Sustainable Manufacturing of Intelligent Connectors: Optimizing Recycled Polymeric Compositions for Smart Technology and Robotics

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ABSTRACT

This study promotes the utilization of sustainable recycled materials to develop polymeric compounds for intelligent connections in robotics and smart technologies. The environmental impact and mechanical performance of plastic composites made from virgin plastic and recycled material from two products, both containing Liquid Crystalline Polymers (LCPs), were evaluated using plastic injection engineering techniques. The objective was to identify an optimal formulation that balances environmental benefits with mechanical effectiveness. The investigation focused on the effects of incorporating recycled runners into the injection molding process, with particular attention to notched Izod impact strength and shrinkage ratio. A D-optimal design model revealed that incorporating 5% of recycled Runner 1 and 20% of recycled Runner 2 significantly enhanced impact strength while maintaining an acceptable shrinkage ratio compared to virgin plastic. Key design considerations, such as product impact zones and mold gravity alignment, were integrated into the development process. The study demonstrates that recycled runners can match the performance of virgin materials, supporting the adoption of sustainable manufacturing practices.

Keywords-sustainable manufacturing; recycled polymer composites; d-optimal design; plastic injection molding; smart technology and robotics

I. INTRODUCTION

The manufacturing sector is continually seeking innovative approaches to enhance product quality and optimize production processes. One of the aspects investigated revolves around the raw materials used in the production of the product of interest, and in this case, connectors. Connectors are essential components in a wide range of mechanical and electronic systems, requiring strict adherence to standards of reliability, dimensional accuracy, and mechanical properties. Traditionally, connector housings are fabricated using virgin plastics to ensure consistent durability and performance. However, increasing emphasis on sustainability and resource conservation has spurred interest in incorporating recycled plastics into manufacturing processes. Recycling offers the potential to support a circular economy, reduce material costs, and lower environmental impact. Nonetheless, integrating recycled plastics into connector manufacturing demands careful consideration to maintain product quality and performance.

This study applies a D-optimal design methodology to optimize the composition of plastic mixtures used in connector manufacturing. By systematically varying the proportions of virgin and recycled plastics, the research aims to identify formulations that maximize performance while minimizing environmental impact and production costs. The analysis focuses on two key performance indicators: Izod impact strength and shrinkage ratio, which reflect mechanical robustness and dimensional stability, respectively. Through comprehensive experimentation and statistical analysis, the research seeks to investigate the relationship between connector performance and material composition. The findings aim to provide manufacturers with actionable insights for producing high-performance, sustainable connector products.

II. LITERATURE REVIEW

Several studies have investigated the optimization of plastic formulations for the production of intelligent connectors, utilizing Engineering Thermoplastics (ETPs), Shape Memory Elastomers (SMEs), and Liquid Crystalline Polymers (LCPs). Authors in [1] provided an in-depth review of ETPs, highlighting their progression and suitability for structural and precision components owing to their mechanical reliability and processing flexibility. Authors in [2] examined SMEs that respond to external stimuli such as heat or UV light, making them suitable for smart systems, including robotics and aerospace. Authors in [3] explored the failure behavior of LCPs under compressive loading, demonstrating the need for accurate material modeling in electronic connector applications. Similarly, authors in [4] showed that reinforcing epoxy composites with zircon nanoparticles significantly improved both impact resistance and tensile strength, reinforcing the role of nano-additives in enhancing composite performance. Authors in [5] studied azobenzene-containing LCPs and noted performance degradation at higher loadings due to photoisomerization, further advancing polymer design. Authors in [6] compared two grades of Necuron-type polymers for bearing applications, concluding that Necuron 1300 offers superior mechanical robustness. Authors in [7] focused on ionic discotic LCPs with shape memory behavior, suitable for smart materials. Authors in [8] applied the Design of Experiments (DOE) methodology to improve machinery performance, highlighting its broader applicability beyond material science. In the context of recycled polymers, authors in [9] successfully optimized Polycarbonate/Acrylonitrile Butadiene Styrene (PC/ABS) composites from automotive waste, confirming the viability of post-industrial plastic reuse. Authors in [10] applied mixture optimization to improve the mechanical properties of wood-plastic composites from waste plastic bags, relevant to structural and construction sectors. Statistical modeling also plays a pivotal role in composite optimization. Authors in [11] evaluated predictive models for flow stress behavior in advanced alloys, while authors in [12] enhanced 3D printing parameters using bio-inspired optimization algorithms. Authors in [13] applied regression techniques to assess the effectiveness of corporate recycling strategies, emphasizing how statistical models support sustainability-driven engineering. Several previous investigations employing D-optimal design in polymer and composite optimization have established a solid methodological foundation that directly informs the present study. For instance, authors in [14] demonstrated how D-optimal mixture design effectively enhanced the thermal performance of recycled polypropylene composites by optimizing constituent ratios, an approach closely mirrored in our methodology for tuning mechanical strength and shrinkage properties in recycled LCP-based materials. Similarly, authors in [15] used D-optimal design to achieve high-efficiency synthesis from complex bio-based inputs, highlighting the value of this approach in managing multifactor experimental constraints where material behavior is nonlinear and interdependent. Authors in [16] optimized Phase-change Materials (PCMs) for thermal regulation, reflecting the role of D-optimal design in performance-critical thermal systems. D-optimal design's utility spans multiple sectors, including mining and process engineering. Authors in [17] modeled the dehydration of zucchini for maximum accuracy, while Authors in [18] applied D-optimal principles to sensor selection in noisy environments. Authors in [19] achieved high iron recovery from low-grade ore using this method. Authors in [20] demonstrated its relevance in producing renewable-source biolubricants. Authors in [21] further enhanced D-optimal mixture design using functional data analysis for food suspensions, ensuring uniformity in large-scale production.

III. RELATED METHODS

This study utilizes sophisticated statistical and experimental methodologies to comprehensively assess the mechanical performance of recycled polymer mixtures through the integration of D-optimal design, Multiple Regression Analysis (MRA) [22], and Analysis of Variance (ANOVA) [23].

A. Multiple Regression Analysis (MRA)

The MRA methodology is utilized to quantify the relationships between independent variables, specifically the proportions of virgin plastic and recycled runners, and dependent variables, namely Izod impact strength and contraction ratio [24]. This approach provides a detailed understanding of how changes in material composition influence performance metrics, enabling accurate predictions and informed optimization. The general form of a multiple linear regression model is expressed as:

$$y_i = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{\substack{i=1 \\ i<j}}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

In this model, y_i represents the random response variable. The coefficients β_0, β_i, β_{ii} and β_{ij} are estimated from sample data, and they describe the relationship between the response and each independent variable. The independent variables x_i and x_j are fixed, non-random variables measured without error, and k is the total number of independent variables in the model. The error term ε accounts for random deviations from the model's predicted values and is assumed to be independently and normally distributed with a mean of zero and constant variance.

B. Analysis of Variance (ANOVA)

ANOVA is employed to evaluate the statistical significance of material compositions on essential mechanical properties, thereby ensuring that the observed variations are substantive and not attributable to arbitrary chance [25]. In the context of multiple regression, ANOVA serves a critical role by evaluating the overall significance of the regression model. It decomposes the total variability in the dependent variable into distinct components: the Total Sum of Squares (SST), representing the overall variation; the Regression Sum of Squares (SSR), indicating the variation explained by the model; and the Residual Sum of Squares (SSE), which accounts for the unexplained error. ANOVA computes an F-statistic to test the null hypothesis that all regression coefficients are equal to zero [26], thereby determining whether the model explains a statistically significant portion of the variance in the response variable. To assess the influence of individual predictors, t-tests are conducted.

C. D-Optimal Design

D-optimal design was selected for this study due to its ability to optimize mixture formulations within practical constraints [27]. Unlike traditional full factorial or central composite designs, this design efficiently selects a subset of experimental runs that yield maximum statistical information from a limited number of trials [28, 29]. Moreover, D-optimal design is well-suited for modeling the non-orthogonal and interdependent relationships inherent in multi-component plastic mixtures, where component proportions must sum to 100%. The methodology achieves this by maximizing the determinant of the information matrix $(X'X)$, where X is the design matrix. This maximization minimizes the volume of the confidence ellipsoid for the estimated parameters, resulting in greater precision and reliability. The D-optimal criterion is mathematically expressed as $\max|det(X'X)|$.

IV. EXPERIMENTAL SETUP AND METHODOLOGY

Reliable data transfer between components and control systems in industrial automation and robotics depends critically on the integrity of the connector housing in connector housing production. This enclosure, typically made from high-performance engineering plastics such as LCP or polycarbonate (PC), protects the internal components of the connector from mechanical stress, temperature fluctuations, and environmental contaminants. Dimensional precision and accurate design are essential to ensure secure connectivity and seamless integration with robotic and automated systems. Additionally, the housing must meet stringent requirements for impact resistance and durability to withstand daily operational stresses, thereby ensuring long-term reliability. The structural characteristics of a typical connector housing used in this study are illustrated in Figure 1.

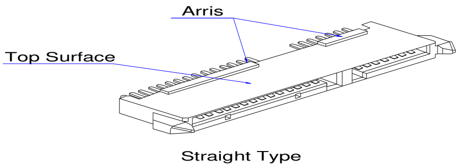

Fig. 1. Connector housing.

A. Material Properties and Experimental Procedure

Vectra E540i, a commercial-grade virgin LCP, was used in this study due to its exceptional mechanical strength, low deformation, and thermal stability, properties that make it ideal for high-precision components. As specified by the manufacturer, this material includes 40% glass/mineral reinforcement. Two post-industrial recycled materials, Runner 1 and Runner 2, were sourced from previously molded connector housings (Product A and Product B, respectively) originally manufactured using Vectra E-series or equivalent polyester-based LCPs with comparable reinforcement levels. Despite their similar base material, these recycled runners differ in their prior processing and geometrical configurations, potentially influencing their mechanical performance and granule morphology upon reprocessing. The recyclability of these LCPs is supported by their demonstrated ability to retain structural integrity after reprocessing. While minor thermal degradation can affect resistance and flow characteristics, the findings from this work suggest that high-performance mechanical and dimensional properties can still be achieved when recycled LCPs are blended in optimized ratios with virgin material. The study aimed to optimize the composition of plastic blends for connector housings by varying the proportions of virgin Vectra E540i (30–75%), Runner 1 (5–40%), and Runner 2 (5–40%). A total of nine formulations were developed across three blend ratios: 75:25, 50:50, and 25:75 (virgin:recycled), as shown in Table I.

TABLE I. COMPOSITION OF THE NINE MIXTURE FORMULATIONS

Composition	Virgin plastic	Runner 1	Runner 2
75:25	75	20	5
	75	15	10
	75	5	20
50:50	50	40	10
	50	25	25
	50	10	40
25:75	25	50	25
	25	37.5	37.5
	25	25	50

A D-optimal DOE approach was employed to evaluate the combined effects of material composition on Izod impact strength and contraction ratio. In order to isolate the impact of material composition, the injection molding process parameters, including temperature, pressure, and cycle time, were maintained at a constant level.

B. Experimental Procedures

The experimental process began with the preparation of three base materials: virgin Vectra E540i LCP, Runner 1, and Runner 2. To eliminate residual moisture and ensure optimal flow characteristics during molding, all materials were oven-dried at 120 °C for 4 hours prior to processing. Given the 40% glass/mineral reinforcement in the LCP matrix, injection molding required meticulous control of multiple processing parameters to ensure optimal outcomes. The complex geometry of the connector housings further necessitated elevated processing temperatures to promote proper melt flow and mold filling. Due to the abrasive nature of the reinforcing fillers, the mold design was optimized to mitigate wear and extend tool life. To minimize shrinkage and warpage, advanced molding techniques were employed. These included precise mold temperature control and regulated cooling cycles, ensuring that the final parts adhered to tight dimensional tolerances and met functional specifications required for electronic connector housings.

For each of the nine mixture formulations, three samples were tested for Izod impact strength (J/m) and shrinkage ratio (%), resulting in 27 observations for each response variable. The experimental order and raw measurements for Izod and shrinkage tests were recorded across three replicates per condition to ensure statistical reliability and support ANOVA analysis. The ASTM D256-06a Izod pendulum impact resistance test is used to evaluate the impact resistance of plastic materials. During testing, as shown in Figure 2, the specimen is securely positioned in the holder, and the pendulum strikes the notched face. The height reached by the pendulum after breaking the specimen is recorded to calculate the energy absorbed. The resulting Izod impact strength quantifies the material's resistance to impact. To assess dimensional stability, the shrinkage ratio was determined by comparing critical dimensions of the molded parts before and after cooling, as shown in Figure 3. Measurements were performed using a calibrated digital micrometer and high-precision measuring instruments. Shrinkage was quantified as the percentage deviation from the original design dimensions.

The virgin LCP used in this study had a flexural modulus of 10.8 GPa and a flexural strength of 156 MPa, measured according to ASTM D790, indicating high rigidity and resistance to bending forces, and serving as the baseline before blending. Its Izod notched impact strength was measured at 44 J/m, which offers adequate resistance to abrupt impacts. Based on [1], the virgin material demonstrates excellent thermal performance, with a Deflection Temperature Under Load (DTUL) of 295 °C at 0.4 MPa and 280 °C at 1.8 MPa (ASTM D648). The coefficient of linear expansion in the Machine Direction (MD) and Transverse Direction (TD) is $0.7 \cdot 10^{-5}$ °C^{-1} and $3.4 \cdot 10^{-5}$ °C^{-1} (ASTM D696), respectively, indicating dimensional stability under temperature fluctuations. Lastly, the MD and TD exhibit mold shrinkage of 0.0% and 0.4%, respectively, which guarantees precise dimensional control throughout the injection molding process. Moreover, specific gravity is 1.74 (ASTM D792), and water absorption is low at 0.01% (ASTM D570), confirming suitability for humid environments. Tensile strength reached 127 MPa, with 1.7% elongation at break (ASTM D638), indicating low ductility but sufficient flexibility. The measured average Izod impact strength and shrinkage ratio for the nine mixture formulations are presented in Table II.

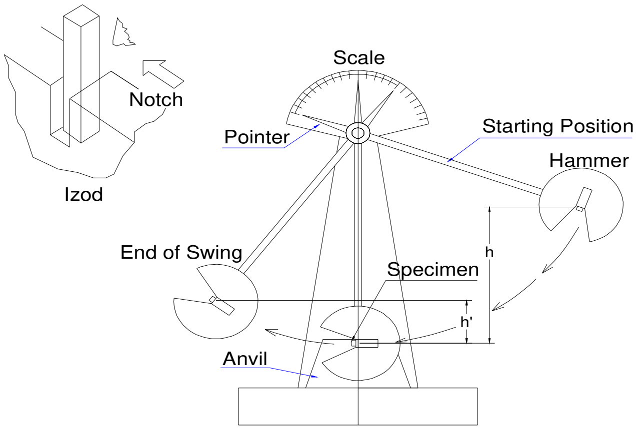

Fig. 2. Izod impact strength tester.

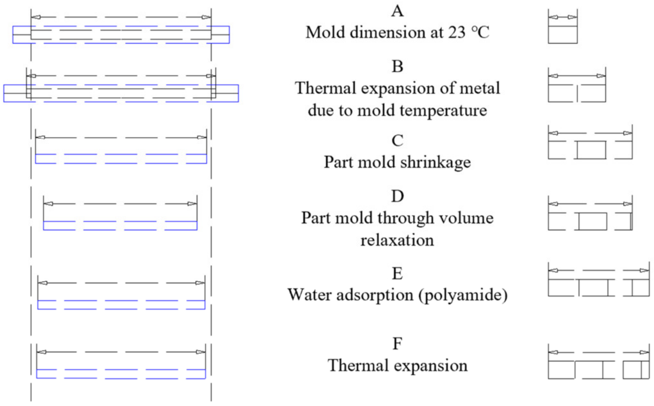

Fig. 3. Shrinkage ratio measuring procedure.

TABLE II. AVERAGE MEASURED IZOD IMPACT STRENGTH AND SHRINKAGE RATIO FOR THE NINE MIXTURE FORMULATIONS

Composition	Average Izod impact strength (J/m)	Average shrinkage ratio (%)
75:20:5	40	0.50
75:15:10	42	0.54
75:5:20	42	0.53
50:40:10	37	0.70
50:25:25	35	0.75
50:10:40	36	0.68
25:50:25	32	0.96
25:37.5:37.5	30	1.20
25:25:50	30	0.90

V. RESULTS AND DISCUSSION

A. ANOVA and Main Effects Analysis

This study employed a Completely Randomized Design (CRD) ANOVA to assess how the proportions of virgin plastic, Runner 1, and Runner 2 influence two critical properties: notched Izod impact strength and shrinkage ratio. The CRD ANOVA statistical analysis results, shown in Table III, revealed significant effects from all three components for both tested factors ($p < 0.05$). The F-statistics for the virgin plastic content were notably high, 40.50 for Izod impact strength and 69.09 for shrinkage ratio, indicating a dominant influence on mechanical and dimensional properties. Similarly, Runner 1 exhibited a substantial effect, with F-values of 28.13 for impact strength and 24.65 for shrinkage ratio. Runner 2 also contributed significantly, with corresponding F-statistics of 27.31 and 38.13, respectively.

TABLE III. ANOVA RESULTS SHOWING THE EFFECT OF COMPONENTS ON NOTCHED IZOD IMPACT STRENGTH AND SHRINKAGE RATIO

Response	**Parameter**	**F-statistic**	**P-value**
Izod impact strength	Virgin Plastic	40.50	<0.001
	Runner 1	28.13	<0.001
	Runner 2	27.31	<0.001
Shrinkage Ratio	Virgin Plastic	69.09	<0.001
	Runner 1	24.65	<0.001
	Runner 2	38.13	0.000

Residual analysis confirmed that model assumptions, including homoscedasticity, independence, and normal distribution, were met. Graphical analysis of residuals against predicted values showed no patterns, confirming constant variance.

B. Regression Model Interpretation

For regression modeling, both linear and nonlinear multiple regression models were used. The linear regression model assessed direct, additive relationships between the independent variables (x_1: virgin plastic, x_2: Runner 1, and x_3: Runner 2) and the responses in notched Izod impact strength (y_1) and shrinkage ratio (y_2). To account for more complex behaviors, a nonlinear regression model was also employed for the shrinkage ratio. This model incorporated interaction and curvilinear terms to capture potential non-additive effects among components. Its flexibility enabled a more accurate representation of relationships between component ratios and performance outcomes, especially where linear models may fall short in identifying subtle synergistic effects.

For Izod impact strength (y_1), the linear model provided a clear and interpretable breakdown of each component's contribution under the assumption of additive effects. The regression coefficients, listed in Table IV, show that all three predictors, virgin plastic (x_1), Runner 1 (x_2), and Runner 2 (x_3), had statistically significant effects ($p < 0.05$), with t-values of 23.90, 9.25, and 9.25, respectively. These results confirm that variations in all three inputs significantly affect impact strength. In contrast, the shrinkage ratio (y_2) was more accurately captured by a nonlinear modeling approach. Among the formulation variables, Runner 2 (x_3) demonstrated a statistically significant influence on shrinkage behavior, while virgin plastic (x_1) exhibited marginal significance. Although certain interaction terms (e.g., x_2x_3) were not individually significant, their inclusion enhanced the overall model fit and reduced residual variance, thereby improving predictive accuracy. The final nonlinear model effectively represented the complex relationship between composition and dimensional stability.

Figure 4 illustrates the model-predicted shrinkage ratios based on the D-optimal design, highlighting how variations in recycled runner proportions influence shrinkage. Two representative formulations were selected for confirmation testing to validate the model predictions: i) 75:20:5, identified by the linear model as optimal for Izod impact strength, and ii) 75:5:20, optimized by the nonlinear model for shrinkage ratio.

TABLE IV. PARTIAL TEST SHOWING SIGNIFICANCE OF INDIVIDUAL PARAMETER COEFFICIENTS FOR PREDICTING IZOD IMPACT STRENGTH AND SHRINKAGE RATIO

Effects	**y_1**			**y_2**		
	$\widehat{\beta_i}$	**t-value**	**p-value**	**$\widehat{\beta_i}$ or $\widehat{\beta_{ij}}$**	**t-value**	**p-value**
x_1	0.4776	23.90	0.000	0.00375	2.23	0.050
x_2	0.2665	9.25	0.000	0.00594	1.36	0.203
x_3	0.2514	9.25	0.000	0.01235	2.79	0.019
x_1x_2	-	-	-	0.000046	0.42	0.681
x_1x_3	-	-	-	-0.000072	-0.67	0.516
x_2x_3	-	-	-	0.000195	1.69	0.122

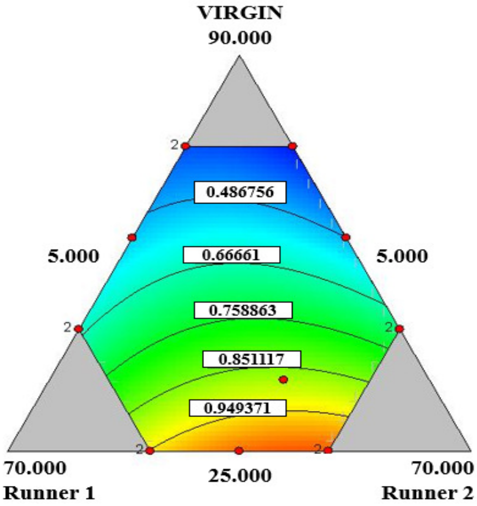

Fig. 4. Shrinkage ratio plot based on D-Optimal design.

C. Confirmation Testing: t-Test on Optimized Formulations

The t-test comparison of Izod impact strength between the 75:20:5 and 75:5:20 mix ratios revealed a statistically significant difference in the confirmation experiments. The 75:20:5 composition exhibited a mean reduction of 2.5 J/m in impact strength compared to the 75:5:20 ratio, with a t-value of –6.4937 and a p-value of 0.0029. Similarly, for the shrinkage ratio, the 75:20:5 mixture showed a mean reduction of 0.01 relative to the 75:5:20 blend, supported by a t-value of –4.92867 and a p-value of 0.016. These findings provide statistical evidence that mix ratio selection significantly affects both impact strength and dimensional stability.

While the 75:20:5 formulation demonstrated slightly lower shrinkage, the higher Izod impact strength of the 75:5:20 blend is prioritized in practical applications where durability and mechanical performance are critical. The marginal increase in shrinkage for the 75:5:20 mix remains within the tolerable range for industrial molding processes and is unlikely to cause mold fatigue or compromise dimensional precision. Therefore, the 75:5:20 mix ratio is preferred for production, offering an optimal balance between mechanical integrity and manufacturability.

Further observations highlighted differences in impact resistance between Runner 1 and Runner 2, attributed to variations in granule morphology and water-resistant granule size during the plastic coating process (Figure 5). Product thickness and minimal variation in coating across cylindrical stages contributed to a consistent and uniform performance. These results underscore the importance of careful selection and characterization of recycled runner materials, as they significantly influence the mechanical and dimensional behavior of the final product.

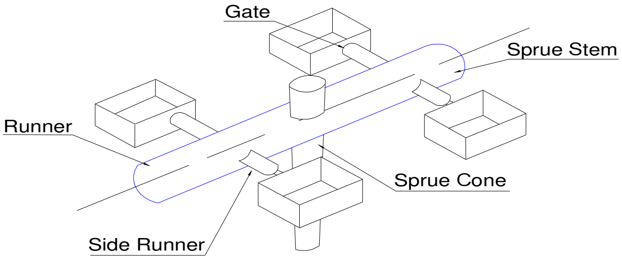

Fig. 5. Runners from Product A.

D. Practical Implications

The optimized recycled polymer formulation developed in this study (75:5:20) achieved a notched Izod impact strength of 42 J/m, a value comparable to results reported in [9], where recycled PC/ABS blends for automotive applications achieved 35–40 J/m. Similarly, [14] demonstrated that recycled polypropylene composites reinforced with oil palm fibers attained impact strengths of 30–38 J/m, but with higher contraction rates. In contrast, the shrinkage ratios observed in this study remained within permissible industrial tolerances, aligning with findings in [10] concerning wood–plastic composites. This indicates that the mechanical robustness and dimensional stability achieved through the proposed formulation meet the stringent requirements of intelligent connector housings used in industrial automation and robotics. Moreover, the results reinforce the viability of partially substituting virgin plastics with post-industrial recycled materials in high-precision applications. The optimized blend effectively balances impact strength and dimensional control, confirming the practical suitability of recycled composites in engineering-grade components. These findings are consistent with conclusions drawn in [14], further supporting the integration of sustainability-driven design strategies in high-performance manufacturing.

VI. CONCLUSION

This study effectively optimized the formulation of recycled Liquid Crystalline Polymers (LCPs) polymeric composites for intelligent connectors, thereby promoting sustainable manufacturing practices within the realms of industrial automation and robotics. Through the incorporation of D-optimal design methodologies, the research conducted a systematic evaluation of the mechanical performance of recycled polymer formulations, with particular emphasis on Izod impact strength and shrinkage ratio, using Analysis of Variance (ANOVA) and Multiple Regression Analysis (MRA).

The results substantiated that the integration of 5% recycled runners from Product A and 20% recycled runners from Product B led to a notable enhancement in impact resistance, while concurrently preserving an acceptable level of dimensional stability in comparison to virgin plastic. These findings substantiate the viability of employing recycled materials in precision-engineered components, thereby enhancing resource efficiency. Despite these promising results, challenges remain. Variability in recycled polymers due to prior use and degradation can affect mechanical consistency and long-term durability. To mitigate these risks, strategies such as tighter process control, adaptive design tolerances, and rigorous material screening are recommended.

The study also offers a framework for integrating recycled polymers into high-performance applications through D-optimal design, which can be extended to various polymer processing techniques. Future research should focus on Life Cycle Assessment (LCA), long-term performance evaluation, and the incorporation of smart manufacturing tools such as real-time monitoring and AI-driven quality control. Scaling up these findings through pilot production trials and expanding the range of recycled sources will further advance the role of sustainable materials in high-precision, environmentally responsible manufacturing.

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