measurement, but no extensive spectral data is required. Its compatibility with the human color perception makes it invaluable in numerous industries and applications [34], and especially for injection molding. Additionally, the ease of translating its results into standard color spaces and its cost-effectiveness render the TCS an attractive choice for color analysis.

3 EXPERIMENTAL

3.1 Measurement setup and materials

For the experimental analyses, discs with a sprue were produced from the materials listed in Tables 2-3 by injection molding with the ENGEL e-mac 180. The process settings of the injection molding machine for the production of the test specimens are listed in Table 1. The parameters of screw speed and back pressure were varied for the experiments performed in section 3.1.2. The injection molded discs had a diameter of 150 mm and a thickness of 2 mm.

Table 1: Injection molding parameters for the production of the circular parts.

Injection molding parameter	Value
T_{Mold}	30°C
$T_{injection/nozzle}$	240°C
Screw rotational speed	0.2 m/s
Holding pressure	170 bar
Holding pressure time	5 s
Back pressure	50 bar

3.1.1 Analysis of Thermochromism

A setup illustrated in Figure 4 was utilized for offline color measurement against a matte background (to avoid reflections) inside a housing (to avoid influences caused by ambient light. The sensor was attached to a bracket that allowed flexible adjustment of the measuring distance. The distance between color sensor and sprue was 45 mm. The color measurements were consistently conducted at the same location on each part, aided by a pressure transducer implemented within the cavity. The imprint of this sensor assisted in orientation. The technical data of the True Color Sensor is described in detail in [25].

Since different processes require different injection mold temperatures, investigating the behavior of color under a variety of temperatures is essential.

To assess the influence of part temperature on color behavior, a temperature sensor was installed in addition to the color sensor, as shown in Figure 4. The temperature sensor and the color sensor were mounted at the same distance from the sprue (45 mm), but on opposite sides. Care was taken to ensure that these two measuring systems did not influence each other.

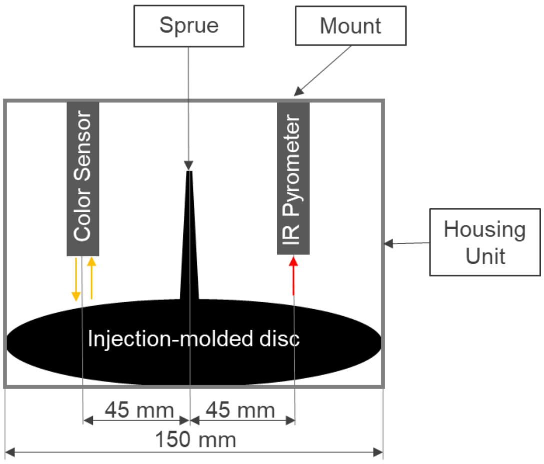


Figure 4: Set-up for color and temperature measurement methods of injection-molded parts

To cover a broad range of colors, mixtures of virgin and recycled polypropylene (PP) materials were created. The virgin material employed was a heterophasic polypropylene copolymer with a melt flow rate (MFR) of 100 g/10 min (230°C/2.16 kg) and a density of 905 kg/m^3 [35]. The recycled material consisted of agglomerated polypropylene homopolymer films from a post-consumer material stream. For the masterbatches (granular form) used, a concentration of 2.0 wt% was recommended by the manufacturer. The granular masterbatches were selected for their suitability in achieving uniform coloration, efficient dispersion, and the ability to facilitate quicker processing changes when using solid colorants [36]. The masterbatches used were based on a polyethylene carrier polymer. Subsequently, the masterbatch was added to these mixtures at the injection molding machine using a masterbatch dosing unit.

In the selection of colors, the focus was on the colors already used for the comparison of the sensors in [25]: yellow, green, and gray. Additionally, a color from the first color quadrant (orange) and a color from the third color quadrant (violet) were chosen to demonstrate whether temperature influence occurs for these colors within the selected temperature range.

This information about thermochromism for the mentioned colors covers representatives from light to dark within the color space and helps gather information about the behavior of thermochromism for future measurements.

Each mixture consisted of virgin material combined with 2 wt% color masterbatch (see Table 2). Note that the color for the gray blend was composed of pure agglomerated recyclate. In total, five distinct mixtures for in-depth analysis of thermochromism were considered.

Table 2: Material mixtures to assess the influence of thermochromism on color measurements

Ex. #	**Experimental designation**	**Virgin material (PP)**	**Recyclate (PP)**	**Color**	**Color of master-batch**
1	V1_yellow_V100%_R0%_MB2%	X	-	Yellow	X
2	V2_green_V100%_R0%_MB2%	X	-	Green	X
3	V3_orange_V100%_R0%_MB2%	X	-	Orange	X
4	V4_violet_V100%_R0%_MB2%	X	-	Violet	X
5	V5_gray_V0%_R100%_MB0%	-	X	Gray	-

3.1.2 Influence of process parameters on color

To examine the influence of process parameters on the color of the final part, inline color measurements were performed using an ENGEL e-mac 180 with a barrier screw (diameter of 35 mm and mixing head) and a robotic arm for demolding the part. Additionally, a photo box was installed near the conveyor belt to shield the set-up from ambient light during measurement (see Figure 5). The sensor configuration in the photobox was kept identical to that of the offline measurements.

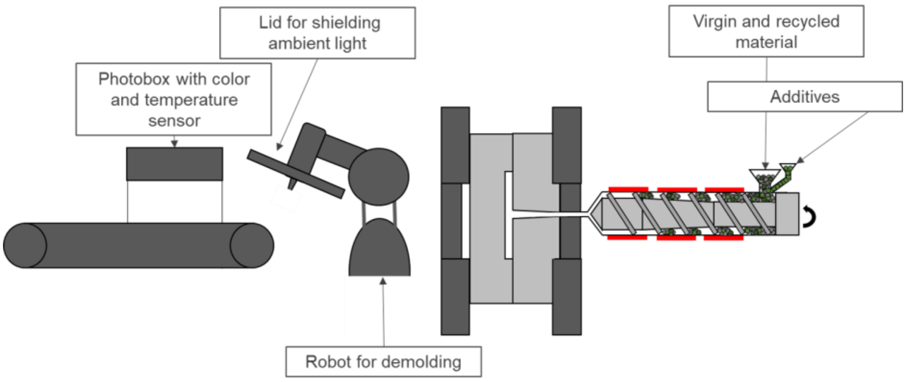


Figure 5: Schematic representation of the injection molding cycle using a D35 barrier screw with automatic removal of the components by a robotic arm and automatic color and temperature measurement of the component after demolding.

In the analysis of the influence of process parameters on the coloration of the injection-molded component, relatively low masterbatch concentrations were selected, to enable the assessment of how well the color spreads and mixes in. An inadequate dispersion of the color would be evidenced by the appearance of different colors among the considered components. Virgin material was mixed with 0.25 wt% masterbatch in yellow and green (see Table 3). Given the expansive array of hues within the color space, the selection process commenced with green and yellow. The selection of these colors was based on their previous use in preliminary research in [25], as the focus was on the second quadrant of the color space, from the negative a-axis to the positive b-axis. The virgin and masterbatch materials used are described in detail in section 3.1.1.

Table 3: Material mixtures for inline color measurements

Ex. #	**Experimental designation**	**Virgin material (PP)**	**Recyclate (PP)**	**Masterbatch color [0.25 wt%]**
6	V6_yellow_V100%_R0%_MB0.25%	X	-	Yellow
7	V7_green_V100%_R0%_MB0.25%	X	-	Green

3.2 Measurement Procedure

3.2.1 Analysis of Thermochromism

Exploring color behavior involved measuring the color after the demolding process. The investigation focused on observing color changes within the temperature range from 60°C to 25°C. First, discs were produced on the injection molding machine and then subjected to heating in an IR oven at 60°C. Upon removal from the oven, the components were placed directly in the measuring device and allowed to cool down to room temperature. Using Equation 4, the color distance between the color of the part at 60°C and the color at 25°C was determined. Three different components were considered for each color masterbatch listed in Table 2. The measurement setup was as shown in Figure 4.

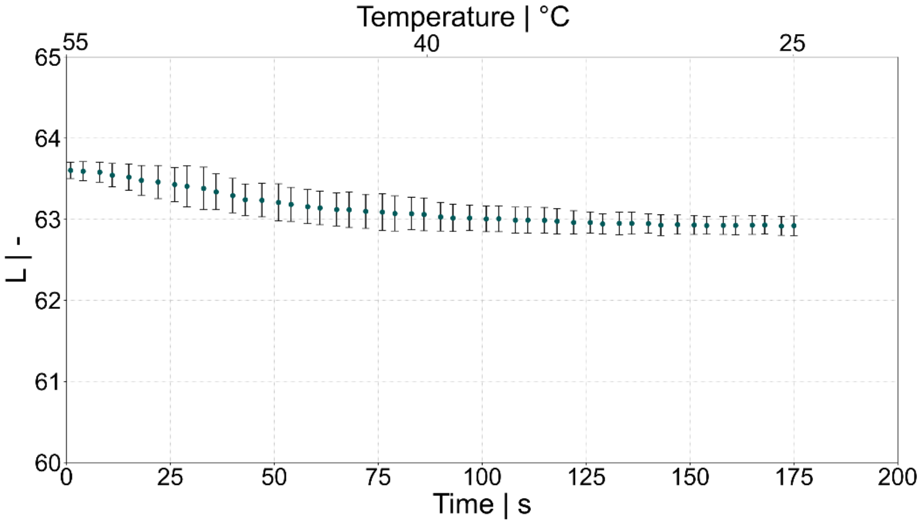
3.2.2 Influence of process parameters on color

To investigate the impact of machine parameters on color, the TCS was integrated into a photobox next to the conveyor belt to measure the color inline after the molding process. This involved demolding the component by means of a robotic arm and placing the disc in front of the sensors within the photobox, neither of which prolonged or interrupted the process. In injection molding, there are process parameters that can be varied to match the process to the requirements. These include injection speed, mold and cylinder temperature, back pressure, screw rotational speed, packing pressure, and packing time. For these experiments, two parameters were selected that have a significant effect on distributive mixing: back pressure and screw speed. Higher back pressure results in better mixing in the melt. Screw speed also affects the residence time of the melt; lower screw speeds increase the residence time in the barrel, while higher screw speeds decrease the residence time. In addition, higher screw rotational speeds increase the shear rate, resulting in better mixing and faster melting. The back pressure values were chosen to demonstrate higher values and therefore better mixing, so a normal value of 50 bar and two higher values (75 bar and 100 bar) were chosen for the investigations. For screw speed, two values in the high and low range were chosen: 0.15 m/s and 0.25 m/s to see if there were color differences between lower and higher screw speeds. Typically, a screw speed of 0.2 m/s is recommended for this process. For each machine parameter setting, 10 measurements of the components were taken once the process had reached a stable state. The effects of different mold temperatures were examined in the course of the thermochromism experiments.

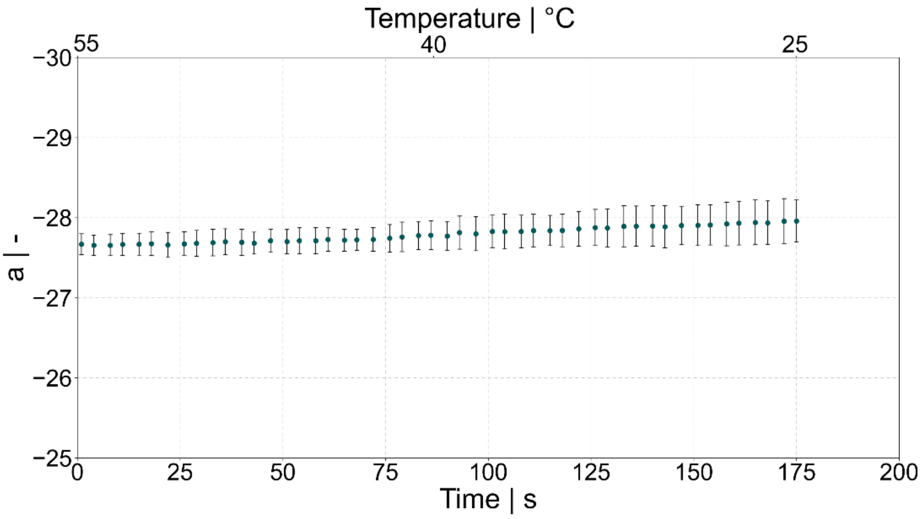
4 RESULTS AND DISCUSSION

4.1 Analysis of Thermochromism

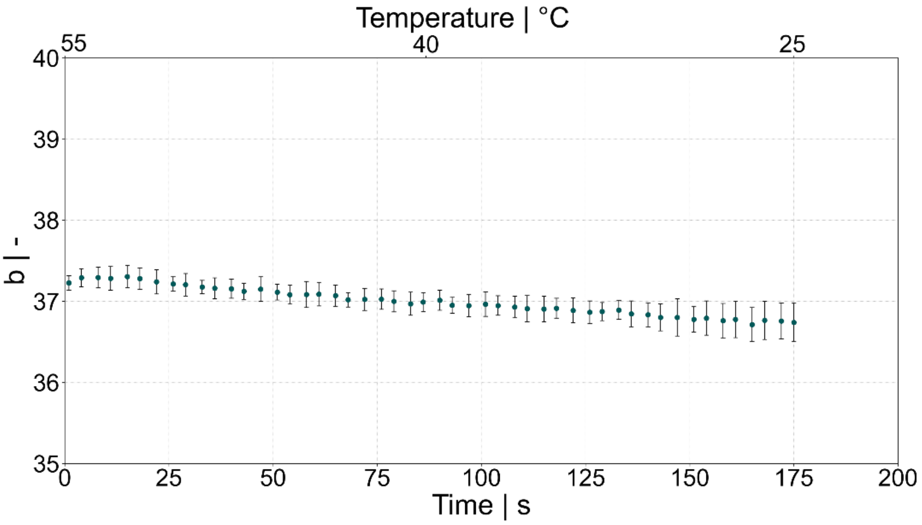
The findings presented in Table 4 show the impact of various temperatures on color in experiments V1_yellow_V100%_R0%_MB2% to V5_gray_V0%_R100%_MB0%. Figure 6(a), (b) and (c) shows the cooling process and resulting influence on the CIELAB color values for one color, green (V2_green_V100%_R0%_MB2%), over time. The CIELAB color values were divided into individual diagrams. All three values exhibited an equal influence on changing color values with respect to temperature variations. These results shown in Figure 6 were obtained for all the colors investigated and the ΔE values were calculated from them and listed in Table 4.



(a)



(b)



(c)

Figure 6: Influence of temperature on the CIELAB color values in experiment V2_green_V100%_R0%_MB2%: (a) L-, (b) a- and (c) b-values

When the temperature was reduced from 55°C to 25°C, a pattern emerged: For components infused with green and yellow masterbatches, the maximum ΔE value was 1, and thus the shift in color was most pronounced. For darker hues, such as the nuanced gray and violet tones, the influence of temperature on color behavior was notably more subdued. The orange shade examined exhibited a maximum ΔE of 0.7, which was higher than for darker shades ($\Delta E \leq 0.6$) but lower than for the lighter ones ($\Delta E \leq 1$). Temperature – at least after demolding – showed no significant effect on the ΔE values obtained.

In order to obtain accurate ΔE values that are not influenced by temperature differences, it is advisable to carry out the reference color and the inline color measurements at the same temperatures.

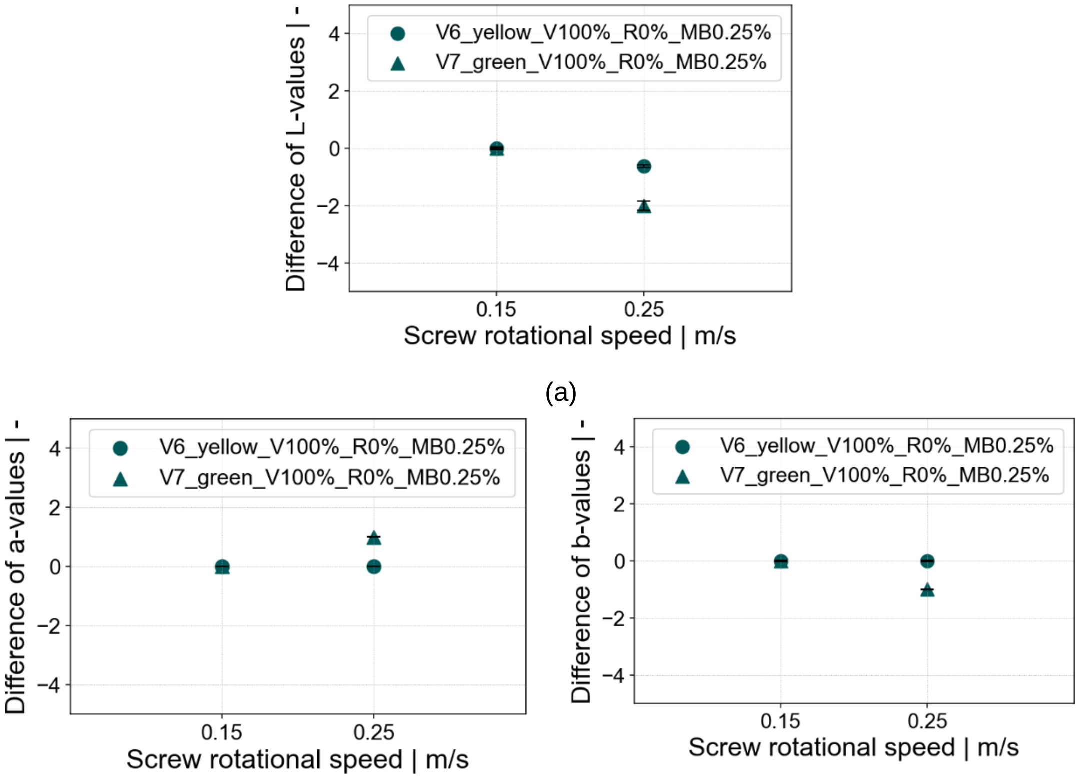
Table 4: Results of the thermochromism measurements

Color	**max. ΔL**	**max. Δa**	**max. Δb**	**max. ΔE**
Yellow	0.5	0.6	0.6	1.0
Green	0.6	0.6	0.6	1.0
Orange	0.3	0.4	0.5	0.7
Violet	0.5	0.3	0.1	0.6
Violet	0.5	0.3	0.1	0.6
Gray (Recyclate)	0.5	0.1	0.2	0.6

4.2 Influence of process parameters on color

To determine the influence of screw rotational speed (see Figure 7), and back pressure (see Figure 8), the material mixtures from experiments V6_yellow_V100%_R0%_MB0.25% and V7_green_V100%_R0%_MB0.25% as listed in Table 3 were used. A relatively low masterbatch content of 0.25% was used to facilitate better analysis of the mixing behavior. As stated previously, it can be assumed that at higher concentrations mixing results in homogeneous blends and thus changing the process parameters have less effect.

For a higher screw rotational speed, no significant impact on color was observed. In experiment V6_yellow_V100%_R0%_MB0.25% (see Figure 7), a maximum ΔE of 0.6 was obtained, which may be attributable to measurement inaccuracies of the system. Experiment V7_green_V100%_R0%_MB0.25% (see Figure 7) resulted in a higher maximum ΔE value of 2. Although this color change is picked up by the sensor, it is perceptible only to the experienced observer. Therefore, it can be concluded that the screw rotational speed has no significant influence on the color.

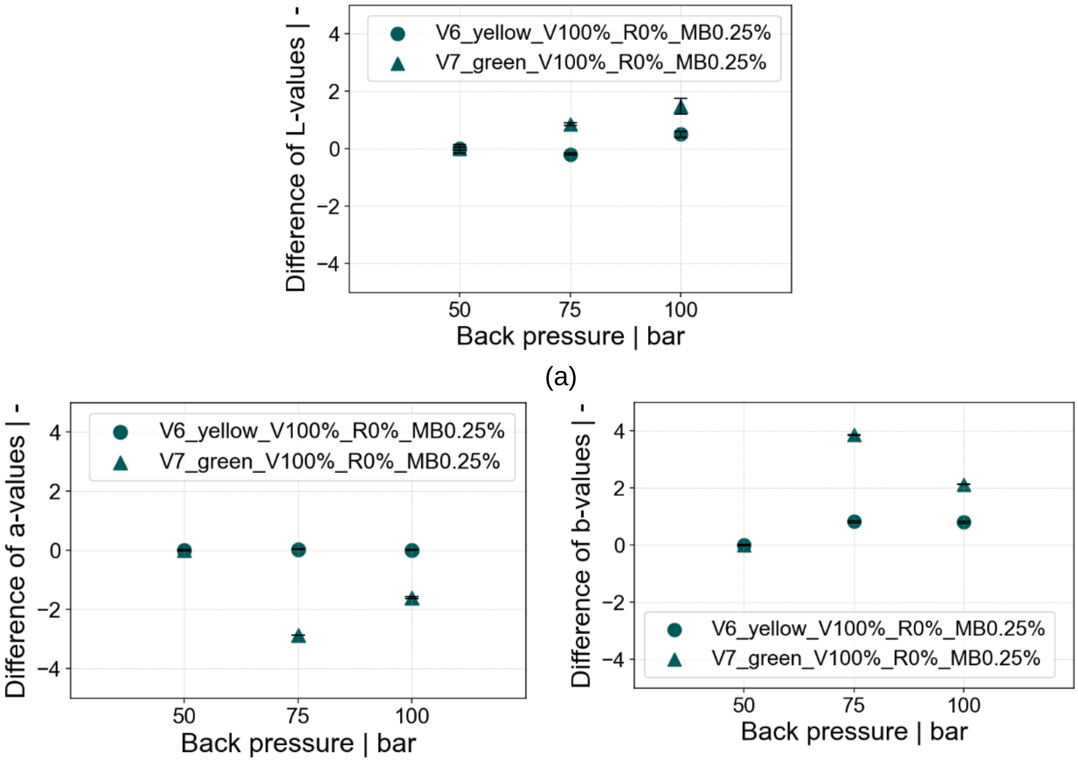


(a)

(b) (c)

Figure 7: Influence of screw rotational speed on the CIELAB color values in V6_yellow_V100%_R0%_MB0.25% and V7_green_V100%_R0%_MB0.25%: (a) L-, (b) a- and (c) b-values

Changing the back pressure in experiment V6_yellow_V100%_R0%_MB0.25% resulted in a different b-value, but not in a significant change in the L- and a-values. The maximum ΔE obtained was thus 0.9. The highest back pressure setting led to the highest b-value (see Figure 8(c)). This demonstrates that increased back pressure promotes better mixing, as these experiments used a yellow masterbatch, which is represented in the positive b-axis in the CIE color space. This effect was also observed for experiment V7_green_V100%_R0%_MB0.25% (see Figure 8(b)), where a higher back pressure setting resulted in an a-value shift towards green. In this experiment, the L- and b-values were also influenced. Since a light green was used, higher L-values were obtained with higher back pressure. Additionally, the b-values shifted towards yellow, as the green hue used is located in the first quadrant of the color space. This resulted in a maximum ΔE of 3. These experiments show that back pressure can affect the color of the molded part, but only a small amount of color variation.



(a)

(b) (c)

*Figure 8: Influence of back pressure on the CIELAB color values in V6*_yellow_*V100%_R0%_MB0.25%* and *V7*_green_*V100%_R0%_MB0.25%*: *(a) L-, (b) a- and (c) b-values*

5 CONCLUSION AND OUTLOOK

This work dealt with the color of injection-molded parts, particularly of those processed from virgin and recycled materials. There are three possible approaches to inline color measurement of plastics: on the incoming material (flakes/granulates), in the melt and on the component. Color measurement on the input material can be challenging, as the material needs to be well-distributed on a conveyor belt to obtain an accurate color value [11]. Additionally, impurities on the material can lead to changes in color values [12]. Also, when measuring color in the melt, additional parameters need to be considered, adding complexity to the process [13]. Color assessment on the final component is a valuable method for process analysis because it allows individual component color to be determined, facilitating sorting in cases where the reference color is not achieved. In addition, the color on the final component is already homogenized because it is processed in the plasticizing unit using appropriate mixing equipment.

For the inline measurement, the selected sensor was integrated into a specially developed photobox, which allowed the color measurement directly on the part without interrupting the injection molding process. The photobox was instrumental in the shielding of ambient light and the creation of a consistent environment for each measurement. In addition, the influence of process parameters was investigated, showing that both the temperature of the part (mold temperature) and the back pressure can affect color values. Different colors were found to respond differently to changes in temperature and pressure. To ensure consistent and stable color measurement results, it is critical to maintain consistent process settings throughout the color measurement series. It is advisable to perform reference color measurements under the same settings to reduce any effects on $\Delta\mathrm{E}$ caused by different settings and temperatures.

As part of future research, implementing direct adjustment of process settings and automated adjustment of color masterbatches may be important approaches to minimizing $\Delta\mathrm{E}$. Studying the color differences between different layers in the polymer melt would be another interesting avenue for future research.

ACKNOWLEDGEMENT

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