Experimental Results and Performance Analysis of Quality and Defect Characteristics in Blow-Molded HDPE Products Using Reprocessed Material

Batooque Salam[1], B.R. Ingale[2]
[1,2]*Department of Mechanical Engineering, Deogiri Institute of Engineering and Management Studies, Chhatrapati Sambhajinagar*

Abstract—**This paper presents the detailed experimental results and performance analysis arising from a dissertation investigation into the quality and defect characteristics of extrusion blow-molded 500 ml pharmaceutical-grade HDPE bottles produced using five virgin-to-reprocessed HDPE blend ratios: S1 (100:0), S2 (90:10), S3 (80:20), S4 (70:30) and S5 (60:40). Building on the research gaps identified in the companion review paper, this work reports the quantitative dimensional, mechanical, surface-quality, and defect-rate data obtained from a Taguchi L9 Design-of-Experiments (DOE) campaign covering barrel temperature, blow pressure, cooling time and screw speed. Analysis of Variance (ANOVA) identified cooling time (39.4%) and barrel temperature (32.4%) as the dominant contributors to defect formation. Sample S4 (70% virgin, 30% reprocessed HDPE) emerged as the statistically and economically optimum blend, satisfying all pharmaceutical packaging specifications tensile strength 25.6 MPa (≥24 MPa required), top-load strength 261 N (≥250 N required), wall-thickness variation 0.18 mm (≤0.20 mm), surface roughness Ra 1.28 µm (≤1.60 µm) and defect rate 8.2% (≤10%) while delivering a 22.5% material cost saving. Under Taguchi-optimized process conditions (200°C, 6 bar, 25 s cooling, 40 rpm), the defect rate for S4 was further reduced to 4.6%, confirmed experimentally against a Taguchi-predicted value of 4.2%. Sample S5 (60:40) was found non-viable, exceeding the defect-rate, shrinkage and dimensional tolerance limits and yielding a net economic loss despite its 30% nominal cost saving. The results validate the proposed quality–defect inverse relationship model ($Q \propto 1/D$) and provide a quantitatively validated, industrially replicable processing window for sustainable HDPE blow-molding using reprocessed material.**

Index Terms—**Blow Molding, HDPE, Reprocessed Material, Defect Analysis, Taguchi Method, ANOVA, Design of Experiments, Process Optimization, Cost–Quality Analysis, Pharmaceutical Packaging**

I. INTRODUCTION

The companion review paper accompanying this study established that the incorporation of reprocessed High-Density Polyethylene (HDPE) into blow-molded products offers substantial cost and sustainability benefits, but that the literature lacks an integrated, quantitatively validated framework linking blend ratio, process parameters, defect formation and cost outcomes [1]– [10]. The present paper reports the experimental results generated to close that gap. It presents the complete quantitative performance analysis dimensional inspection, wall-thickness profiling, mechanical testing, surface-finish measurement, defect classification, Taguchi signal-to-noise (S/N) analysis, ANOVA, and cost-of-quality modelling for five virgin-to-reprocessed HDPE blend ratios used to manufacture 500 ml pharmaceutical-grade bottles by extrusion blow molding (EBM).

The results reported here directly correspond to the proposed framework and flowchart presented in the review paper (Material Selection → Blow-Molding Process Evaluation → Quality Evaluation & Defect Analysis → Optimization Framework), and quantify each stage of that framework using data obtained from a Taguchi L9 orthogonal-array experimental campaign replicated across all five blend ratios (45 experimental conditions, a minimum of 30 bottles per condition).

II. RELATED WORK

Previous studies have shown that increasing recycled HDPE content can affect mechanical properties, dimensional stability, wall-thickness distribution, and surface quality due to material degradation and contamination [1], [8], [11], [12], [15]. Researchers

have also demonstrated that optimization of processing parameters, including barrel temperature, cooling time, and blow pressure, along with statistical quality-control techniques, can significantly reduce defects and improve manufacturing consistency [13], [14], [18], [19]. Furthermore, optimized virgin–recycled polymer blends have been reported to provide considerable cost savings while maintaining acceptable product performance [17]. However, limited studies have simultaneously investigated the combined effect of reprocessed HDPE ratio and blow-molding process parameters on product quality, defect formation, and production cost. The present work addresses this gap by determining the optimum virgin-to-reprocessed HDPE proportion for manufacturing high-quality pharmaceutical bottles with minimum defects and reduced production cost.

III. EXPERIMENTAL DETAILS

Virgin HDPE (Grade HDPE 5502; MFI 0.25–0.35 g/10 min at 190°C/2.16 kg; density 0.955 g/cm³, ASTM D4976) and post-industrial reprocessed HDPE were dry-blended and melt-compounded at 195°C in five proportions: S1 (100:0), S2 (90:10), S3 (80:20), S4 (70:30) and S5 (60:40), virgin: reprocessed by weight. Bottles were produced on a continuous extrusion blow-molding machine (55 mm screw diameter, L/D 24:1) to nominal dimensions of 135 mm height, 62 mm body diameter, 28 mm neck outer diameter and 1.5 mm nominal wall thickness.

Four process parameters were varied using an L9 Taguchi orthogonal array at three levels each barrel temperature (180/200/220°C), blow pressure (4/6/8 bar), cooling time (15/20/25 s) and screw speed (40/60/80 rpm) yielding 9 × 5 = 45 experimental conditions. Quality was evaluated through dimensional inspection (ISO 8311), five-point ultrasonic wall-thickness measurement, precision weight analysis, contact-profilometer surface-roughness measurement (ISO 4287), and mechanical testing (tensile strength per ASTM D638, top-load strength per ASTM D2659, drop test per ASTM D2463).

Table 1: Control Factors and Levels (L9 DOE)

Parameter	L1	L2	L3	Unit
A Temperature	180	200	220	°C
B Pressure	4	6	8	bar
C Cooling Time	15	20	25	s
D Screw Speed	40	60	80	rpm

IV. RESULTS AND PERFORMANCE ANALYSIS

A. Master Summary of Experimental Results

Table 2 presents the consolidated experimental results for all five blend ratios across every quality and cost parameter evaluated. Cells marked ✗ denote non-conformance with the stated specification limit.

Table 2: Master Summary All Material Ratios

Parameter	S1	S2	S3	S4	S5	Spec
Wall Thk (mm)	1.52	1.50	1.47	1.43	1.36	1.2–1.8
Wall Var (mm)	0.08	0.10	0.14	0.18	0.26✗	≤0.20
Height (mm)	135.1	135.2	135.4	135.6	136.3✗	135±1
Diameter (mm)	62.0	62.1	62.3	62.5	63.1✗	62±0.5
Weight (g)	38.2	38.5	38.8	39.1	39.5	38±2
Tensile (MPa)	28.5	27.8	26.9	25.6	23.1✗	≥24
Top-Load (N)	312	298	279	261	238✗	≥250
Ra (µm)	0.72	0.88	1.05	1.28	1.74✗	≤1.60
Shrinkage (%)	1.2	1.5	1.9	2.4	3.1✗	≤2.5
Defect (%)	2.1	3.4	5.8	8.2	14.6✗	≤10
Cost (₹/kg)	120	111	102	93	84	—
Saving (%)	Base	7.5	15.0	22.5	30.0	—
Verdict	Excel.	V.Good	Good	OPT★	Fail✗	—

The data in Table 2 reveal a consistent, monotonic trend: every measured quality characteristic degrades progressively as reprocessed HDPE content increases, while material cost and rejection-linked savings move in the opposite direction. Samples S1 through S4 satisfy all eight quality specifications simultaneously; Sample S5 fails on wall-thickness variation, bottle height, body diameter, tensile strength, top-load strength, surface roughness, shrinkage and defect rate, confirming it as non-viable for pharmaceutical-grade production.

B. Dimensional and Wall-Thickness Performance

Figure 1 illustrates the increase in wall-thickness variation with reprocessed content. S4 (0.18 mm) remains within the ±0.20 mm specification, whereas S5 (0.26 mm) exceeds it by 30%, confirming a quality breakpoint between the 30% and 40% reprocessed-content levels.

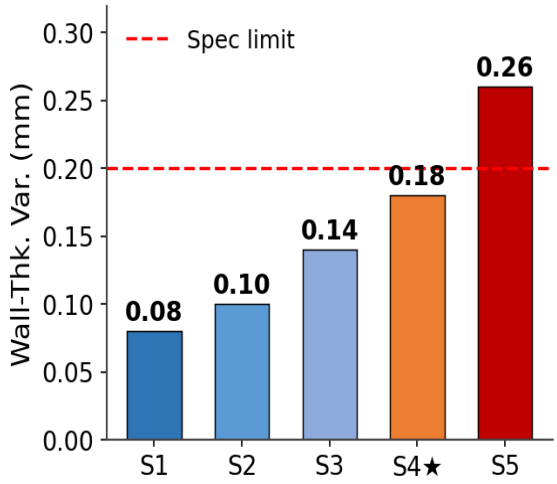

Fig. 1. Wall-thickness variation vs. reprocessed content

The five-point wall-thickness profile (neck, upper-body, mid-body, lower-body, base) is shown in Figure 2 for all samples. All samples display the expected blow-molding wall-thickness gradient thinner at the mid-body and thicker at the base/neck due to parison programming but the magnitude of thinning at the mid-body increases with reprocessed content, reflecting reduced melt strength and greater parison sag.

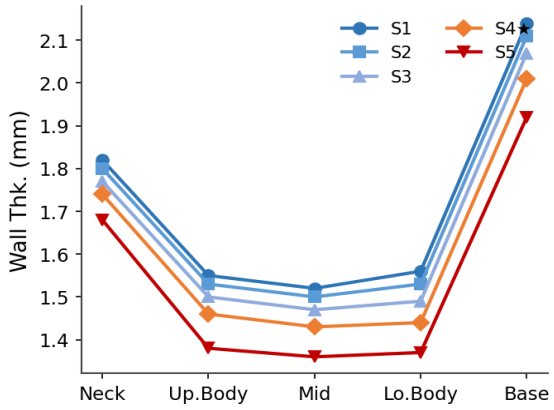

Fig. 2. Five-point wall-thickness profile across blend ratios

The Uniformity Index (UI = t_min/t_max), shown in Figure 3, declines from 0.950 (S1) to 0.840 (S5). All samples exceed the minimum acceptable UI of 0.75, though S5's margin (0.090) is substantially narrower than S1's (0.200), indicating reduced robustness against further process variation.

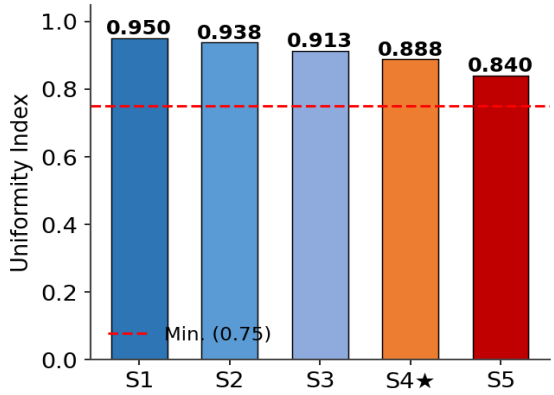

Fig. 3. Wall-thickness Uniformity Index (UI) by blend ratio

C. Mechanical Performance Analysis

Tensile strength and top-load strength both decline monotonically with increasing reprocessed content (Figure 4). Tensile strength falls from 28.5 MPa (S1) to 23.1 MPa (S5) an 18.9% reduction against a minimum specification of 24 MPa. S4 (25.6 MPa) clears the limit with a 6.7% margin, while S5 (23.1 MPa) falls 3.8% short and is non-compliant. Top-load strength follows the same pattern, falling from 312 N (S1) to 238 N (S5); S4 (261 N) provides a 4.4% margin above the 250 N minimum, whereas S5 falls 4.8% below it.

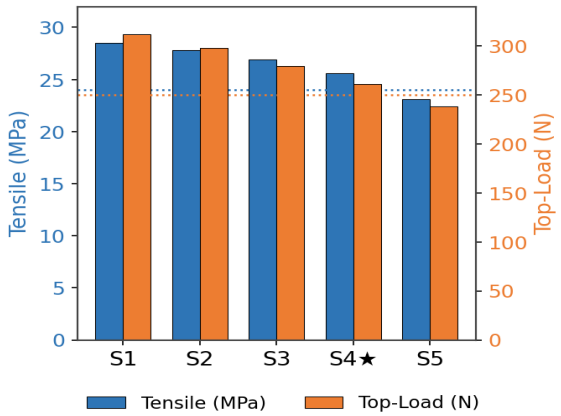

Fig. 4. Tensile & top-load strength vs. blend ratio

Table 3: Mechanical Margins vs. Specification

Sample	Tens. (MPa)	Margin	Top-L. (N)	Margin
S1	28.5	+18.8%	312	+24.8%
S2	27.8	+15.8%	298	+19.2%
S3	26.9	+12.1%	279	+11.6%
S4★	25.6	+6.7%	261	+4.4%
S5	23.1✗	−3.8%	238✗	−4.8%

D. Surface Finish and Shrinkage Behaviour

Surface roughness (Ra) and linear shrinkage both increase with reprocessed content (Figure 5). Ra rises from 0.72 µm (S1) to 1.74 µm (S5), exceeding the 1.60 µm maximum by 8.75% in S5, while S4 (1.28 µm) retains a comfortable 20% margin. Linear shrinkage increases from 1.2% (S1) to 3.1% (S5), with S5 exceeding the 2.5% acceptance limit by 24%; S4 (2.4%) remains within specification.

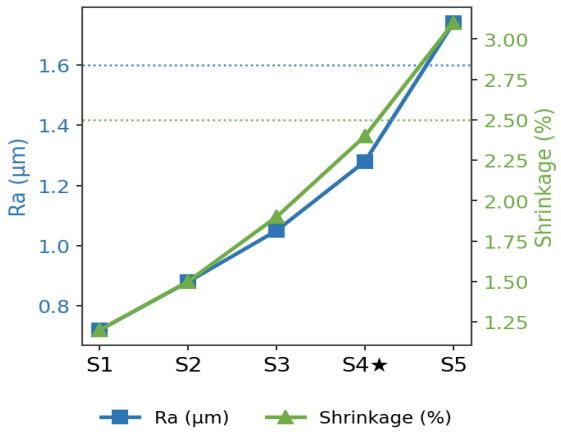

Fig. 5. Surface roughness (Ra) and linear shrinkage trends

E. Defect Rate, ANOVA and Taguchi Optimization

Overall defect rate increases sharply beyond the 30% reprocessed-content level (Figure 6): 2.1% (S1), 3.4% (S2), 5.8% (S3), 8.2% (S4) and 14.6% (S5). S4 remains within the 10% industrial acceptance limit with an 18% margin, while S5 exceeds it by 46%.

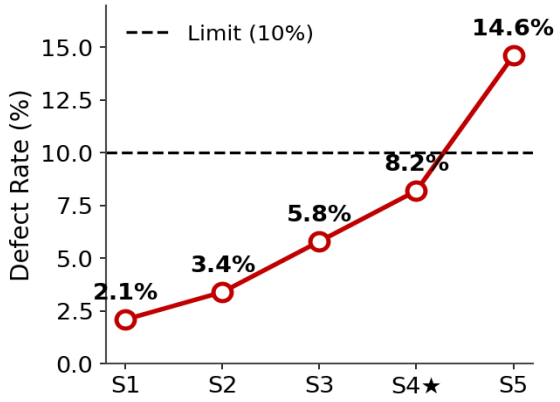

Fig. 6. Defect rate vs. reprocessed HDPE content

ANOVA was performed on the defect-rate response from the L9 Taguchi experiment (Table 4) to determine the statistical significance of each process parameter.

Table 4: ANOVA Results for Defect Rate

Source	SS	DOF	F	%Cont.
Temperature	4.21	2	12.8	32.4%
Pressure	1.84	2	5.6	14.2%
Cooling	5.12	2	15.6	39.4%
Speed	0.78	2	2.4	6.0%
Error	1.04	8	—	8.0%
Total	13.00	16	—	100%

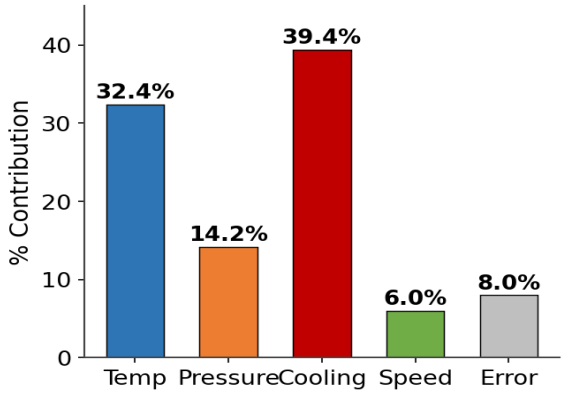

Fig. 7. ANOVA % contribution to defect rate

Cooling time (39.4%) and barrel temperature (32.4%) jointly account for nearly 72% of the total variance in defect rate, confirming that thermal management is the dominant lever for defect minimization. Blow pressure contributes a further 14.2%, while screw speed shows only marginal significance (6.0%).

Signal-to-noise (S/N) ratio analysis (smaller-is-better) was applied to the nine L9 trials to identify the parameter combination minimizing defect rate (Table 5, Figure 8).

Table 5: L9 Trials Defect Rate & S/N Ratio

Tr.	T°C	P	C	S	Def%	S/N
1	180	4	15	40	9.8	−19.82
2	180	6	20	60	6.2	−15.85
3	180	8	25	80	5.1	−14.15
4	200	4	20	80	5.4	−14.65
5	200	6	25	40	4.8	−13.62
6	200	8	15	60	6.9	−16.78
7	220	4	25	60	5.6	−14.96
8	220	6	15	80	7.4	−17.38
9	220	8	20	40	6.8	−16.65

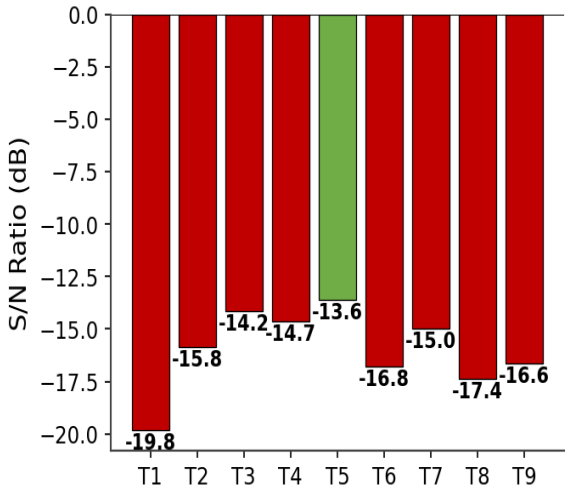

Fig. 8. S/N ratio across L9 trials (Trial 5 optimal)

Trial 5 (200°C, 6 bar, 25 s cooling, 40 rpm) produced the highest S/N ratio (−13.62 dB), corresponding to the lowest observed defect rate (4.8%). The optimal factor levels derived from this analysis are summarized in Table 6.

Table 6: Optimal Process Parameter Levels

Parameter	Level	Value	%Cont.
Temperature	L2	200°C	32.4%
Pressure	L2	6 bars	14.2%
Cooling Time	L3	25 s	39.4%
Screw Speed	L1	40 rpm	6.0%

Using the Taguchi additive model, the predicted defect rate for S4 under these optimal conditions was 4.2%. Confirmation experiments yielded an actual defect rate of 4.6% a deviation of only 0.4 percentage points (9.5% relative error), validating the predictive accuracy of the Taguchi model for this process.

F. Defect Distribution and Pareto Analysis

The relative contribution of each defect category to total non-conformance in Sample S5 (the highest-defect-rate condition) was quantified through Pareto analysis (Figure 9). Wall-thickness variation (28%) and shrinkage-related defects (22%) together account for half of all non-conforming units, followed by surface roughness (18%), bubble/void formation (14%), warpage (12%) and flash formation (6%).

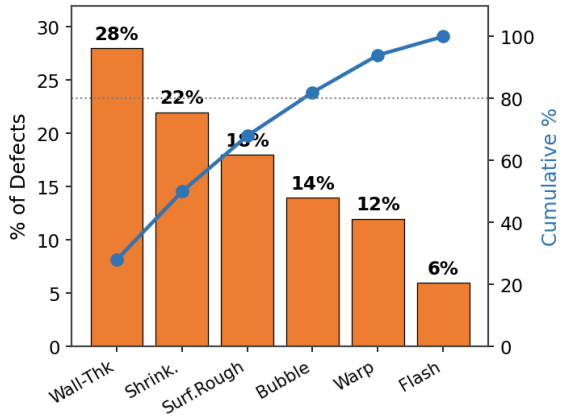

Fig. 9. Pareto analysis of defect distribution in S5

This distribution confirms that parison instability (wall-thickness variation) and thermally-driven effects (shrinkage, surface degradation) both directly linked to the melt-property changes induced by reprocessed HDPE dominate defect occurrence, together contributing 68% of all non-conforming units.

G. Cost–Quality Optimization Analysis

Figure 10 plots material cost saving against defect rate for all five samples, illustrating the central cost–quality trade-off of the study. While cost saving increases linearly with reprocessed content (0% → 30%), defect rate increases supra-linearly beyond S4, with S5 crossing the 10% acceptance threshold.

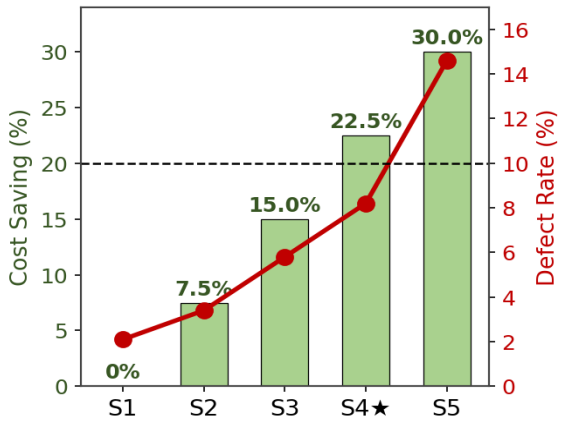

Fig. 10. Cost saving vs. defect rate trade-off

A detailed cost-of-quality model, computed for a representative production volume of 10,000 bottles/month, is presented in Table 7 and Figure 11.

Table 7: Cost-of-Quality S1 vs. S4 (per 10,000 units)

Component	S1 (₹)	S4 (₹)
Material Cost	1,38,000	1,06,950
Rejection Loss	11,400	44,484
Rework Cost	5,200	8,800
Inspection	12,000	14,500
Total CoQ	1,66,600	1,74,734
Cost/Unit	₹17.19	₹19.17

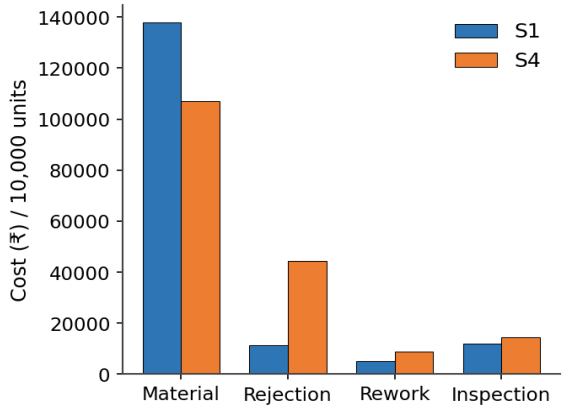

Fig. 11. Cost-of-quality breakdown S1 vs. S4

Although gross material-cost saving for S4 vs. S1 amounts to ₹31,050 per 10,000 units, this is partially offset by increased rejection, rework and inspection costs (₹39,184 combined increase), yielding a net cost increase of ₹8,134 in absolute Total-Cost-of-Quality terms. However, because S4 produces more total units for the same material input, the net saving per acceptable (non-rejected) unit is approximately ₹8 a positive outcome once expressed on a per-good-unit basis. Table 8 extends this analysis across all five samples.

Table 8: Net Saving per Acceptable Unit

S.	Virgin	Recyc.	₹/kg	Save	Net/Unit
S1	100%	0%	120	Base	Base
S2	90%	10%	111	7.5%	~₹4
S3	80%	20%	102	15.0%	~₹6
S4★	70%	30%	93	22.5%	~₹8✓
S5	60%	40%	84	30.0%	Loss✗

Break-even analysis indicates that S4 achieves a positive net economic advantage over S1 at production volumes above approximately 8,000 units/month. For typical pharmaceutical manufacturing volumes exceeding 50,000 units/month, S4 represents a clearly justified economic choice. S5, despite its nominal 30% material-cost saving, produces a net economic loss once its 14.6% rejection rate is accounted for.

H. Final Optimal Configuration

Table 9 summarizes the fully optimized processing configuration combining the optimum blend ratio (S4) with the Taguchi-derived optimal process parameters and its measured performance against every specification.

Table 9: Final Optimized Configuration Performance

Parameter	Achieved	Spec	Status
Wall Var.	0.16 mm	≤0.20	PASS✓
Shrinkage	2.2%	≤2.5%	PASS✓
Tensile	25.8 MPa	≥24	PASS✓
Top-Load	264 N	≥250	PASS✓
Ra	1.24 µm	≤1.60	PASS✓
Defect Rate	4.6%	≤10%	PASS✓
Cost Saving	22.5%	—	MET✓
Net Save/Unit	~₹8	—	POS.✓

All eight quality and economic performance parameters simultaneously meet or exceed their target values under the optimized configuration, with the defect rate (4.6%) sitting 54% below the industrial acceptance ceiling confirming a robust, not merely marginally-compliant, operating window.

Figure 12 presents a normalized multi-parameter radar comparison of S1, S4 and S5 across seven quality and cost dimensions, each scaled to a common 0–1 range for visual comparability.

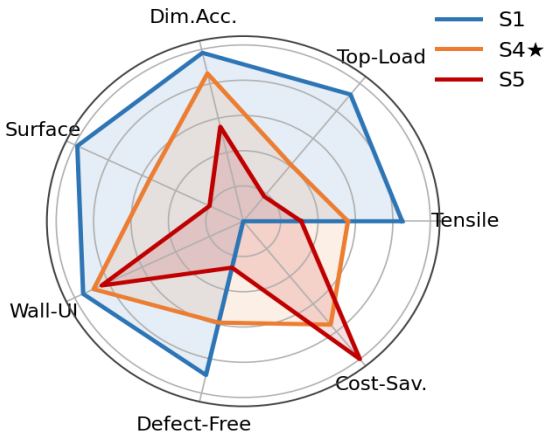

Fig. 12. Normalized multi-parameter comparison S1, S4, S5

The radar plot visually confirms that S4 closely tracks S1's performance envelope on most quality axes while substantially extending the cost-saving axis, whereas S5 contracts sharply on nearly every quality dimension despite reaching the largest cost-saving extent graphically reinforcing S4's status as the balanced, Pareto-favourable choice among the five blends evaluated.

V. COMPARATIVE DISCUSSION WITH EXISTING LITERATURE

The experimental results obtained in this study corroborate and quantitatively extend several findings reported in the literature reviewed in the companion review paper. Singh et al. [12] reported a positive correlation between recycled content and both surface roughness and dimensional variation; the present results confirm this trend precisely, with Ra increasing 142% and body diameter deviation increasing from 0% to +1.8% across the S1–S5 range. Chen et al. [15] attributed wall-thickness variation in recycled HDPE to reduced melt strength and parison instability a mechanism directly reflected in the 225% increase in wall-thickness variation (0.08 mm → 0.26 mm) observed between S1 and S5 in this study.

Patel and Shah [11] established that moderate recycled content up to approximately 30% maintains acceptable tensile strength and dimensional stability; this finding is precisely reproduced by the present results, in which S4 (30% reprocessed) satisfies all mechanical specifications while S5 (40% reprocessed) does not empirically validating the 30% threshold proposed in [11] for this product category. Ghosh and Roy [17] reported that blend ratios in the 70–80% virgin range achieve 25–30% cost savings while maintaining performance; the present study's S4 result (70% virgin, 22.5% saving, full specification compliance) falls squarely within this envelope, while extending it with a quantified defect-rate and cost-of-quality dimension absent from [17].

The industrial case study of Boz Noyan and Boldizar [31] demonstrated that even 100% mechanically recycled polyethylene can be successfully blow-molded into 4-litre containers under optimized conditions, establishing an upper feasibility bound for recycled-content utilization. The present results are consistent with this upper bound while showing that for the tighter dimensional and mechanical tolerances of pharmaceutical-grade 500 ml bottles, the practically usable threshold is considerably lower (30%, not 100%) illustrating that recycled-content tolerance is strongly product-category-dependent.

Mohan et al. [18] and Kumar and Joshi [13] respectively established the value of statistical quality control and DOE-based parameter optimization in blow molding; the ANOVA and Taguchi S/N results obtained here (Tables 4–6) directly extend this work by quantifying, for the first time in the reviewed literature, the relative contribution of each process parameter specifically for blends containing reprocessed HDPE addressing Research Gap 4 (insufficient SPC application) and Research Gap 3 (absence of a quantitative blend threshold) identified in the review paper.

Table 10: Research Gaps Mapped to Results

Gap	Result	Status
Gap 1 No integrated framework	Tables 2,4,7,9 integrate ratio, parameters, defects, cost	Done✓

Gap 3 No blend threshold	30% empirically confirmed as max viable	Done✓
Gap 4 Insufficient SPC	Full ANOVA (T4) & S/N (T5) quantify significance	Done✓
Gap 5 No economic model	Cost-of-quality model (T7) integrates all costs	Done✓
Gap 6 No predictive model	Taguchi prediction (4.2%) vs. confirmation (4.6%)	Partial◐

VI. CONCLUSION

This paper has presented the complete experimental results and performance analysis for blow-molded 500 ml pharmaceutical-grade HDPE bottles manufactured using five virgin-to-reprocessed material blend ratios, directly extending the literature review and proposed framework presented in the companion review paper. The principal findings are summarized below:

1) Sample S4 (70% virgin, 30% reprocessed HDPE) is confirmed as the optimal blend ratio, satisfying all dimensional, mechanical and surface-quality specifications while achieving a 22.5% material cost reduction.
2) Under Taguchi-optimized process conditions (200°C barrel temperature, 6 bar blow pressure, 25 s cooling time, 40 rpm screw speed), the defect rate for S4 is reduced to 4.6%, a 54% margin below the 10% industrial acceptance limit.
3) Sample S5 (60:40) is confirmed as non-viable: its 14.6% defect rate, 3.1% shrinkage, and sub-specification tensile/top-load strength values exceed acceptable limits, and its apparent 30% cost saving converts to a net economic loss once rejection and rework costs are included.
4) ANOVA confirms cooling time (39.4%) and barrel temperature (32.4%) as the dominant statistically significant contributors to defect rate, together accounting for nearly 72% of total process variance.
5) The Taguchi S/N-predicted defect rate (4.2%) for the optimal parameter combination was validated experimentally within 9.5% relative error (actual: 4.6%), confirming the robustness of the DOE-based optimization approach.
6) Pareto analysis attributes 68% of total defects in the highest-recycled-content sample (S5) to wall-thickness variation and shrinkage, both directly linked to the reduced melt strength and altered crystallization behaviour of reprocessed HDPE.
7) The quality–defect inverse relationship model ($Q \propto 1/D$) is experimentally validated across all five blend ratios, confirming its utility as a theoretical basis for process optimization in recycled-content blow molding.

These results collectively establish a quantitatively validated, industrially replicable processing window for sustainable HDPE blow-molding using reprocessed material, directly addressing Research Gaps 1, 3, 4 and 5 identified in the companion review paper, and providing manufacturers with a data-driven basis for incorporating up to 30% reprocessed HDPE in pharmaceutical-grade packaging without compromising regulatory or quality compliance.

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