Comparison of post-consumer recycling PET bottles from flakes and regranulate

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Abstract: Mechanical, optical, and thermal properties of cosmetic bottles made from two types of post-consumer waste (PCR) PET were studied: solid-state polycondensation (SSP) regranulate and flakes decontaminated using an infrared cleaning system. The bottles were manufactured using a single-stage injection stretch blow molding (ISBM) process. The intrinsic viscosity, wall thickness distribution, top load strength, degree of crystallinity, CIELab color parameters, and acetaldehyde (AA) and other volatile organic compounds (VOC) content were determined. The regranulate bottles had higher intrinsic viscosity, and a higher degree of crystallinity. They also exhibited higher top load strength and improved optical and aesthetic quality, due to more effective chain rebuilding and filtration during SSP processing. Bottles made from decontaminated flakes had a more uniform wall thickness distribution, but contained more and larger contaminants. Both materials meet the mechanical requirements for cosmetics packaging, confirming the suitability of 100% PCR PET for applications with high aesthetic requirements.

Keywords: PET recycling, PET decontamination, mechanical properties, sustainability.

Porównanie butelek PET z płatków i regranulatu pochodzących z recyklingu pokonsumenckiego

Streszczenie: Zbadano właściwości mechaniczne, optyczne i termiczne butelek kosmetycznych, wykonanych z dwóch rodzajów odpadów poużytkowych (PCR) PET tj. regranulatu PET wytworzonego w technologii polikondensacji w stanie stałym (SSP) oraz płatków dekontaminowanych w systemie czyszczenia na podczerwień. Butelki otrzymano w procesie jednostopniowego formowania z rozciąganiem wtryskowym (ISBM). Oznaczono lepkość graniczną, rozkład grubości ścianek, wytrzymałość na zgniatanie osiowe (*top load*), stopień krystaliczności, parametry barwy w przestrzeni CIELab oraz zawartość aldehydu octowego (AA) i innych lotnych związków organicznych (VOC). Butelki z regranulatu miały większą lepkość graniczną i wyższy stopień krystaliczności. Charakteryzowały się również większą wytrzymałością *top load* oraz lepszą jakością optyczną i estetyczną, co wynikało z efektywniejszej odbudowy łańcuchów polimerowych i filtracji podczas procesu SSP. Butelki z płatków dekontaminowanych cechowały się bardziej równomiernym rozkładem grubości ścianek, ale zawierały więcej zanieczyszczeń o większej wielkości. Oba materiały spełniały wymagania mechaniczne stawiane opakowaniom kosmetycznym, co potwierdza możliwość stosowania 100% PCR PET w produktach o wysokich walorach estetycznych.

Słowa kluczowe: recycling PET, dekontaminacja PET, właściwości mechaniczne, zrównoważony rozwój.

Plastic bottles are widely used as primary packaging for various liquid products including beverages, cosmetics, household chemicals, and pharmaceuticals. Among the most common polymers used are poly(ethylene terephthalate) (PET), polypropylene (PP), high-density polyethylene (HDPE), and biodegradable materials such as polylactic acid (PLA). PET dominates the market due to its excellent optical clarity (comparable to glass), high strength-to-weight ratio, good barrier properties, chemical resistance, and safety in food contact applications. It

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is also highly versatile in design, allowing the production of containers in various shapes, sizes, and colors – which is important from both technical and marketing perspectives [1].

Over the past two decades, increasing environmental pressure has shifted the industry's focus toward sustainable packaging solutions. PET has responded particularly well to these demands, owing to its ease of collection and recycling. Due to its widespread use in beverage bottles, PET is one of the easiest polymers to sort mechanically using optical and infrared technologies, enabling effective recycling since the early 2000s [2, 3].

The regulatory landscape in Europe has further promoted circularity. Since 2008, post-consumer recycled (PCR) PET can be used in direct food-contact packaging, provided it undergoes approved decontamination processes (EC Regulation No. 282/2008 [4], EC No. 10/2011 [5]), under European Food Safety Authority (EFSA) supervision. Similar provisions exist in the United States under Food and Drugs Administration (FDA) guidelines [6–10]. As a result, extensive research is conducted [10, 11], and several industrial-scale, energy efficient technologies for producing "food-grade" PCR PET have emerged [12–16].

These technologies vary in process sequence, energy efficiency, and final material quality. Most fall into two categories:

– Solid-State Polycondensation (SSP)-based technologies, used by companies like Starlinger [17] Erema [18, 19] and Buhler, where washed PET flakes are re-extruded, filtered, and polymer chains are rebuilt in SSP reactors under vacuum or inert gas.

– Infrared dryer + vacuum decontamination systems, such as Kreyenborg IR Clean [20], which skip the SSP step and offer faster but less intensive purification.

The final products from these technologies include PCR PET regranulate (typically used in injection molding) and decontaminated flakes (which can be processed directly in some applications).

In recent years, chemical recycling of polymers, including PET, has gained growing attention as a complementary alternative to conventional mechanical recycling. While standard recycling methods rely on the physical processing of post-consumer PET through grinding, washing, and re-melting (commonly referred to as mechanical recycling), chemical recycling involves depolymerization of PET flakes via hydrolysis or glycolysis, breaking the ester bonds in the polymer backbone. The resulting monomers (terephthalic acid and ethylene glycol) can be reintroduced into virgin PET polymerization processes, typically at ratios of 25–30%. The final polymer is considered post-consumer recycled PET (PCR PET) under EU and U.S. legislation and can be used in standard preform and bottle manufacturing [2, 21].

Despite the widespread industrial use of both regranulate and flakes, there is a lack of comparative studies evaluating their mechanical, optical, and aesthetic performance when used under identical processing conditions – especially in applications requiring high appearance standards, such as cosmetics.

This study aims to compare the performance of 400 mL bottles manufactured from two types of "food-approved" PCR PET feedstocks: regranulate obtained using Buhler's SSP-based technology; and decontaminated flakes prepared using Kreyenborg IR Clean Plus. The materials were processed using single-stage ISBM (injection stretch blow molding) under the same conditions. The resulting bottles were evaluated for mechanical strength, material distribution, optical clarity, color properties, crystallinity, acetaldehyde and VOC content, and aesthetic appearance, to evaluate their suitability for high-quality, sustainable packaging applications.

EXPERIMENTAL PART

Materials

PCR PET flakes from the Polish selective municipal waste collection system (yellow bag system) were used. The flakes were decontaminated using the Kreyenborg IR Clean Plus system (Senden, Germany). The flakes were pre-dried in an infrared dryer for approximately 18 min (6 min in each zone): first zone – 100°C, second zone – 130°C, third zone – 170°C. After decontamination, the PET flakes were dried at 170–180°C for 2 h. Food-grade PCR PET regranulate (CB602R) produced by extrusion and solid-state polycondensation (SSP) under vacuum conditions, supplied by Far Eastern New Century Corporation (Taipei, Taiwan) (Fig. 1). Bottle-grade virgin PET that meets EU food contact standards and is used as a reference in selected analyses. All materials were stored in sealed containers and dried prior to processing. Key material properties were measured prior to sampling, including intrinsic viscosity (IV), moisture content, bulk density, and impurity levels (Table 1).

Bottle and sample preparation

The bottles were manufactured using a single-stage injection stretch blow molding (ISBM) process on a Nissei DPH70

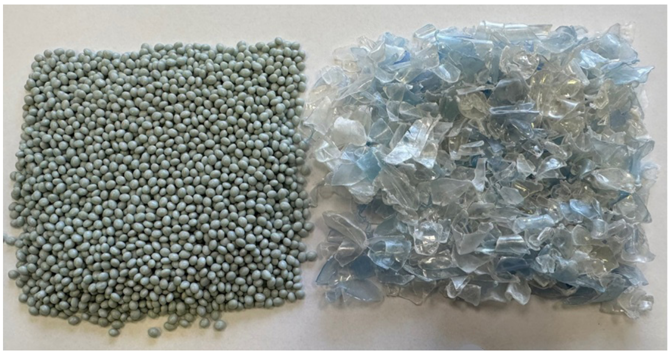

Fig. 1. Decontaminated PCR PET samples

v4 machine (Nagano-Ken, Japan). Approximately 500 400 ml, 23 g bottles were produced using a 5-cavity, hot-runner injection stretch blow mold. A Maguire Ultra vacuum dryer (Aston, PA, USA) was used for pre-drying. Pre-drying parameters: drying time – approx. 4 h; temperature – 165°C. Injection parameters: section 1 temperature – 300°C, middle of extruder – 295°C, front of extruder – 293°C, nozzle – 290°C, hot runner – 265°C, injection pressure – 13.9 MPa, injection time – 2.58 s, blow time – 1.6 s, stretch time – 2 s.

For bottles made from virgin PET, pre-drying temperatures and increased vacuum levels were used to minimize degradation.

Methods

Intrinsic viscosity (IV)

Intrinsic viscosity (IV) of flakes, decontaminated flakes, regranulate and final bottles were measured with same method described further, with Dynisco LMI 5000 plastometer. The method used was in accordance with the PN-EN ISO 1133 standard and described in detail in the literature [22]. Samples weighted approximately 5 g were cut from wall of the bottle. In the first step were dried for 4 hours at 140 ± 2°C in vacuum dryer. Then, the intrinsic viscosity of samples was measured using semi-automatic method (A/B). The measurement temperature was 285°C and the piston loading 2.16 kg.

Bulk density

Bulk density was assessed using Coesfeld tester with internal Hanex method, based on ISO 60 standard.

Moisture content

Moisture content was determined using a Radwag MA. R (Radom, Poland) electronic laboratory moisture analyzer. Approx. 10 g of material was placed in the device and weighted. After drying at 120°C, the measurement was repeated, and moisture content was calculated according to Equation 1.

$$Moisture\ content = \frac{m_1}{m_2} \cdot 100\,\% \tag{1}$$

where: m_1 – weight before drying, m_2 – weight after drying.

Appearance assessment

Bottles were visually inspected under controlled lighting for optical defects (cloudiness, color uniformity, black spots, opalescence). 200 g of sample on a metal tray was placed in a drying oven preheated to 200°C for 1 h. After cooling, parts with visible stains and discolorations were further examined for assessment of contaminants.

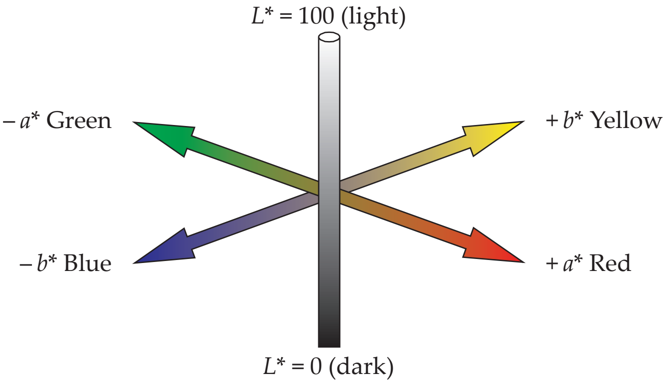

Fig. 2. Color evaluation using CIELab color space [23]

Color

The color of used PET samples was tested using with spectrophotometer HunterLab /Ultrascan VIS/ USVIS1677, assessed with CIELab color space. The color was described as a combination of L*, a* and b*, with following meaning shown in Figure 2.

Top load

The top load was evaluated using a Zwick/Roell Z 2.5 test apparatus (Zwick, Ulm, Germany) with a 2.5 kN measuring head and a travel speed of 60 mm/min. The test was performed in accordance with industry standards.

External dimensions and wall thickness

The wall thickness was measured by ElectroPhysik Minitest 7200H (Cologne, Germany). Material distribution was calculated using Equation 2:

$$Material\ distribuion = \frac{max_{wall\ thickness} - min_{wall\ thickness}}{max_{wall\ thickness}} \cdot 100\,\% \tag{2}$$

Measurements of bottles wall thickness were made according to the points indicated in Figure 3.

Differential scanning calorimetry

Differential scanning calorimetry (DSC) was performed using a Netzsch model DSC-200 F3 Maia in accordance with PN-EN ISO 11357. 4.5–5.0 mg samples, taken from bottles walls were analyzed in 3 cycles: heating-cooling-heating under nitrogen atmosphere with a flow rate of 30 ml/min. First heating cycle from 23°C to 300°C at 10 K/min heating rate. Afterwards, the sample was cooled from 300°C to 23°C at 10 K/min cooling rate. In the last step, the sample was heated again from 23°C to 300°C at 10 K/min heating rate. Measurements were performed with the use of aluminum crucibles with one empty as a reference sample. The following crystallization and melting parameters were determined: melting temperature (T_m), melting enthalpy (ΔH_m), crystallization temperature (T_c), and degree of crystallinity (X_c). The

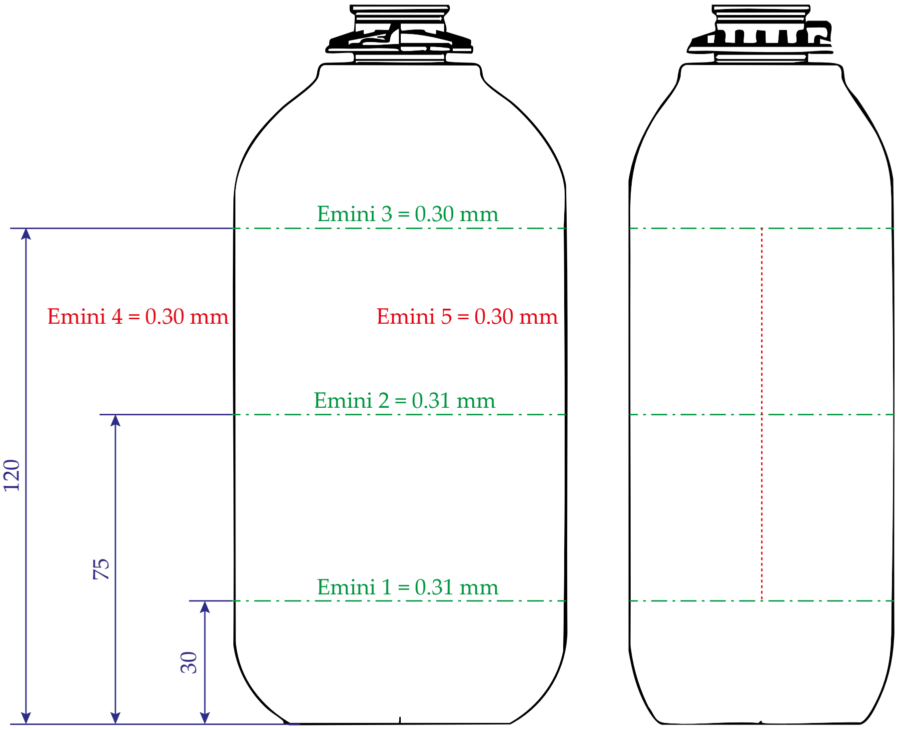

Fig. 3. Thickness measurements of PET bottles

degree of crystallinity was calculated using following Equation 3:

$$X_c = \frac{\Delta H_m}{\Delta H_{100}} \tag{3}$$

where ΔH_m is the measured melting enthalpy (J/g) and ΔH_{100} is the mean melting enthalpy of full crystalline PET, which equals 140 J/g [24].

Acetaldehyde and volatile organic compounds

Content of acetaldehyde (AA) and other volatile organic compounds (VOC) was measured by Perkin Elmer Clarus 500 gas chromatograph (GC) with Turbo Matrix TMX HS16 autosampler and flame ionization detector (FID). Samples cut from the bottle walls (approx. 3 g) were ground in a SPEX Sample Prep 6770 cryogenic mill for 15 min, then sieved through a 0.85 mm mesh sieve and 1 ± 0.01 g were weighed for analysis. The content of acetaldehyde and volatile organic compounds (in ppm) was calculated from the area under the curve.

RESULTS AND DISCUSSION

The intrinsic viscosity, moisture content, and contamination levels of all PET materials are summarized in Table 1.

As shown in Table 1, PET flakes had the lowest intrinsic viscosity (0.65–0.72 dL/g; average 0.68–0.69 dL/g). Decontaminated flakes showed slightly higher values (0.68–0.74 dL/g), which can be attributed to the removal of surface contaminants and the effect of high-temperature, low-vacuum treatment during decontamination. These conditions, like those in solid-state polycondensation (SSP) but without catalysts, may result in a slight increase in the intrinsic viscosity.

Regranulate achieved an IV of 0.76–0.84 dL/g, typically 0.76–0.80 dL/g, with IVs above 0.80 dl/g observed after SSP treatment during recycling. Virgin PET had an IV in the range of 0.78–0.84 dL/g, most commonly 0.80–0.82 dL/g. The similarity between virgin PET and regranulate confirms the effectiveness of SSP in chain reconstruction during recycling.

Table 1. Characteristics of flakes, decontaminated flakes, regranulate and virgin PET

Property	IV dL/g	Bulk density g/dm^3	Moisture %	Other polymers contamination ppm	Other materials contamination ppm	Acetaldehyde AA ppm	Color *L**
Flakes	0.65–0.72	230–380	<1	60	250	Below 3	Min. 65
Flakes decontaminated	0.68–0.74	300–380	<0.4	50	200	Below 1	Min. 60
Regranulate	0.76–0.84	800–950	~0.1	10	10	Below 1	65–78
Virgin PET	0.78–0.84	800–950	<0.05	0	0	Below 1	Min. 82

Bulk density revealed significant differences between flakes and granulates. Flakes showed values of 230–380 g/dm^3, which is 2–3 times lower than regranulate and virgin PET granules (800–950 g/dm^3). The density of granulates is determined by their regular shape, while irregular flake geometry reduces bulk density and usually lowers feeding efficiency in screw plasticizing units [25–27]. In the case of this study, this effect was not observed (or observed to a small extent), and the efficiency was, respectively: 1200 bottles/h (virgin PLA), 1200 bottles/h (regranulate) and 1100 bottles/h (decontaminated flakes).

For polyesters such as PET, moisture content before processing should not exceed 0.005 % to avoid hydrolytic degradation of ester bonds. Typical moisture levels in the tested materials were: 1% for post-consumer PET flakes, 0.4% for decontaminated flakes, 0.1% for regranulate and 0.05% for virgin PET.

Low moisture content is crucial to prevent reductions in IV, loss of mechanical and optical properties (whitening, haze), and processing issues [2, 28–30]. These results show that both regranulate and decontaminated flakes, when properly dried, meet moisture requirements for bottle production.

Contamination by other polymers in PCR PET flakes did not exceed 60 ppm and was reduced to 50 ppm after decontamination. Regranulate, due to filtration during extrusion, contained a maximum of 10 ppm, primarily polyethylene or polypropylene.

Foreign matter (wood, paper, sand, aluminum) reached 250 ppm in PCR flakes and 200 ppm in decontaminated flakes, but only 10 ppm in regranulate. No polymer or foreign material contamination was detected in virgin PET.

AA content in PCR flakes was 3 ppm, decreasing to 1 ppm after decontamination. Regranulate and virgin PET also had AA levels of 1 ppm. These values meet market requirements for mineral water and other food-contact bottles (<3 μg/g according to EFSA). The reduction in AA in decontaminated flakes demonstrates the effectiveness of the cleaning process, while the additional filtration and SSP steps in regranulate production provide further quality assurance.

Color of input materials and bottles (regranulate decontaminated flakes) and its changes in the CIELab color space parameters are summarized in Table 2.

The CIELab color space is commonly used to evaluate the color of materials and products [9, 23]. In this system, L^* represents lightness ($L^* = 0$ for black, $L^* = 100$ for white), a^* is the green (–) to red (+) axis, and b^* is the blue (–) to yellow (+) axis [31].

The color of recycled PET input material is strongly correlated with the quality of washing, purification, and recycling processes. PET flakes typically show lower L^* values compared to regranulate, due to their heterogeneous size and thickness, as well as surface whitening and creasing caused by hot washing. Regranulate, being uniform and highly crystalline, exhibits higher L^* values.

The a^* and b^* coordinates depend on the degree of purification, the presence of other polymers, and the color composition of the PET feedstock – especially the proportion of green flakes or flakes containing oxygen-barrier additives, most often polyamides. Over the past decade, a shift of a^* and b^* values towards the blue range have been observed, resulting from the intentional addition of light blue flakes (up to 10 ppm). This practice is widely used by recyclers to improve the visual appearance of RPET and is accepted by end-users. A slightly bluish–grayish shade of RPET packaging is preferred over a greenish–yellowish tone, which is associated with food degradation.

In the last 3–5 years, especially in Western Europe, the increased number of recycling cycles of PCR PET bottles has caused both flakes and regranulate to appear darker and more grayish. However, there is no direct predictive relationship between the L^*, a^*, b^* values of flakes and regranulate; only the general visual appearance of the final product can be anticipated rather than precise numeric values.

For reference, original PET granules from RAMAPET Company showed the following minimum CIELab values: $L^* = 78$; $a^* = -0.8$; $b^* = 1$ [32]. By comparison, Szymczak [33] reported for RPET: injection-molded samples: $L^* = 60.13$, $a^* = -1.28$, $b^* = 4.77$; and for RPET film samples: $L^* = 88.97$, $a^* = 1.42$, $b^* = -2.37$.

Bottles from both trials were visually inspected for impurities using standardized impurity-size templates. The results clearly showed superior quality in bottles made from regranulate, which benefited from a full filtration stage with backflushing filters during the regranulation process.

In a sample of 100 bottles, only 39 black specks were detected in bottles from regranulate, compared to over 300 in the case of bottles from decontaminated flakes. In addition to being more numerous, impurities in bot-

Table 2. Color L*, a*, b* parameters of input materials and bottles

Sample	L^* Lightness	a^* Green/-Red	b^* Blue/-Yellow
Regranulate	77.59 ± 0.71	-1.73 ± 0.13	-1.34 ± 0.21
Decontaminated flakes	66.82 ± 0.77	-1.52 ± 0.07	0.83 ± 0.12
Bottles from regranulate	89.56 ± 2.10	-0.47 ± 0.04	0.95 ± 0.05
Bottles from decontaminated flakes	86.61 ± 2.30	-0.43 ± 0.04	1.41 ± 0.08

T a b l e 3. Comparison of RPET bottles from regranulate and decontaminated flakes – impurities

Amount of black spots pcs/100 buttles	Flakes	Regranulate
0.2	0	29
0.3	269	9
0.4	79	1
0.5	42	0
0.6	14	0
0.7	16	0
0.8	10	0
0.9	10	0
1.0	17	0
1.1	0	0
1.2	11	0
1.3	4	0
1.4	4	0
1.5	3	0
1.6	3	0
1.7	2	0
1.8	3	0
1.9	1	0
2.0	0	0
2.5	2	0
3.0	0	0
3.5	0	0
4.0	1	0

tles from decontaminated flakes were significantly larger than those in regranulate bottles.

Table 3 presents the detailed impurity counts and size distribution. The high impurity level in bottles made from decontaminated flakes indicates a need for further improvements in flake purification and cleanliness.

One of the key quality concerns for post-consumer recycled (PCR) PET packaging – particularly bottles intended for water or milk – is the presence of volatile degradation products. The most significant is acetaldehyde (AA), but other compounds classified by the European Food Safety Authority (EFSA) as non-intentionally added substances (NIAS) may also be present.

Although AA levels in PCR PET bottles and its migration into water (the most sensitive product) are well below the limits set by European and US regulations, even small amounts can impart a detectable "green apple" flavor. Industry guidelines recommend AA levels in blown bottles of 5–7 ppm for flat or carbonated mineral waters, while values of 12–15 ppm are acceptable for juices and carbonated soft drinks (CSD) such as cola.

Other volatile organic compounds (VOCs) occasionally detected in recycled PET include 1,3-dioxolane, benzene, toluene, and ethylene glycol, though their concentrations are typically below a few ppm.

The measured contents of AA and VOCs in 400 ml PCR PET bottles from decontaminated flakes and from regranulate are shown in Table 4. Bottles made from regranulate exhibited lower levels of volatiles - especially AA - compared to bottles from decontaminated flakes. This difference can be attributed to the more effective decontamination of regranulate, which is produced from material already filtered and plasticized in extruders equipped with vacuum systems.

In contrast, decontaminated flakes undergo only a single vacuum-based cleaning step, without the benefit of additional filtration. This demonstrates the advantage of regranulate in applications requiring very low volatile content, although both materials meet "food-approved" standards for PCR PET bottles, even for sensitive products.

The top-load parameter is a key indicator of the mechanical strength of PET bottles. It determines their resistance to vertically compressive forces and has practical implications such as calculating the maximum stack-

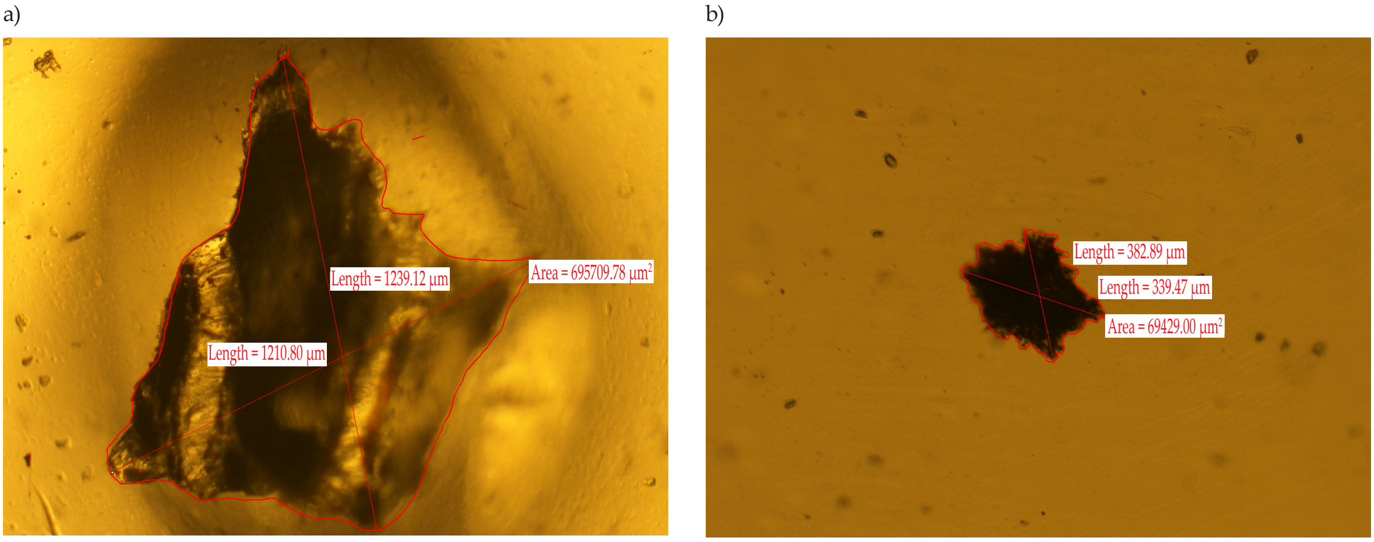
a) b)

Fig. 4. Images of impurities from PCR PET (magnification ×100): a) decontaminated flakes, b) regranulate

T a b l e 4. AA and VOC content in examined PCR PET bottles

Compound	Decontaminated flakes	Regranulate
Acetaldehyde, ppm	6.21 ± 0.16	3.35 ± 0.37
1,3-dioxolane, ppm	1.65 ± 0.02	0.46 ± 0.01
Toluene, ppm	1.18 ± 0.14	0.51 ± 0.03
Benzene, ppm	1.59 ± 0.19	0.04 ± 0.01
Ethylene glycol, ppm	4.74 ± 0.17	3.64 ± 0.11

ing height of filled bottles on logistics pallets or assessing the force required to squeeze bottles used for products like ketchup or skin balms.

As shown in Figure 5, the top-load results for bottles from both materials were comparable, with higher values recorded for regranulate. The average top-load strength was 586 ± 31 N for bottles made from regranulate and 516 ± 77 N for bottles from decontaminated flakes.

For reference, typical top-load values for 400–500 mL PET bottles range from 150 to 250 N, while for this bottle design the minimum requirement specified by the customer was 200 N. Both materials exceeded these thresholds by a substantial margin.

Intrinsic viscosity is a key parameter for evaluating PET quality, processing behavior, and mechanical performance. It is related to polymer chain length, which in turn influences product strength. Higher IV values indicate longer polymer chains, leading to improved mechanical strength, better chemical resistance, and enhanced CO_2 barrier properties - factors that are critical in industrial PET processing [35, 36].

Bottles produced from decontaminated flakes had lower IV values compared to those from regranulate. This difference results from the recycling technologies applied: decontaminated flakes underwent cleaning and pre-drying without an additional Solid-State Polycondensation (SSP) phase, which typically increases IV. In contrast, regranulate production included SSP, resulting in longer polymer chains and, consequently, better performance.

The results confirm a strong correlation between IV and bottle mechanical strength. Bottles from regranulate was 0.68 ± 0.009 dL/g, compared to 0.58 ± 0.009 dL/g for bottles from decontaminated flakes. This difference directly explains the higher top-load strength observed for regranulate bottles.

In addition, as presented in Table 6, bottles from regranulate exhibited higher crystallinity levels, further enhancing their mechanical properties. Since wall thickness distribution was comparable and regular for both materials (Tables 5 and 6), the higher IV level remains the primary factor influencing the top-load results, consistent with literature findings [9, 31].

Another important factor affecting the mechanical properties of PET bottles is wall thickness and their uniformity. For standard bottles available on the market for cosmetics or water, wall thickness typically ranges from 0.25 to 0.35 mm in the labelling area and from 0.15 to 0.20 mm along the bottle edges. In PCR PET bottles, a material distribution dispersion below 20% is considered indicative of high production quality.

In this study, the distribution of wall thickness at selected measurement points showed slightly better regularity and lower deviation in bottles made from decontaminated flakes (Table 5). Bottles produced from regranulate (Table 6) also demonstrated particularly good uniformity, meeting the requirements of even the most demanding cosmetics packaging market.

External dimensions for all tested bottles were within the specification defined in the technical drawing, and no dimensional differences were observed between the two recycled PET materials.

Thermal properties determined by differential scanning calorimetry are summarized in Table 7. Figures 6 and 7 present the DSC thermograms for bottles made from decontaminated flakes and from regranulate, respectively.

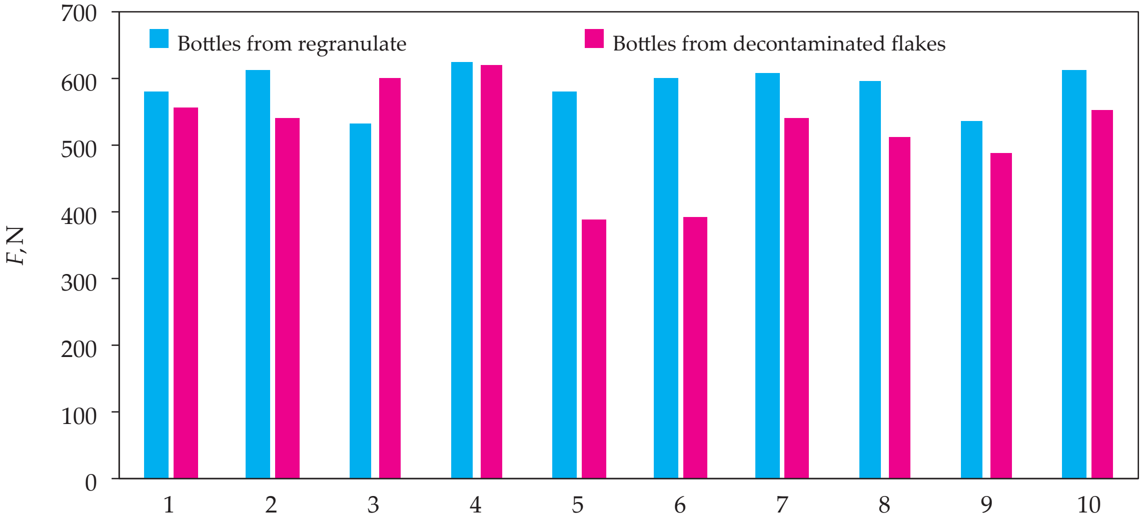

Fig. 5. Top load for regranulate and decontaminated flakes RPET bottles

Table 5. Wall thickness distribution of RPET bottles from PCR PET – decontaminated flakes

Parameter	Value
Min. wall thickness at height 120 mm in the label area, mm	0.319 ± 0.008
Min. wall thickness at height 120 mm on the side of bottle, mm	0.295 ± 0.012
Min. wall thickness at height 75 mm in the label area, mm	0.330 ± 0.008
Min. wall thickness at height 75 mm on the side of bottle, mm	0.314 ± 0.023
Min. wall thickness at height 30 mm in the label area, mm	0.365 ± 0.017
Min. wall thickness at height 30 mm on the side of bottle, mm	0.363 ± 0.034
Material distribution at 120 mm in the label area, %	7.470 ± 3.078
Material distribution at 75 mm in the label area, %	9.610 ± 4.202
Material distribution at 30 mm in the label area, %	11.420 ± 4.817

Table 6. Wall thickness distribution of RPET bottles from PCR PET – regranulate

Parameter	Value
Min. wall thickness at height 120 mm in the label area, mm	0.293 ± 0.010
Min. wall thickness at height 120 mm on the side of bottle, mm	0.261 ± 0.022
Min. wall thickness at height 75 mm in the label area, mm	0.319 ± 0.009
Min. wall thickness at height 75 mm on the side of bottle, mm	0.290 ± 0.027
Min. wall thickness at height 30 mm in the label area, mm	0.387 ± 0.043
Min. wall thickness at height 30 mm on the side of bottle, mm	0.353 ± 0.070
Material distribution at 120 mm in the label area, mm	12.690 ± 5.345
Material distribution at 75 mm in the label area, mm	11.420 ± 4.287
Material distribution at 30 mm in the label area, mm	16.340 ± 9.178

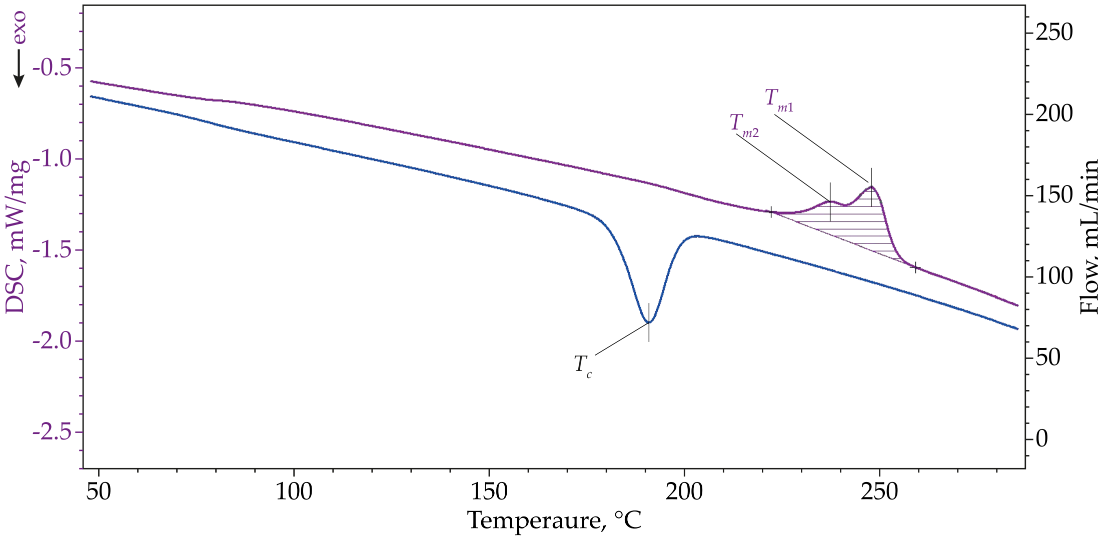

Fig. 6. DSC curves for decontaminated flakes bottle: cooling and second heating

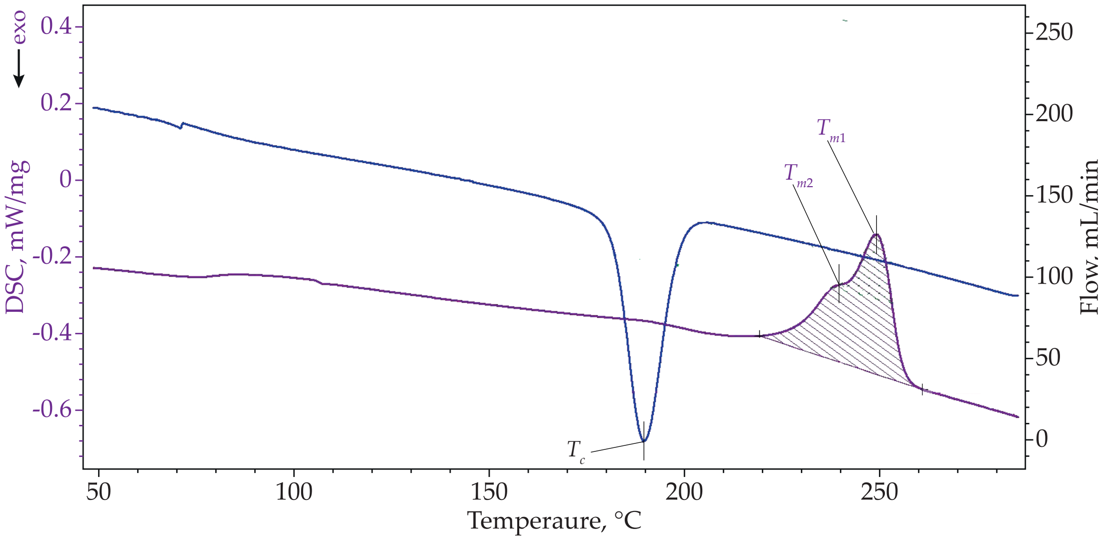

Fig. 7. DSC curves for regranulate bottle: cooling and second heating

Table 7. DSC data of investigated samples

Sample	T_{m1}, °C	ΔH_{m1}, J/g	X_{c1}, %	T_c, °C	T_{m2}, °C	ΔH_{m2}, J/g	X_{c2}, %
Bottle from decontaminated flakes	253.2	44.8	32.0	190.8	247.7	30.7	21.9
Bottle from regranulate	253.0	46.6	33.3	189.6	249.2	34.9	25.0

The obtained degree of crystallinity ranged from 32 to 33.3% during the first heating cycle and from 21.9 to 25% during the second heating. These values are typical for slow-cooled PET resin; in contrast, fast-cooled PET exhibits crystallinity in the range of 12.5–16.4%, as confirmed by previous studies [35, 37, 38]. The difference between the two materials was small – 1.3% in the first heating and 3.1% in the second heating. The observed 3% deviation is within the typical measurement uncertainty of the DSC method and cannot be considered a significant shift.

The melting temperatures for the analyzed materials in the first heating were identical: 253.2°C for bottles from decontaminated flakes and 253°C for bottles from regranulate. In the second heating, they shifted slightly to 247.7°C and 249.1°C, respectively.

On the DSC thermograms, a small additional melting peak was observed at approximately 235°C, which can be attributed to the formation of secondary crystal structures with thinner lamellae. As reported in previous studies, the presence of impurities can promote the formation of such structures, resulting in a double melting peak [36, 39].

These results confirm that the slightly higher crystallinity of bottles made from regranulate may contribute to their improved mechanical strength, as observed in the top-load tests, while both materials maintain crystallinity levels typical for high-quality, slow-cooled PET.

CONCLUSIONS

The injection stretch blow molding process for 400 mL PCR PET cosmetic bottles was stable and repeatable on standard production machines. The mechanical and dimensional properties achieved for both tested materials met industry standards.

Bottles made from regranulate exhibited higher top-load strength, intrinsic viscosity, and degree of crystallinity, which can be attributed to the re-building of molecular chains during the SSP process. In contrast, bottles produced from decontaminated flakes showed more uniform material distribution and wall thickness – this was the only parameter in which they outperformed the regranulate-based bottles.

For all other evaluated parameters, the results were comparable, and both trial series can be considered successful. However, optical, and aesthetic properties showed notable differences, with bottles from regranulate clearly superior. Pre-treatment of flakes on the Starlinger line, particularly vacuum degassing, and backflushing filtration – had a significant positive effect on the final bottle appearance, especially in reducing the number of black spots and improving the shade.

The findings demonstrate strong potential for using recycled PET materials other than standard "food-approved" grades, even at 100% content, in the production of high-aesthetic-quality bottles such as those used in the cosmetics industry. Future work will focus on improving the pre-treatment quality of decontaminated flakes to match the performance of regranulate, as well as on enhancing the energy efficiency of these processes in line with sustainability goals.

Authors contribution

M.G. – conceptualization, methodology, investigation, writing-original draft, writing-review and editing; M.S. – conceptualization, methodology, writing-original draft; P.R. – investigation, A.K. – review and editing, supervision.

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Conflict of interest

The authors declare no conflict of interest.

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