OPEN ACCESS
International Journal of Innovations in Science & Technology
IJIST

Experimental Design-Based Optimization of Football Manufacturing: A Case Study of Anwar Khawaja Industries

Muhammad Nauman[1], Misbah Ullah[1], Muhammad Junaid[1]
[1]Department of Industrial Engineering University of Engineering and Technology Peshawar, Pakistan
*Correspondence: misbah@uetpeshawar.edu.pk

Citation | Nauman. M, Ullah. M, Junaid. M, "Experimental Design-Based Optimization of Football Manufacturing: A Case Study of Anwar Khawaja Industries", IJIST, Vol. 07 Special Issue. pp 25-37, May 2025
Received | April 05, 2025 **Revised |** May 02, 2025 **Accepted |** May 04, 2025 **Published |** May 05, 2025.

This study aims to investigate the critical factors influencing the weight and quality of football bladders during the manufacturing process, with a focus on optimizing production at Anwar Khwaja Industries (Pvt) Limited, Sialkot. This research employs the Definitive Screening Design (DSD) to identify and quantify the impact of key variables, including material composition and process parameters, on the final product's performance. Among the factors analyzed, Calcium Carbonate (CaCO3) emerged as the most significant factor, demonstrating a strong effect on the response variable. Additionally, interactions between Sulphur–CaCO3, Zinc Oxide–BHT, and CaCO3–BHT were found to be critical in determining football quality, durability, and cost–efficiency. Statistical analysis, including regression modeling and ANOVA, underscores these relationships but also reveals model limitations. This study also addresses model accuracy concerns, reporting an R–R-squared value of 52.2%, while the low adjusted R2 (19.4%) and predicative R2 (0.0%) indicate limited generalizability. To address multicollinearity concerns, the factor reduction technique was applied, improving the reliability of experimental findings. The study emphasizes the role of advanced statistical techniques in optimizing manufacturing processes to maintain Pakistan's global leadership in football production.

Keywords: Manufacturing, Football Bladder, Definitive Screening Design (DSD), ANOVA

Introduction:

This chapter provides a comprehensive overview of football manufacturing, tracing its evolution from basic, rigid designs to the high–quality, technologically advanced footballs used today. Football's global popularity is unparalleled, making it one of the most accessible sports worldwide. Despite regional naming variations, the essence of the game, kicking a ball to score, has remained unchanged for centuries.

Although football as a sport span back over 3,000 years, its production in Pakistan began in the late 19th and early 20th centuries during British colonial times. A British soldier in Sialkot brought a punctured football to a local cobbler for repairs. The cobbler not only mended it but also created a replica, resulting in consistent football production. This event marked the beginning of football manufacturing in Sialkot [1][2][3].

For over 30 years, Pakistan has been the leading exporter, particularly through Sialkot, a globally recognized hub for FIFA-certified footballs and high–quality sports goods. While some firms in the region manage their brands and supply top global companies, outdated technology has made Pakistan vulnerable to competition, especially from East Asia (particularly China) [4]. One significant barrier to technological adoption in Pakistan's football industry is labor resistance, driven by fears of wage reductions. As a result, China has strengthened its position, securing major supply contracts and surpassing Pakistan in market influence [5][6].

Labor standards and process innovations are central concerns in football manufacturing. China's large workforce and technological advancements have attracted global firms, mirroring trends in industries like electronics manufacturing. Sialkot, Pakistan, remains a major production hub, housing approximately 1,000 football manufacturing units and employing over 60,000 people. It supplies more than 70% of the world's footballs, exporting over 37 million footballs for the 2018 FIFA World Cup. The intricate manufacturing process, from sourcing raw materials to stitching panels. It demonstrates the craftsmanship behind every football.

The continuous advancement of football manufacturing is driven by the pursuit of innovative materials and improved production techniques. Manufacturers explore cutting–edge technologies to enhance durability, performance, and sustainability. This includes integrating advanced manufacturing processes and rigorous quality control measures to meet evolving industry standards. Every football undergoes precise testing to ensure compliance with FIFA's stringent criteria before reaching the market.

Several studies have examined factors influencing football weight, bladder composition, and material properties, highlighting their impact on performance and sustainability. Recent advancements in football design focus on materials, smart technology, and aerodynamics. Smart football embedded with sensors provides real-time performance data, while advanced materials like graphene enhance durability and flight stability [7][8]. Aerodynamic studies using CFD simulations optimize panel designs to improve flight characteristics [9][10].

The weight of a football plays a crucial role in player performance and safety. Studies highlight the importance of maintaining standardized weights to ensure consistency and reduce injury risks. Emerging technologies, such as 3D printing [11], enable the creation of customized football designs tailored to specific needs. Additionally, energy–harvesting innovations are paving the way for sustainable, smart footballs [8]. These advancements are transforming modern football manufacturing, and driving improvements in performance, safety, and accessibility. Quality assurance extends beyond materials and production methods to include rigorous testing for strength, durability, rebound properties, and water resistance[12][13]. These tests simulate real–game conditions, ensuring consistent performance. Compliance with FIFA's quality standards is essential for certification, serving as a benchmark of excellence in the global sports industry.

Despite Pakistan's prominence in global football production, especially through firms such as Anwar Khawaja Industries (Pvt.) Ltd., the lack of systematic process optimization and over-reliance on traditional manufacturing methods result in variability in product quality, particularly the weight of football bladders. This inconsistency not only compromises product performance but also reduces manufacturing efficiency and increases production costs. The absence of robust experimental approaches to identify and control critical process parameters has created a significant gap in quality assurance and process optimization.

This study aims to identify and optimize critical factors influencing the weight and quality of football bladders in the manufacturing process at Anwar Khawaja Industries, Sialkot, with a focus on enhancing product performance, consistency, and cost-efficiency through a structured experimental approach. A key factor in determining the quality of a football bladder is the material selection, as the bladder is typically made from latex, butyl, and synthetic rubber [14], with a different composition that influences the weight and quality of the football bladder. The quality of these materials plays a crucial role in the bladder's durability, air retention, and overall performance. High-quality materials ensure that the bladder maintains proper inflation, provides consistent bounce, and can withstand the stresses of regular use, ultimately contributing to improved product quality and performance.

Objective & Novelty of this Study:

Objective:

This study was designed with the following specific aims:

- To identify the key process and material factors that influence the weight and quality of latex-based football bladder at Anwar Khawaja Industries, Sialkot.
- To quantify the main and interaction effects of selected factors (Sulphur, Zinc Oxide, ZDEC, Latex content, Calcium Carbonate, BHT, and Carbon Black) on bladder weight using a DSD.
- To determine optimal factor settings that enhance product performance (weight consistency and material properties) while potentially reducing material cost.

In particular, we sought to determine how each factor and their combinations affect bladder weight and to use these insights to recommend practical adjustments in the production process.

Novelty:

This work is novel in several respects. First, it is, to our knowledge, the first application of a definitive screening design in the context of industrial sport football manufacturing in Pakistan. DSD is a relatively recent type of design of experiments that can estimate linear, quadratic, and some two-factor interactions with very few runs. Its use in this sector is unprecedented. Secondly, by modeling both individual factors and their pairwise interactions, our study provides new insights into how ingredients like Calcium Carbonate ($CACO_3$) interact with vulcanizing agents (e.g. Sulphur) and additives (e.g. BHT antioxidant), which has not been reported before in football or similar polymer manufacturing contexts, Third, the process optimization focus (linking statistical findings to practical recommendations) sets this study apart: we not only identify significant factors but also directly translate them into actionable process improvements. Finally, the combination of DSD methodology, factor reduction to address multicollinearity, and a focus on manufacturing efficiency contributes new knowledge to both the design of experiments literature and the rubber manufacturing industry.

Comparison of Experimental Designs:

Experimental design using Definitive Screening Design (DSD) processes has developed extensively to boost industrial and scientific procedures by discovering key factors that influence the response variable. Developed by Bradley Jones and Chris J. Nachtsheim in the early 2010s. This design offers generous corrections over conventional screening designs, as it can assess the main effects, two–factor relations, and quadratic effects with a lowered number of experimental runs [15][16].

For readers unfamiliar with the definitive Screening Designs (DSD), it is helpful to contrast them with more traditional experimental designs. A full factorial design at two levels evaluates all possible combinations of factor settings, which provides comprehensive information on both main effects and interactions. However, the number of required runs increases exponentially with the number of factors—specifically, 2^k for 'k' factors. For instance, a full two-level factorial design with 7 factors would require $2^7 = 128$ runs, which is often impractical in an industrial setting. In contrast, a DSD requires only 2m + 3 runs for m (odd) factors—just 17 runs for 7 factors—making it far more efficient for screening purposes.

A Box−Behnken Design (BBD) and Central Composite Design (CCD) are both types of response surface methodology (RSM) used primarily for optimization rather than initial screenings. BBD is more efficient than CCD in terms of a few runs and avoids extreme factor settings, which can be beneficial for sensitive systems. While BBD can estimate full quadratic models with reasonable efficiency, it still typically requires significantly more runs than a DSD—for example, more than 57 runs for 7 factors with a single center point.

Methodology:

This research followed a systematic methodology to ensure a structured and reliable approach, as illustrated in Figure 1. The methodology comprised the following steps:

Figure 1. Research Methodology Flowchart

Defining the Research Problem:

The research focused on optimizing the production process of latex-based football bladders within a specific weight range (395 to 450 grams). The aim was to identify key factors influencing product weight and enhance process efficiency using experimental design and statistical analysis.

Literature Review and Variable Selection:

A thorough literature review was conducted to assess current knowledge and practices in polymer blending, latex-based products, and experimental optimization. This review facilitated the selection of seven critical variables deemed influential in the quality and weight of football bladders, including Sulphur, Zinc Oxide, ZDEC, Latex, Calcium Carbonate, BHT, and Carbon Black.

Experimental Design:

We employed a 17-run DSD for 7 factors, allowing estimation of each factor's linear effect, one quadratic term per factor, and selected two-factor interactions. This design structure ensures main effects are orthogonal and not aliased with two-factor interactions. Compared to a fractional factorial, the DSD provides "definitive" screening by also capturing potential curvature. However, it uses only a single center point and a relatively small number of runs, so its power to detect subtle quadratic curvature is limited.

Data Collection:

Primary data were collected on-site at the production line in Anwar Khwaja Industries Ltd., Sialkot. Each experimental batch (300 kg) was produced by precisely adjusting the mixing concentrations of the seven factors (Table I). To ensure measurement consistency across batches, all weighing and monitoring equipment were regularly calibrated and standardized. For instance, the precision balance used to measure the final bladder weight was calibrated before each batch following industry best practices. Standard operating procedures and a single trained operator were used to conduct each batch and record data, minimizing human variability. In addition, all process conditions (mixing time, temperature, curing pressure) were kept consistent according to the facility's standard protocols. In this way, we maintained accurate, repeatable measurements across runs, ensuring that observed effects could be attributed to factor settings rather than measurement error.

Table 1. Percentage of Factors for Manufacturing Football Bladder

S.No.	Factor	Percentage
1	Sulfur	1 – 3
2	Zinc–Oxide	2 – 8
3	ZDEC (Accelerator)	0.5 – 1
4	Latex	70 – 95
5	Calcium Carbonate (CaCO3)	10 – 30
6	BHT	0.2 – 0.5
7	Carbon Black	1 – 10

Statistical Analysis:

Before analysis, data preprocessing was conducted to ensure data quality and suitability for modeling. A manual inspection was performed to verify consistency in measurement units and eliminate any transcription errors from factory logs. As a result, the dataset was found to be complete, with no missing entries.

To facilitate effective comparison across variables with different scales, all continuous input variables were normalized using min-max scaling, transforming their values to a standard range of (0, 1). This step was critical in ensuring that no single variable disproportionately influenced the regression model due to magnitude differences.

Subsequently, the factors were encoded using orthogonal polynomial contrasts, **BY** the requirements of the DSD methodology. This encoding strategy preserves the ability to estimate the main effects, quadratic terms, and two-factor interactions while maintaining orthogonality and interpretability within the model structure.

A DSD was employed to assess the effect of seven experimental factors on the response variable (bladder weight). The design allows the estimation of:

1. Main effects for each factor
2. Quadratic effects for detecting curvature.
3. Limited two-factor interactions

Table 2 provides a summary of the experimental design structure used in this study.

Table 2. Design Summary

Factors:	7	Replicates:	1
Base runs:	17	Total runs:	17
Base blocks:	1	Total blocks:	1

The design involved seven independent variables (factors), each with two levels (low and high). Each experimental condition was tested once, resulting in a total of 17 runs to evaluate the main effects and possible interactions of all factors. The design included only one base block, indicating that all the runs were conducted in a single block without any external variations.

The response variable (RV) — representing the bladder weight — was modeled using second-order regression with interactions. The resulting regression model is expressed as follows:

$$RV = 5268 - 72.0(\text{Sulphur}) + 46.7(\text{Zinc Oxide}) + 1(\text{ZDEC}) - 23.52(\text{CaCO3}) - 4.26(\text{Latex}) - 4550(\text{BHT}) - 3.6(\text{Carbon Black}) - 0.015(\text{Sulphur}^2) + \cdots\cdots + 2.6(\text{BHT} * \text{Carbon Black}) \quad (1)$$

This model includes all main effects, quadratic terms, and two-factor interactions that were statistically significant or practically relevant to the optimization of the bladder weight.

Results and Discussion:

This chapter depicts the consequences gained from the experimental analysis done using the Definitive Screening Design (DSD) method. The study wants to discover the critical factors affecting the response variable (RV) in the manufacturing procedure at Anwar Khwaja Industries (Pvt.) Limited, Sialkot. The conclusions are conferred about their statistical significance and practical consequences.

Model Summary and Statistical Analysis:

The fitted regression model had R^2 = 52.2%, adjusted R^2 = 19.4, and a predictive R^2 of 0.0%. The very low predictive R^2 indicates that while the model fits the experimental data, its ability to predict new observations is limited. However, this should be interpreted in context: definitive screening designs are primarily intended for identifying significant factors and interactions, not for building highly predictive models. The DSD runs were far fewer than a full-factorial or a full quadratic design would require, so the model's power is inherently low. In fact, with only one center point, the DSD has reduced sensitivity to detect modest quadratic curvature. Thus, the low adjusted and predictive R^2 values mainly reflect the limited scale of the experiment rather than flaws in the analysis.

The Analysis of Variance (ANOVA) results are evaluated and listed in Table III, the overall model was marginally meaningful with a p-value of 0.0640, demonstrating that the selected factors and interactions impact the response variable but not strongly. The linear terms had a p-value of 0.161, implying that the individual factors alone might not be sufficient in explaining the response variability.

Significant Factors:

Among the main effects, Calcium Carbonate ($CaCO_3$) was found to be statistically significant (p=0.029), suggesting a strong impact on the response variable. Other linear factors such as Sulphur, Zinc Oxide, BHT, Latex, and Carbon Black did not show significant effects individually.

Several interaction effects were found to be statistically significant at the 5% level:

1. Sulphur * Calcium Carbonate ($CaCO_3$) (p=0.023)
2. Zinc Oxide * BHT (p=0.018)
3. Calcium Carbonate ($CaCO_3$) * BHT (p=0.020)
4. Zinc Oxide * ZDEC (Accelerator) (p=0.050)

These interactions suggest that the effect of one factor on the response variable is dependent on the presence of another factor, emphasizing the importance of considering combined factor influences.

Interpretation of Regression Coefficients:

The regression equation in uncoded units provides an estimate of the response variable based on factor levels. The coefficient values indicate the direction and magnitude of each factor's influence.

The high coefficient of BHT (–4550) suggests that its presence has a substantial negative impact on RV when considered alone. However, its interaction with Calcium Carbonate ($CaCO_3$) and Sulphur yielded significant positive contributions.

Residual Analysis and Model Adequacy:

The diagnostic analysis revealed five unusual observations (Obs 17, 22, 52, 59, and 67) with large residuals. These data points may represent experimental variability or unidentified factors affecting the response. The presence of high variance inflation factors (VIFs), particularly for Sulphur (34.07), Zinc Oxide (17.54), and BHT (15.38), indicates potential multicollinearity, which could affect the stability of the regression coefficients.

Discussion & Recommendation:

The findings indicate that Calcium Carbonate ($CaCO_3$) plays a critical role in the process, both as an individual factor and in interaction with Sulphur and BHT. The high multicollinearity among certain factors suggests that some variables might be redundant or highly correlated, necessitating further refinement in factor selection.

The following recommendations can be implemented for the desired results.

1) **Increase $CaCO_3$ content**: If the goal is to increase bladder stiffness (weight) while lowering costs, raising $CaCO_3$ levels (closer to the higher end of the studied range) is advised. This aligns with glove manufacturing experience that optimal $CaCO_3$ concentration of approximately 30% yields the best mechanical strength [17][18].

2) **Optimize BHT and ZnO Interaction**: The interaction between BHT and ZnO indicates they should be jointly optimized. Higher BHT alone had a negative effect, its combination with $CaCO_3$ or ZnO showed a positive effect on weight. Thus, we recommend using BHT near 0.5% and ZnO at a mid-range level (~5%) to enhance flexibility and air retention without compromising cure strength. This aligns with literature showing that appropriate use of fillers and antioxidants can improve tensile properties [19].

3) Increase Sulphur (up to 3.5%) and maintain BHT (0.3%) if durability is the objective.

4) Increase BHT (0.5%) and maintain Sulphur (2.5%) if flexibility and air retention are the objective.

Additionally, the non–non-significant predictive R^2 value (0.00%) suggests that the current model may not be fully generalizable for predicting future outcomes. Further experiments or the addition of surplus method variables might be necessary to enhance the accuracy of the model.

Table 3. Analysis of Variance

Source	DF	Adj SS	Adj MS	F–Value	P–Value
Model	35	1113.03	31.801	1.59	0.064
Linear	7	221.58	31.655	1.58	0.161
Sulfur	1	48.44	48.440	2.42	0.126
Zinc Oxide	1	35.49	35.485	1.78	0.189
ZDEC (Accelerator)	1	0.27	0.270	0.01	0.908
Calcium carbonate ($CaCO_3$)	1	100.50	100.500	5.03	0.029
Latex	1	29.09	29.086	1.46	0.233
BHT	1	41.48	41.479	2.08	0.156
Carbon Black	1	0.14	0.142	0.01	0.933
Square	7	246.11	35.158	1.76	0.116
Sulphur * Sulphur	1	0.11	0.111	0.01	0.941
Zinc Oxide * Zinc Oxide	1	44.08	44.079	2.21	0.144

Source	DF	Adj SS	Adj MS	F–Value	P–Value
ZDEC (Accelerator) * ZDEC (Accelerator)	1	22.37	22.370	1.12	0.295
Calcium carbonate ($CaCO_3$) * Calcium carbonate ($CaCO_3$)	1	51.19	51.190	2.56	0.116
Latex * Latex	1	24.80	24.804	1.24	0.270
BHT * BHT	1	32.13	32.133	1.61	0.210
Carbon Black * Carbon Black	1	50.45	50.452	2.53	0.118
2–Way Interactions	21	724.58	34.504	1.73	0.057
Sulfur * Zinc Oxide	1	17.18	17.185	0.86	0.358
Sulfur * ZDEC (Accelerator)	1	0.00	0.004	0.00	0.988
Sulphur * Calcium carbonate ($CaCO_3$)	1	110.47	110.470	5.53	0.023
Sulphur * Latex	1	12.35	12.352	0.62	0.435
Sulphur * BHT	1	33.98	33.975	1.70	0.198
Sulfur * Carbon Black	1	0.06	0.058	0.00	0.957
Zinc Oxide * ZDEC (Accelerator)	1	80.77	80.768	4.04	0.050
Zinc Oxide * Calcium carbonate ($CaCO_3$)	1	0.04	0.045	0.00	0.963
Zinc Oxide * Latex	1	1.94	1.941	0.10	0.757
Zinc Oxide * BHT	1	119.53	119.535	5.98	0.018
Zinc Oxide * Carbon Black	1	11.61	11.610	0.58	0.449
ZDEC (Accelerator) * Calcium carbonate ($CaCO_3$)	1	0.11	0.110	0.01	0.941
ZDEC (Accelerator) * Latex	1	0.48	0.479	0.02	0.878
ZDEC (Accelerator) * BHT	1	0.32	0.324	0.02	0.899
ZDEC (Accelerator) * Carbon Black	1	48.75	48.751	2.44	0.124
Calcium carbonate ($CaCO_3$) * Latex	1	5.34	5.344	0.27	0.607
Calcium carbonate ($CaCO_3$) * BHT	1	116.18	116.181	5.82	0.020
Calcium carbonate ($CaCO_3$) * Carbon Black	1	0.04	0.042	0.00	0.964
Latex * BHT	1	13.00	12.997	0.65	0.424
Latex * Carbon Black	1	22.48	22.480	1.13	0.294
BHT * Carbon Black	1	0.78	0.779	0.04	0.844
Error	51	1018.90	19.978		
Total	86	2131.93			

The findings are consistent with those of industrial research on the mixing of rubber and polymers where the performance of the material is greatly affected by component interactions. BHT and calcium carbonate interact to improve the material qualities of the football bladder, as shown in Figure. 2, by the significance of BF and DF interactions.

Additionally, previous investigations revealed the GG's (Carbon Black) influence on material durability and elasticity which supports the existence of the GG as a significant component [20][21].

In the production of football, these concepts support the claim that increasing the proportion of these elements may improve material performance, durability, and impact resistance. Additional research might increase the percentage of these principal factors to more effectively achieve the desired response variable.

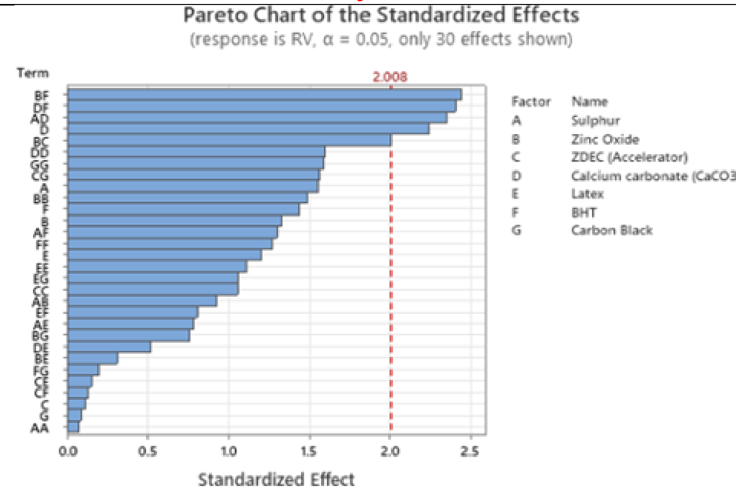

Figure 2. Pareto Chart of Standardized Effects

Figure. 3 shows the residual plots, which give vital information about the suitability of the current model. The Normal Probability Plot (top–left) addresses that residuals closely follow the straight–line pattern, which shows that the errors are normally distributed. This normality assumption is essential for verifying the strength of statistical conclusions drawn from the current model.

The random scatter of points without any clear pattern in the Residuals vs. Fits plot (top–right) shows that the residuals establish a constant variance and no regular bias. This means that the experimental model suitably tells the deviation in the response variable without having any major errors/issues. There are some outliers presents, which might indicate minor variability due to experimental states or material randomness.

The normality assumption in the Histogram of Residuals (bottom–left) is shown by a balanced distribution centered around zero. This regularity confirms that the experimental model correctly predicts the response without meaningful variations.

The residuals change randomly over the experimental runs as shown in the Residuals vs. Observation Order plot (bottom–right), with no apparent trend. This randomness means that there are no time-dependent errors in the experiment.

These residual plots support the experimental model acquired using Definitive Screening Design (DSD) and strengthen its robustness in forecasting the response variable in football manufacturing. Further improvement of key factor relations, such as BF, DF, and CG, could lead to higher material performance and improved manufacturing processes.

The correlation matrix in the sensitivity analysis represents the relationship between the selected factors (Sulfur, Zinc Oxide, ZDEC, Calcium Carbonate, Latex, BHT, and Carbon Black), and the resultant variable is evaluated and shown in Figure 4.

Table 4. Selected factors correlation with RV and its Effects

Factor	Correlation with Resultant Variable	Effect
Calcium Carbonate ($CaCO_3$)	Positive (Strong)	Increasing the output
Latex	Positive (Moderate)	Increasing the output
BHT	Positive (Weak to Moderate)	Slightly increases the output
Sulfur (S)	Positive (Weak)	Slightly increases the output
Zinc Oxide (ZnO)	Negative (Weak)	Slightly decreases the output
ZDEC (Accelerator)	Negative (Moderate)	Decreases the output
Carbon Black	Negative (Moderate)	Decreases the output

Table 4 presents the correlation between the response variable and the input parameters. High positive correlations indicate key factors affecting the resultant variable, while weaker correlations indicate non–non-significant.

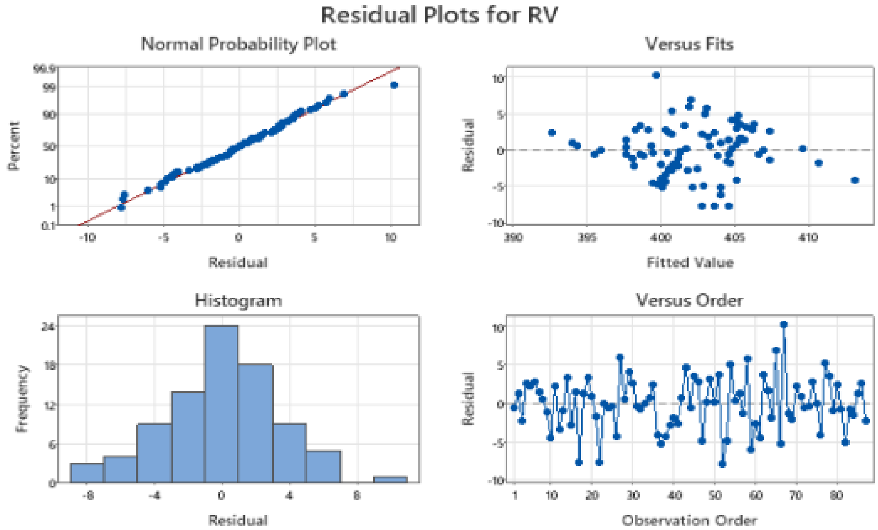

Figure 3. Residual Plots for RV

Each value in the matrix ranges from –1 to 1, where the closeness of values to 1 indicates a strong positive correlation, meaning that an increase in one variable tends to increase the resultant variable while the closeness of values to –1 indicates a strong negative correlation, indicating that an increase in one variable tends to decrease the resultant variable. A value near 0 suggests little to no correlation.

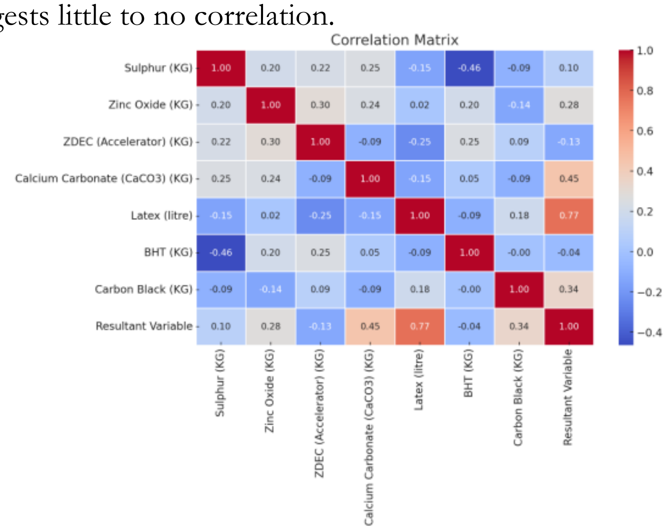

Figure 4. Correlation matrix of selected factors

By analyzing these relationships, it can determine the impact of factors on response variables. This information is necessary for optimizing processes and making data-driven decisions. This matrix helps in understanding dependencies, identifying key contributors, and guiding future experimental designs. Sensitivity analysis using correlation helps in prioritizing variables for further study.

Conclusion:

This study, conducted for Anwar Khwaja Industries (Pvt.) Limited, Sialkot, utilizes a Definitive Screening Design to identify critical factors influencing football quality. Statistical analysis reveals that Calcium Carbonate ($CaCO_3$) is the most significant factor, with a p-value of 0.029, indicating a strong impact on the manufacturing process. An increase in $CaCO_3$

content correlates with increased bladder stiffness. This observation is consistent with findings from glove manufacturing, where an optimal $CaCO_3$ concentration of approximately 30% has been shown to provide the best mechanical strength [17].

Additionally, significant interaction effects were observed, particularly among Sulphur–$CaCO_3$, Zinc Oxide–BHT, and $CaCO_3$–BHT, demonstrating that combined variable influences can outweigh individual effects. This underscores the complexity of the manufacturing process.

The R–R-squared value (52.2%) suggests the model explains a moderate portion of response variation, but the low adjusted R^2 (19.4%) and predictive R^2 (0.0%) indicate limitations in generalizability, requiring further model refinement.

Multicollinearity was identified among Sulphur, Zinc Oxide, and BHT, complicating parameter estimation and prediction. The Factor Analysis technique was applied to mitigate these issues and enhance experimental reliability [22].

Residual analysis revealed potential undocumented factors, necessitating further research to determine whether variations stem from external influences or measurement errors. This study highlights the need for a more robust experimental design to account for internal and external variability in football manufacturing.

This research lays a solid foundation for finding the key factors affecting the weight and quality and highlights the potential models and processes that may improve the response variable.

Recommendations for Future Work:

The current study has a profound impact on finding the key factors resulting in direct effects on the response variable (quality). To enhance the application of the current findings, the following recommendations may increase strength and applicability.

1. Incorporation of additional factors
2. Enhancing the levels of current factors
3. Larger and updated datasets

References:

[1] P. Lund-Thomsen and K. Nadvi, "Global Value Chains, Local Clusters and Corporate Social Responsibility: A Comparative Assessment of the Sports Goods Clusters in Sialkot, Pakistan and Jalandhar, India," *Copenhagen Bus. Sch.*, 2009, Accessed: May 03, 2025. [Online]. Available: https://research.cbs.dk/en/publications/global-value-chains-local-clusters-and-corporate-social-responsib

[2] E. V. David Atkin , Azam Chaudhry , Shamyla Chaudry , Amit K. Khandelwal, "Organizational Barriers to Technology Adoption: Evidence from Soccer-Ball Producers in Pakistan," *Q. J. Econ.*, vol. 132, no. 3, pp. 1101–1164, Aug. 2017, doi: https://doi.org/10.1093/qje/qjx010.

[3] Muhammad Zaheer, "Knowledge on the Fingertips: A Study of Football Production in Pakistan," Paradigms. Accessed: May 03, 2025. [Online]. Available: https://www.researchgate.net/publication/355156505_Knowledge_on_the_Fingertips_A_Study_of_Football_Production_in_Pakistan

[4] T. Raza, "Measuring Technology Differences Across Football Manufacturers in Sialkot," *Lahore J. Econ.*, vol. 21, no. special edition, pp. 237-251–237–251, 2016, Accessed: May 03, 2025. [Online]. Available: https://nja.pastic.gov.pk/LJE/index.php/LJE/article/view/1122

[5] M. A. Tanveer, S. Rizvi, and W. Riaz, "Declining market share of Pakistan in football industry.," *Asian J. Bus. Manag.*, 2012, Accessed: May 03, 2025. [Online]. Available: https://www.semanticscholar.org/paper/Declining-market-share-of-Pakistan-in-football-Tanveer-Rizvi/7210012eb0366b646a379a01871bf0e7a4c9cb8c

[6] K. Nadvi, "Labour standards and technological upgrading: Competitive challenges in the global football industry," *Int. J. Technol. Learn. Innov. Dev.*, vol. 4, no. 1–3, pp. 235–257, 2011, doi: 10.1504/IJTLID.2011.041906.

[7] 김창수, "Football equipment innovation Revolutionizing the Game: How Innovative Football Equipment Startups Are Changing the Playing Field," FasterCapital. Accessed: May 03, 2025. [Online]. Available: https://fastercapital.com/content/Football-equipment-innovation-Revolutionizing-the-Game--How-Innovative-Football-Equipment-Startups-Are-Changing-the-Playing-Field.html

[8] S. I. Harnadi and S. H. Supangkat, "Smart Football: A Systematic Review for Constructing Optimum Team Formation in Football," *10th Int. Conf. ICT Smart Soc. ICISS 2023 - Proceeding*, 2023, doi: 10.1109/ICISS59129.2023.10291603.

[9] S. K. Vinod, R. V Menon, and S. Babu, "Analysis of footballs to study their overall performance using design parameters and explain the knuckling effect using CFD," *Turkish Online J. Qual. Inq.*, vol. 12, no. 7, pp. 8185–8193, Aug. 2021, Accessed: May 03, 2025. [Online]. Available: https://www.tojqi.net/index.php/journal/article/view/5146

[10] Milad Mafi, "Football Aerodynamics Simulation with SimScale," SimScale. Accessed: May 03, 2025. [Online]. Available: https://www.simscale.com/blog/aerodynamics-simulation-in-football/

[11] S. Hong, J. E. Goff, and T. Asai, "The Aerodynamics of New Design Soccer Balls Using a Three-Dimensional Printer," *Appl. Sci. 2024, Vol. 14, Page 3932*, vol. 14, no. 9, p. 3932, May 2024, doi: 10.3390/APP14093932.

[12] Net World Sports, "FIFA QUALITY MARKS FOR SOCCER BALLS GUIDE," Net World Sports. Accessed: May 03, 2025. [Online]. Available: https://www.networldsports.com/buyers-guides/fifa-quality-marks-explained?srsltid=AfmBOoq2VzoKwwOCLwg9Het5X_gA7qxaygRYq5OuEXgZ9tgvDCeT1kxH&utm_source=chatgpt.com

[13] Net World Sports, "FIFA Quality Marks for Soccer Balls Explained | Net World Sports," Net World Sports. Accessed: May 03, 2025. [Online]. Available: https://www.networldsports.com/buyers-guides/fifa-quality-marks-explained

[14] Victeam Sport, "The Difference Between a Latex, Butyl and Synthetic Rubber (SR) Bladder - Victeam Sports," Victeam Sport. Accessed: May 03, 2025. [Online]. Available: https://www.victeamsports.com/the-difference-between-a-latex-butyl-and-synthetic-rubber-sr-bladder/

[15] M. L. Weese, P. J. Ramsey, and D. C. Montgomery, "Analysis of definitive screening designs: Screening vs prediction," *Appl. Stoch. Model. Bus. Ind.*, vol. 34, no. 2, pp. 244–255, Mar. 2018, doi: 10.1002/ASMB.2297;WGROUP:STRING:PUBLICATION.

[16] R. Hayasaka, J. HÄnisch, and P. Cayado, "DSDApp: An Open-Access Tool for Definitive Screening Design," *J. Open Res. Softw.*, vol. 12, pp. 1–8, 2024, doi: 10.5334/JORS.462.

[17] W. A. N. . H.G.I.M., WijesingheW.G.T.W., Gamage, Ariyananda P., Jayasinghe, H.A.S.L., "Optimization of calcium carbonate (CaCO 3) loading in Natural rubber latex based disposable gloves," International Journal of Scientific and Research Publications. Accessed: May 03, 2025. [Online]. Available: http://ijsrp.org/research-paper-0316/ijsrp-p5146.pdf

[18] C. H. Chan, J. Joy, H. J. Maria, and S. Thomas, "CHAPTER 1. Natural Rubber-Based Composites and Nanocomposites: State of the Art, New Challenges and Opportunities," pp. 1–33, Dec. 2013, doi: 10.1039/9781849737654-00001.

[19] I. Surya, H. Ismail, and J. Anto, "Processing and Tensile Properties of Natural Rubber Filled with Calcium Carbonate or Silica in the Presences of Lauryl Alcohol," *BIO Web Conf.*, vol. 94, Mar. 2024, doi: 10.1051/BIOCONF/20249403002.

[20] Z. Wang *et al.*, "Study of the Effect of Carbon Black Filling on the Mechanical Behavior of Rubber Hyper-Elasticity," *Mater. 2023, Vol. 16, Page 6561*, vol. 16, no. 19, p. 6561, Oct. 2023, doi: 10.3390/MA16196561.

[21] E. M. Ginting, N. Bukit, Muliani, and E. Frida, "Mechanical properties and mophology natural rubber blend with bentonit and carbon black," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 223, no. 1, p. 012003, Jul. 2017, doi: 10.1088/1757-899X/223/1/012003.

[22] Muhammad Hassan, "Factor Analysis – Steps, Methods and Examples," *Anal. Types*, 2024, [Online]. Available: https://researchmethod.net/factor-analysis/?utm_source=chatgpt.com.