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Optimization of Impact Performance of Injection Moulded Products for Cold Storage Applications: A Case Study on Ice Cream Packaging

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Abstract

Sub-zero mechanical failure of rigid polypropylene (PP) packaging is a major concern in frozen food cold-chain applications operating at temperatures down to −35 °C. This study presents a ten-trial formulation approach using blends of a high-flow PP homopolymer (Borouge HJ333; melt flow rate (MFR) 75 g/10 min) and a propylene ethylene random copolymer (Borouge BJ368MO; MFR 70 g/10 min), together with a metallocene-based propylene ethylene elastomer (ExxonMobil Vistamaxx 6202; MFR 20 g/10 min) at two concentrations. A 1-litre square injection-moulded container was manufactured on a 350-tonne industrial injection-moulding machine and evaluated through 1.2 m flat-bottom drop testing at −35 °C per ASTM D2463, and impact strength testing per IS 2508. Food-contact safety was assessed using overall migration (IS 9845) and specific migration standards (IS 10146, IS 14882, EU 10/2011). Progressive homopolymer replacement with copolymer improved impact strength from 180 gf to 390 gf but failed to ensure consistent drop-test performance. Elastomer addition significantly enhanced toughness, reaching from 430 to 470 gf and meeting drop-test requirements. The optimal formulation was 88 w t% BJ368MO, 10 wt% Vistamaxx 6202, and 2 wt% masterbatch added for white colour appearance, demonstrating superior sub-zero impact resistance and full food-contact compliance.

Keywords: *polypropylene packaging; sub-zero impact resistance; injection moulding; frozen food cold chain; rubber toughening additives*

1. Introduction

1.1 Rigid plastic packaging

Rigid plastic packaging encompasses containers, closures, and protective enclosures fabricated from thermoplastic or thermoset polymers that retain a fixed geometry under normal service loads [1]. Rigid plastic containers have become a dominant format in the food industry due to their dimensional accuracy, structural

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integrity, lightweight nature, and compatibility with high-speed automated filling lines [2].Injection-moulded containers have become the conventional packaging format for frozen desserts, driven by their dimensional accuracy and compatibility with high-speed in-mould labelling (IML) decoration [3].

1.2 Market context: India ice cream sector (2025–2030)

The Indian ice cream market was valued at approximately USD 3 billion in 2023 and is projected to expand at a compound annual growth rate of 13.49% during 2025–2030, driven by rising ambient temperatures, prolonged summers, and evolving consumer preferences [4]. This growth trajectory underscores the commercial relevance of robust, cold-chain-compliant packaging solutions.

1.3 Injection moulding with in-mould labelling

In-mould labelling (IML) during injection moulding is a technology used to enhance surface quality and achieve diverse decorative finishes. A pre-printed film is placed against one wall of the mould cavity, and molten polymer is subsequently injected to fill the cavity, bonding the label integrally to the part surface [5].

1.4 Polypropylene as a packaging material

Polypropylene (PP) was first synthesised in 1954 and has since gained broad commercial prominence as the lowest-density commodity thermoplastic [6]. It is produced from the olefin monomer propylene via addition polymerisation, with properties governed by process conditions, copolymer composition, and molecular weight distribution. Three principal grades are commercially available: homopolymer (general purpose, high stiffness); block copolymers (incorporating 5–15 wt% ethylene for improved impact resistance to approximately −20 °C); and random copolymers (containing 1–7 wt% ethylene, offering lower melting point, flexibility, and enhanced optical clarity) [6].

PP exhibits a semi-crystalline structure with typical crystallinity of 40–60%, conferring high stiffness and a melting point superior to most commodity thermoplastics. With a density of 0.90 g/cm³, it is among the lightest commodity polymers. However, PP undergoes a brittle-to-ductile transition as temperature decreases below approximately 0 °C, with onset temperature varying by grade and formulation [7].

1.5 Polymer blends and rubber toughening

A polymer blend is defined as a mixture of at least two polymers or copolymers [8]. For rubber-toughened polymer systems, interparticle distance (matrix ligament thickness) is a primary factor governing the brittle-to-tough transition: when matrix ligament thickness falls below a critical threshold, the blend deforms in a ductile manner; above that threshold, brittle behaviour predominates [9]. This principle, first formalised by Wu [10] for polyamide systems and subsequently extended to PP matrices, provides the mechanistic basis for elastomeric toughening strategies.

2. Experimental methodology

2.1 Materials

Borouge HJ333 (PP homopolymer)

BorPure™ HJ333MO is a high-flow nucleated PP homopolymer based on Borstar Nucleation Technology (BNT), characterised by excellent organoleptic properties and processability. Its high crystallinity delivers stiffness and dimensional stability required for thin-wall moulding, but places the amorphous-phase glass transition

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temperature (Tg) in the range of −10 °C to 0 °C, rendering it mechanically inadequate at the −35 °C service temperature [11].

Borouge BJ368MO (PP random copolymer)

BJ368MO is a nucleated propylene–ethylene random copolymer characterised by good melt flow and an optimised combination of stiffness and impact strength. Ethylene co-units incorporated at ≥7 wt% reduce long-range crystalline order, shifting the amorphous-phase Tg to the range of −15 °C to −5 °C and improving chain mobility at moderately sub-zero temperatures [12].

ExxonMobil Vistamaxx 6202 (metallocene elastomer)

A propylene–ethylene elastomer with MFR 20 g/10 min, density 0.862 g/cm³ (ASTM D1505), and 14–16 wt% ethylene (ExxonMobil method) [13]. The propylene-rich backbone provides thermodynamic affinity with the PP matrix, promoting fine dispersion. As a propylene-based elastomer with a Tg well below the service temperature (ranging from −30 °C to −20 °C), Vistamaxx 6202 remains in the rubbery state throughout the service window, acting as an effective stress concentrator [13]. The key physical and rheological properties of all three polymeric components are summarised in Table 1.

Table 1. Key physical and rheological properties of the three polymeric components

Sr No.	Property	HJ333	BJ368MO	Vistamaxx 6202
1	Density / Test Standard	900–910 kg/m³ ISO 1183	900–910 kg/m³ ISO 1183	862 kg/m³ ASTM D1505
2	Melt flow rate (2.16 kg, 230 °C)	75 g/10 min ISO 1133	70 g/10 min ISO 1133	20 g/10 min ExxonMobil method
3	Ethylene content	0 wt%	≧7 wt%	14–16 wt% ExxonMobil method
4	Approximate Tg	−10 °C to 0 °C	−15 °C to −5 °C	−30°C to −20°C

White masterbatch (Ref. No. 219440424)

A PP-carrier masterbatch held constant at 2 wt % across all ten trials. Fixing the masterbatch loading isolates the influence of the three polymeric components on mechanical behaviour and removes colorant contribution as an experimental variable [14].

2.2 Product specification

A survey of the commercial injection-moulded container range (capacities 120 mL to 1000 mL; round, oval, square, and rectangular configurations; container masses 11 g to 58 g) led to selection of the 1-litre square format as the structural benchmark. This geometry combines the largest flat panel area, the smallest corner radii, and the highest wall-to-volume aspect ratio within the commercial range features known to concentrate stress at locations most susceptible to brittle fracture under impact loading. Components were manufactured on a 350-tonne

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Milacron injection-moulding machine using a 2-cavity hot-runner tool equipped with IML capability. The selected container and lid are shown in Figure 1, and the detailed dimensional and gravimetric specifications are provided in Table 2.

Figure 1. 1-litre square injection-moulded container and lid.

Table 2. Dimensional and gravimetric specifications of the 1-litre square container

Sr No.	Parameter	Unit	Standard value	Tolerance (±)	Actual
1	Container weight	g	40	1.5	40.1
2	Lid weight	g	19	0.5	19.1
3	Product weight	g	59	2	59.2
4	Top (L×W)	mm	149×149	0.5	149×149
5	Bottom (L×W)	mm	125×125	0.5	125×125
6	Wall thickness	mm	0.65–0.70	0.05	0.65–0.70
7	Product height	mm	78	0.5	78
8	Content volume	mL	1130	10	1130
9	Brimfull volume	mL	1275	10	1275

2.3 Design of formulations

Ten blend compositions were constructed across two distinct modification strategies to yield mechanistically interpretable data. Trials 1–8 constitute a binary substitution series in which the homopolymer fraction decreases from 98 wt% to 0 wt% while the random copolymer fraction increases correspondingly; Trial 1 (98 wt% HJ333) serves as the baseline. Compositional increments of 5 wt% were applied in Trials 1–6 to resolve early performance

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changes with fine resolution; Trial 7 (50 wt% BJ368MO) and Trial 8 (98 wt% BJ368MO) bracket the upper composition range to confirm plateau behaviour. Trials 9 and 10 introduce Vistamaxx 6202 at 5 wt% and 10 wt% into a copolymer-only matrix to evaluate the additional contribution of a dispersed rubbery phase. The two-strategy structure permits direct mechanistic attribution of performance differences. The complete formulation matrix is presented in Table 3.

Table 3. Formulation matrix

(all values in wt%; masterbatch constant at 2 wt%; all rows sum to 100 wt%)

Trial no.	HJ333 (wt %)	BJ368MO (wt %)	Vistamaxx 6202 (wt %)	Masterbatch (wt %)
1	98	0	0	2
2	93	5	0	2
3	88	10	0	2
4	83	15	0	2
5	78	20	0	2
6	73	25	0	2
7	48	50	0	2
8	0	98	0	2
9	0	93	5	2
10	0	88	10	2

2.4 Sample preparation

Polymers and masterbatch mixing was performed in a dry mixer for 10 minutes at ambient temperature following gravimetric batching on a calibrated precision balance, ensuring compositional uniformity prior to machine feeding. Containers were produced on a Milacron 350-tonne reciprocating-screw injection-moulding machine under the following optimised process parameters: melt temperature 230–250 °C; mould temperature 40–45 °C; injection pressure 120–150 bar; holding pressure 80–90 bar; total cycle time 11 s. These conditions were held constant across all ten trials to prevent processing variation from confounding formulation effects. Five containers per trial were filled to the declared net weight of 540 g with commercial ice cream to replicate mass-loading conditions encountered during distribution.

The filled assemblies were conditioned in a Remi RQVD-200 Plus deep-freeze cabinet maintained at −35 °C ± 1 °C for 24 h, with continuous thermocouple monitoring to verify thermal uniformity throughout the conditioning interval (Figure 2).

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Figure 2. Deep-freeze cabinet (Remi RQVD-200 Plus) used for conditioning.

2.5 Mechanical testing

Impact strength (IS 2508). Five specimens per trial were evaluated for impact strength at ambient temperature. Results are reported as average impact strength in gram-force (gf), calculated over the five-specimen replicate set.

Cold-temperature drop impact test (ASTM D2463). Conditioned containers were retrieved individually from the deep-freeze cabinet and subjected to a single flat-bottom free-fall drop from 1.2 m onto a rigid platform at ambient room temperature, in accordance with ASTM D2463 [15]. Each drop was initiated within 30 s of retrieval to minimise thermal relaxation. Pass/fail assessment was by unaided visual examination; the acceptance criterion was complete absence of visible cracking, fracture, or breach of structural continuity on any surface. A result of 5/5 container passes was classified as “Pass”; 0/5 as “Fail”; 1–4/5 as “Intermittent”.

2.6 Characterisation of the tenth trial formulation

2.6.1 Fourier transform infrared spectroscopy (FTIR)

The chemical composition of the injection-moulded tenth trial sample was characterised using Fourier transform infrared (FTIR) spectroscopy (PerkinElmer Spectrum IR, v10.6.2) over a wavenumber range of 450–4000 cm^{-1} in transmittance mode. The resulting spectra are shown in Figure 3.

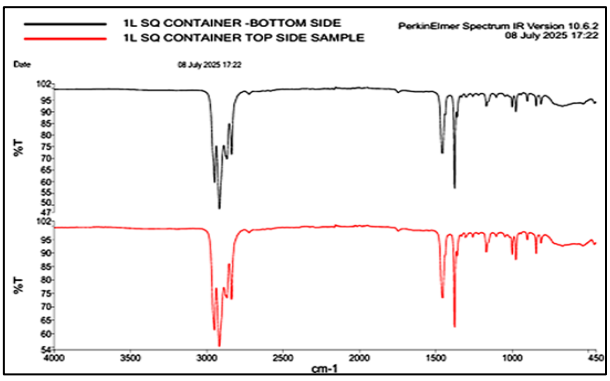

Figure 3. FTIR spectra of tenth trial formulation: bottom surface (black) and top surface (red).

FTIR spectroscopy was performed on the 1-litre square injection-moulded container bottom and top surfaces using a PerkinElmer Spectrum IR (version 10.6.2) across 450–4000 cm^{-1} in percentage transmittance (%T) mode, to confirm the material composition and assess chemical integrity post-moulding. Both spectra exhibited near-identical absorption profiles, confirming uniform blend distribution of PP and Vistamaxx™ propylene-based

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elastomer (ExxonMobil) throughout the moulded container. The dominant absorption bands at 2916 cm^{-1} and 2950 cm^{-1} correspond to symmetric and asymmetric C–H stretching of $–CH_2–$ and $–CH_3$ groups inherent to both the PP matrix and the propylene–ethylene segments of Vistamaxx™. The slight broadening of this absorption envelope, relative to neat PP, is attributed to the additional $–CH_2–$ sequences introduced by the ethylene comonomer units within the Vistamaxx™ phase. The diagnostic $–CH_3$ deformation doublet at ~1375 cm^{-1} and isotactic PP skeletal vibration bands in the 840–998 cm^{-1} region confirmed the PP matrix identity, while a subtle $–CH_2–$ rocking absorption near 720–730 cm^{-1} provided direct spectral evidence of the ethylene comonomer content characteristic of Vistamaxx™. The marginally attenuated intensity of the 998 cm^{-1} crystallinity-sensitive band, compared to neat isotactic PP, is consistent with the dilution effect of the amorphous Vistamaxx™ elastomeric phase on overall PP crystallinity.

Critically, no absorption was detected in the carbonyl region (~1700–1750 cm^{-1}) or the hydroxyl stretching region (3200–3600 cm^{-1}), confirming the absence of thermo-oxidative degradation and moisture uptake both essential requirements for food-grade cold storage packaging integrity.

A notable difference in minimum transmittance was observed between the bottom surface (~47%T) and the top surface (~54%T) in the C–H stretching region, indicating a higher crystalline PP fraction at the bottom surface due to greater mould-wall contact and localised packing pressure during injection moulding. This surface-to-surface crystallinity gradient directly influences the anisotropic impact resistance of the container a central focus of the mechanical optimisation conducted in this study.

FTIR spectroscopy confirmed the container material as a PP/Vistamaxx™ propylene-based elastomer blend, evidenced by C–H stretching at 2916 and 2950 cm^{-1}, the $–CH_3$ deformation doublet at ~1375 cm^{-1}, isotactic PP bands at 840–998 cm^{-1}, and ethylene comonomer rocking vibrations near 720 cm^{-1}, with no carbonyl or hydroxyl absorption detected, confirming chemical integrity post-moulding.

2.6.2 Differential scanning calorimetry (DSC)

Differential scanning calorimetry (DSC) was performed on the PP/Vistamaxx™ injection-moulded container sample (4.450 mg) using a heat–cool–heat protocol at 20 °C/min over 30–250 °C to evaluate thermal transitions, crystallinity, and blend thermal stability. The DSC thermogram is presented in Figure 4.

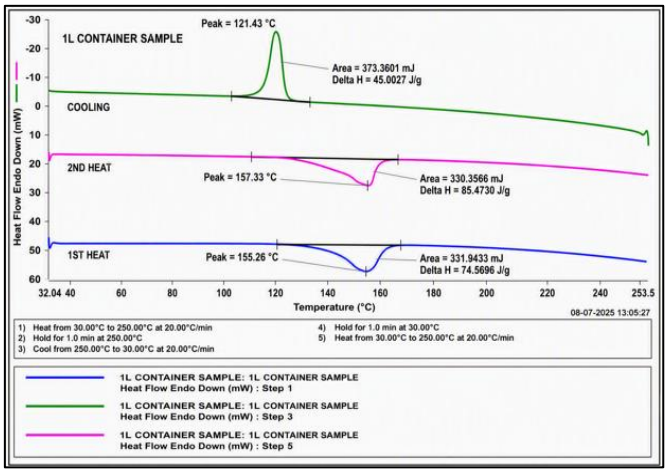

Figure 4. DSC thermogram of the tenth trial formulation.

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First heating cycle (1st heat). The first heating scan revealed a melting endotherm with a peak melting temperature (Tm) of 155.26 °C and an associated enthalpy of fusion ΔHm = 74.59 J/g (area = 331.94 mJ). The degree of crystallinity (Xc) is calculated as: Xc (%) = (ΔHm / ΔH°m) × 100 = (74.59 / 209) × 100 ≈ 35.7%. This reduced crystallinity relative to neat PP is consistent with the presence of the amorphous Vistamaxx™ elastomeric phase, which disrupts PP chain packing regularity a deliberate material design feature to enhance low-temperature impact toughness.

Cooling cycle (crystallisation). A crystallisation exothermic was recorded with a peak crystallisation temperature (Tc) of 121.43 °C and a crystallisation enthalpy Δ Hc = −85.02 J/g. The supercooling (ΔT = Tm − Tc = 33.83 °C) reflects the nucleation energy barrier for PP crystallisation in the presence of the Vistamaxx™ phase. The relatively large super cooling value suggests that the elastomeric phase moderately retards PP nucleation kinetics, resulting in a finer crystalline microstructure upon solidification, which is constructive for impact resistance.

Second heating cycle (2nd heat). The second heating scan yielded Tm = 157.33 °C and ΔHm = 85.47 J/g, giving Xc ≈ 40.9%. The difference in crystallinity between the 1st heat (~35.7%) and 2nd heat (~40.9%) quantifies the thermal history effect introduced by injection moulding, confirming that moulding parameters particularly cooling rate and packing pressure directly govern the final crystalline morphology and, consequently, the mechanical performance of the container. No glass transition step or secondary melting peaks attributable to a distinct Vistamaxx™ phase were detected as discrete thermal events within the scanned range (lower limit 30 °C), consistent with the known Tg of Vistamaxx™ lying between approximately −20 °C and −35 °C below the scanning window. The absence of a separate high-temperature melting peak confirms that Vistamaxx™ is well-dispersed within the PP matrix as a miscible to semi-miscible elastomeric phase, essential for achieving uniform toughening across the container wall.

2.7 Food contact migration assessment of the tenth trial formulation

Overall migration testing was conducted in accordance with IS 9845:1998 using five food simulants: distilled water (Simulant A), 3% acetic acid (Simulant B), 10% ethanol (Simulant C), 50% ethanol (Simulant D), and n-heptane (Simulant E) representing aqueous, acidic, lower-alcohol, higher-alcohol, and fatty food contact conditions, respectively [16]. Migration testing was performed on the commercially selected ternary formulation (Trial 10). The overall migration limit was applied at 60 mg/kg as specified under IS 9845:1998 and EU Regulation (EU) No. 10/2011 [16].Specific migration of heavy metals and regulated plasticisers was assessed against limits prescribed under IS 10146, IS 14882, and EU Regulation (EU) No. 10/2011, Annex I [17]. Overall migration results are reported in Table 4, and specific migration results are reported in Table 5.

Table 4. Overall migration test results

Sr No.	Test condition	Unit	Method	Result	Specification / Limit
1	10% ethanol at 40 °C for 10 days	mg/L	IS 9845 Cl. 5: 1998	5.76	≤60 mg/L
2	3% acetic acid at 40 °C for 10 days	mg/L	IS 9845 Cl. 5: 1998	9.58	≤60 mg/L

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Sr No.	Test condition	Unit	Method	Result	Specification / Limit
3	50% ethanol at 40 °C for 10 days	mg/L	IS 9845 Cl. 5: 1998	7.01	≤60 mg/L
4	Distilled water at 40 °C for 10 days	mg/L	IS 9845 Cl. 5: 1998	4.16	≤60 mg/L
5	n-Heptane at 38 °C for 30 min	mg/L	IS 9845 Cl. 5: 1998	6.10	≤60 mg/L
6	Colour migration – 10% ethanol, 40 °C, 10 days	–	IS 9845 Cl. 11: 1998	No colour migration	Not visible to naked eye
7	Colour migration – 3% acetic acid, 40 °C, 10 days	–	IS 9845 Cl. 11: 1998	No colour migration	Not visible to naked eye
8	Colour migration – 50% ethanol, 40 °C, 10 days	–	IS 9845 Cl. 11: 1998	No colour migration	Not visible to naked eye
9	Colour migration – distilled water, 40 °C, 10 days	–	IS 9845 Cl. 11: 1998	No colour migration	Not visible to naked eye
10	Colour migration – n-heptane, 38 °C, 30 min	–	IS 9845 Cl. 11: 1998	No colour migration	Not visible to naked eye

Table 5. Specific migration test results

Sr No.	Parameter	Unit	Method	Result	Limit
1	Antimony (as Sb)	mg/kg	FHHL/SOP/INST/F/01	<0.004	0.04 max.
2	Barium (as Ba)	mg/kg	FHHL/SOP/INST/F/01	0.039	1.0 max.
3	Cobalt (as Co)	mg/kg	FHHL/SOP/INST/F/01	<0.025	0.05 max.
4	Copper (as Cu)	mg/kg	FHHL/SOP/INST/F/01	<0.025	5.0 max.
5	Iron (as Fe)	mg/kg	FHHL/SOP/INST/F/01	<0.025	48.0 max.
6	Lithium (as Li)	mg/kg	FHHL/SOP/INST/F/01	<0.15	0.6 max.
7	Manganese (as Mn)	mg/kg	FHHL/SOP/INST/F/01	<0.025	0.6 max.
8	DEHP (bis(2-ethylhexyl) phthalate)	mg/kg	FHHL/SOP/INST/F/50	<0.05	1.5 max.

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3. Results and discussion

3.1 Impact strength and drop test results

The impact strength and drop test outcomes for all ten formulation trials are summarised in Table 6, which reveals a monotonic improvement in impact strength with increasing random copolymer content (Trials 1–8) and with the addition of Vistamaxx 6202 (Trials 9–10). Failure images for Trials 1–8 are shown in Figure 5, and pass images for Trials 9–10 are shown in Figure 6.

Table 6. Impact strength and drop test results for all ten-formulation trials (n = 5 per trial; drop height: 1.2 m; temperature: −35 °C)

Trial No.	Avg. impact strength (gf)	Drop test result (1.2 m, −35 °C)	Failure mode
1	180	Fail	Brittle fracture at bottom and side wall
2	205	Fail	Brittle fracture at bottom and side wall
3	230	Fail	Brittle fracture at bottom
4	260	Fail	Brittle fracture at bottom
5	290	Fail	Brittle fracture at bottom and side wall
6	325	Fail	Crack observed at bottom
7	360	Intermittent[a]	Intermittent crack observed at bottom
8	390	Intermittent[a]	Intermittent cracks observed at side wall
9	430	Pass	No cracks; slight stress whitening only
10	470	Pass	No cracks; complete structural integrity maintained

(a)Intermittent: defined as 1–4 of 5 containers passing the drop test.

Figure 5. Product failure images after drop test (Trials 1–8).Red markings indicate observed cracks, breakage, and surface damage

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Figure 6. Product pass images after drop test (Trials 9–10). No visible cracks, breakage, or surface damage observed

3.2 Discussion

Trials 1–5 (0–20 wt% copolymer substitution) all exhibited brittle fracture in the drop test, confirming that partial homopolymer substitution is insufficient to prevent catastrophic failure at −35 °C. Although impact strength improved steadily from 180 gf (Trial 1) to 290 gf (Trial 5), the threshold for drop-test survival was not reached. Trial 6 (25 wt% copolymer) showed a qualitative transition from brittle fracture to cracking, suggesting that a critical level of chain mobility is being approached in the amorphous phase. Trials 7 and 8 displayed intermittent performance, indicating that the copolymer-substitution strategy reaches a toughening plateau at 30–50 wt% substitution (360–390 gf). These observations are consistent with the ligament-thickness model of Wu [10], which predicts a transition from brittle to ductile failure when the interparticle ligament thickness falls below a critical value, and with the extension of this model by Wilbrink et al. [18], in which copolymer addition alone cannot reduce the matrix ligament thickness below the critical threshold for the brittle-to-ductile transition at −35 °C.

The introduction of Vistamaxx 6202 in Trials 9 (5 wt%) and 10 (10 wt%) produced a marked discontinuity in performance. Impact strength rose to 430 gf and 470 gf, respectively, and both trials consistently passed the 1.2 m drop test at −35 °C without cracks. The toughening mechanism is proposed to result from fine dispersion of Vistamaxx 6202 particles within the semi-crystalline PP copolymer matrix. As a propylene-based elastomer with a Tg well below −35 °C, Vistamaxx 6202 remains in the rubbery state throughout the service window, acting as stress concentrators that trigger multiple localised yielding events, thereby dissipating impact energy without catastrophic crack propagation a mechanism analogous to that reported for Vistamaxx-modified PP systems in the literature [19]. The slight stress whitening observed in Trial 9 is consistent with localised plastic deformation of the matrix, an established energy-absorption mechanism indicative of ductile yielding rather than crack propagation [20]. The absence of stress whitening in Trial 10, combined with its higher impact strength, suggests that the 10 wt% elastomer loading promotes a more distributed energy-dissipation response.

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4. Conclusion

This study investigated the sub-zero impact performance of injection-moulded polypropylene containers for frozen food packaging through a systematic ten-trial formulation programme, comparing two distinct toughening strategies: progressive copolymer substitution and metallocene-elastomer modification.

Progressive substitution of PP homopolymer (Borouge HJ333) with a propylene ethylene random copolymer (Borouge BJ368MO) produced a monotonic increase in dart impact strength from 180 gf to 390 gf (Trials 1–8). However, no blend ratio achieved consistent pass performance in the 1.2 m flat-bottom drop test at −35 °C, demonstrating that copolymer dilution alone is incapable of driving the brittle-to-ductile transition required at sub-zero service temperatures.

The addition of Vistamaxx 6202 metallocene elastomer at 5 wt% and 10 wt% into a pure copolymer matrix (Trials 9 and 10) produced a decisive improvement, elevating impact strength to 430 gf and 470 gf, respectively, and achieving consistent drop-test passes without visible cracking. The proposed toughening mechanism involves rubbery elastomeric particles that remain compliant at −35 °C, acting as stress concentrators that initiate multiple localised yielding events dissipating impact energy without catastrophic fracture.

The ternary blend comprising 88 wt% BJ368MO, 10 wt% Vistamaxx 6202, and 2 wt% white masterbatch is identified as the commercially optimal formulation. This blend also satisfied overall and specific migration requirements under IS 9845:1998, IS 10146, IS 14882, and EU Regulation 10/2011, confirming food-contact safety. The methodology and formulation principles developed here are potentially transferable to other container geometries and frozen food packaging formats.

5. Limitations of the present work

The elastomeric modifier was examined at only two concentration levels (5 wt % and 10 wt %), which is insufficient to map the complete toughening response curve or to define the minimum commercially viable loading. Furthermore, a single commercial elastomer grade was used throughout; the extent to which the findings apply to alternative propylene-based or ethylene-based elastomers remains unverified.

Thermal characterisation was restricted to a lower scanning boundary of 30 °C, placing the glass transition Tg of the elastomeric phase outside the measured window. The thermal behaviour of all blends at the actual service temperature (−35 °C) was therefore inferred rather than directly determined. Similarly, the impact strength measurements used for inter-trial ranking were obtained at ambient temperature under IS 2508, introducing a disconnect with the sub-zero service environment; no low-temperature instrumental impact data were collected to validate this ranking.

Microstructural evidence supporting the proposed toughening mechanism was not obtained. Elastomer particle dimensions, spatial distribution, and matrix ligament thickness the physical parameters underpinning the cited toughening model were not measured by electron microscopy. The mechanistic interpretation therefore relies entirely on macroscopic mechanical outcomes.

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At five specimens per trial, the sample size is modest, and no inferential statistical analysis was performed. The intermittent classification assigned to Trials 7 and 8 may partly reflect random variability rather than a genuine performance plateau. Finally, food-contact migration testing was limited to the selected commercial formulation; the remaining nine trials were not assessed.

6. Scope for future work

A systematic composition sweep at finer intervals (2–3 wt% increments) up to approximately 15 wt% elastomer, analysed within a structured design-of-experiments framework, would establish the minimum effective loading and the stiffness–toughness trade-off boundary. Drop testing across a graduated temperature range (−10 °C to −35 °C) would identify the brittle-to-ductile transition temperature for each formulation and confirm applicability across standard frozen-food cold-chain conditions.

Sub-ambient dynamic mechanical analysis and extended DSC to −60 °C are recommended to directly measure the glass transition Tg of the elastomeric phase and to characterise viscoelastic behaviour throughout the service window. Electron microscopy of cryogenically fractured surfaces would provide the morphological data needed to evaluate the interparticle ligament-thickness criterion quantitatively and to confirm the proposed energy-dissipation mechanism.

Benchmarking against alternative metallocene elastomers and conventional rubber tougheners would assess the selectivity of the observed performance improvement. Oscillatory rheometry of the blended systems would facilitate processing optimisation by characterising melt viscosity ratios that govern dispersed-phase particle size during injection moulding.

Longer-term assessments including repeated thermal cycling, vibration testing, and stacking-load evaluation would address durability under realistic distribution conditions. Extending migration testing across a broader set of formulations, supported by GC-MS screening for oligomeric species, would strengthen the food-safety evidence base. Finally, validation across the full commercial container range and on higher-cavitation production tooling would confirm the transferability and scalability of the identified optimal formulation.

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Declarations

Author contributions

Yasmeen Khan: Conceptualisation, experimental investigation, data curation, formal analysis, writing, original draft. Vijendra Chaudhari: Supervision, methodology, writing, review and editing, project administration. Both authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

Competing interests

No conflict of interest.

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Research ethics

Not applicable. This study did not involve human participants, animal subjects, or any research requiring ethical approval.

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Data availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. Raw experimental data (formulation compositions, impact strength measurements, drop test records, FTIR and DSC files, and migration test certificates) are retained by the corresponding author and may be provided to the Editor(s) upon request.

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