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Research article

# Optimization of Hot Press Temperature and Eggshell Filler Composition in Biocomposite Fabrication Using the Taguchi Method

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A B S T R A C T

The utilization of biomass waste as a reinforcing agent for biocomposites presents an attractive alternative in the development of environmentally friendly materials. This study aims to analyze the effect of varying percentages of chicken eggshell and crumb rubber fillers, as well as the hot press temperature, on the mechanical properties of the biocomposite, including the Modulus of Rupture (MOR), Modulus of Elasticity (MOE), and strain. The Taguchi method with an L9 orthogonal array design was employed to evaluate the effect of each factor and determine the optimum process combination. The research findings indicate that a 10% filler concentration yielded the highest stiffness, while a 20% filler concentration resulted in the largest strain value and demonstrated the best balance between strength and flexibility. A temperature of 170°C emerged as the most stable condition for most mechanical parameters, whereas a temperature of 190°C provided an increase in strength at higher filler compositions. From this study, it was ascertained that the optimal parameters are a 20% filler concentration and a temperature of 170°C (N1), yielding MOR, MOE, and strain values of 1473.53 MPa, 1186 MPa, and 2.86%, respectively. These findings affirm the critical importance of controlling the filler composition and processing parameters in producing biocomposites that are consistent and high-performing.

## 1. INTRODUCTION

The development of composite materials derived from natural resources has continued to advance in response to the increasing demand for lightweight, environmentally friendly materials with competitive mechanical properties [1]. One of the emerging approaches is the utilization of biomass waste, such as chicken eggshells, as a reinforcing filler in biocomposites. Eggshells are known to contain a high amount of calcium carbonate, which has the potential to enhance material stiffness, while the appropriate addition of fillers can improve flexibility and resistance to deformation [2, 3, 4]. The combination of these materials enables the production of biocomposites that not only possess high functional value but also support the principles of a circular economy [5].

Previous studies have demonstrated that the mechanical properties of composite materials are strongly influenced by the type of filler, filler composition, and processing parameters such as hot press temperature [6, 7]. Variations in processing temperature can affect interfacial bonding quality, matrix flow behavior, structural homogeneity, and

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the degree of mechanical interlocking within the material [8]. However, the interaction characteristics of eggshell fillers under varying pressing temperatures have not been extensively investigated in a systematic manner, particularly in relation to tensile and flexural behavior [9]. This indicates the need for a more structured experimental study.

The Design of Experiment (DOE) approach using the Taguchi method is an efficient optimization technique for evaluating the influence of multiple factors simultaneously on the mechanical response of materials [10]. Through the use of orthogonal arrays, this method not only reduces the number of experimental trials but also identifies the most robust process conditions, which provide optimal performance with minimal variability [11]. The application of the Taguchi method is particularly relevant in biocomposite research due to the inherently high variability of natural materials [12]. Based on these considerations, this study aims to analyze the effect of filler composition (10%, 20%, and 30%) and hot press temperature (170°C, 180°C, and 190°C) on the mechanical properties of biocomposites, including Modulus of Rupture (MOR), Modulus of Elasticity (MOE), and strain. Furthermore, this study seeks to determine the optimal combination of process parameters using Taguchi analysis to achieve the most stable and optimal biocomposite fabrication conditions. The results are expected to contribute to the development of cost-effective, environmentally friendly biocomposites with reliable mechanical performance suitable for lightweight structural applications.

## 2. MATERIALS AND METHODS

To determine the number of specimens and experimental runs, the Taguchi method, which is based on the Design of Experiment (DOE) concept, was employed [13]. The orthogonal array approach is a key feature of this method, allowing efficient experimental design involving multiple factors with different levels, while minimizing the number of required experiments without compromising the quality of information obtained [14, 15]. he primary objective is to develop a product or process that is robust against noise factors from the early design stage [16]. onsequently, variability caused by uncontrollable factors can be reduced, product quality becomes more consistent, and testing costs can be optimized [17].

In this study, three factors with three levels each were considered, resulting in a total degree of freedom of eight. Based on this, an L9 orthogonal array was selected as the experimental design. This design yielded nine experimental combinations, corresponding to nine specimens.

Table 1. Data DOE Penelitian

| Code | Composition | | Temperature |
|---|---|---|---|
| | **Filler (%)** | **Matriks (%)** | **Pressing (°C)** |
| M1 | 10 | 90 | 170 |
| M2 | 10 | 90 | 180 |
| M3 | 10 | 90 | 190 |
| N1 | 20 | 80 | 170 |
| N2 | 20 | 80 | 180 |
| N3 | 20 | 80 | 190 |
| O1 | 30 | 70 | 170 |
| O2 | 30 | 70 | 180 |
| O3 | 30 | 70 | 190 |

Based on these combinations, the test specimens were fabricated following the procedure outlined in Figure 1.

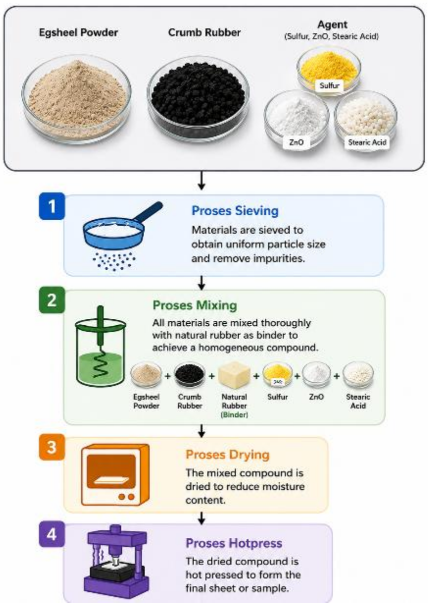


Figure 1. Composite Material Fabrication Process


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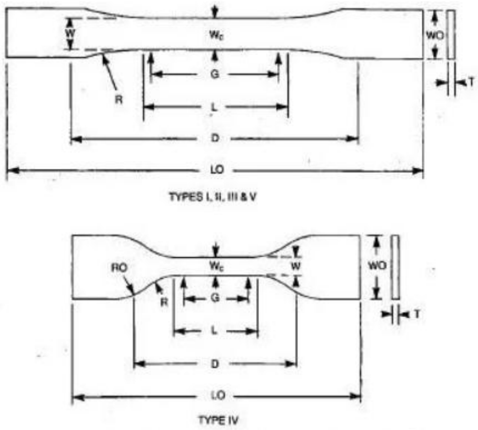
The specimen preparation process began with sieving crumb rubber to 50 mesh and eggshell particles to 100 mesh. This step was intended to facilitate mixing and improve the homogeneity of the resulting biocomposite. The mixed particles were then placed into molds, followed by oven heating at 100°C for 4 hours. Subsequently, the samples were processed using a hot press machine under a pressure of 10 MPa for 30 minutes, with temperature variations ranging from 170°C to 190°C.

Mechanical testing was conducted using a tensile test based on the ASTM D638 Type I standard. The tests were performed using a Universal Testing Machine (UTM) with a maximum capacity of 100 kN.




Specimen Dimensions for Thickness, $T$, mm (in.)[A]

| Dimensions (see drawings) | 7 (0.28) or under | | Over 7 to 14 (0.28 to 0.55), incl | 4 (0.16) or under | | Tolerances |
|---|---|---|---|---|---|---|
| | Type I | Type II | Type III | Type IV[B] | Type V[C,D] | |
| *W*—Width of narrow section[E,F] | 13 (0.50) | 6 (0.25) | 19 (0.75) | 6 (0.25) | 3.18 (0.125) | ±0.5 (±0.02)[B,C] |
| *L*—Length of narrow section | 57 (2.25) | 57 (2.25) | 57 (2.25) | 33 (1.30) | 9.53 (0.375) | ±0.5 (±0.02)[C] |
| *WO*—Width overall, min[G] | 19 (0.75) | 19 (0.75) | 29 (1.13) | 19 (0.75) | ... | + 6.4 ( + 0.25) |
| *WO*—Width overall, min[G] | ... | ... | ... | ... | 9.53 (0.375) | + 3.18 ( + 0.125) |
| *LO*—Length overall, min[H] | 165 (6.5) | 183 (7.2) | 246 (9.7) | 115 (4.5) | 63.5 (2.5) | no max (no max) |
| *G*—Gage length[I] | 50 (2.00) | 50 (2.00) | 50 (2.00) | ... | 7.62 (0.300) | ±0.25 (±0.010)[C] |
| *G*—Gage length[I] | ... | ... | ... | 25 (1.00) | ... | ±0.13 (±0.005) |
| *D*—Distance between grips | 115 (4.5) | 135 (5.3) | 115 (4.5) | 65 (2.5)[J] | 25.4 (1.0) | ±5 (±0.2) |
| *R*—Radius of fillet | 76 (3.00) | 76 (3.00) | 76 (3.00) | 14 (0.56) | 12.7 (0.5) | ±1 (±0.04)[C] |
| *RO*—Outer radius (Type IV) | ... | ... | ... | 25 (1.00) | ... | ±1 (±0.04) |

Figure 2. Standard ASTM D638 [18]

## 3. RESULTS

### *3.1 Modulus of Rupture*

The Modulus of Rupture (MOR) represents the maximum flexural strength of a material before failure. It indicates the material's ability to withstand tensile stress on the underside during bending. A higher MOR value reflects greater resistance to fracture under bending loads, indicating a stronger internal structure[19].

At a filler composition of 10%, the MOR value decreases significantly with increasing hot press temperature. The highest MOR is observed in M1, indicating that 170°C represents the optimal temperature for low filler content. As the temperature increases to 180–190°C, the flexural strength declines, which is likely attributed to thermal degradation of the liquid natural rubber matrix and/or weakening of interfacial bonding due to excessive heat exposure. This behavior suggests that, at low filler loading, the composite structure is more susceptible to thermal sensitivity.

At a filler composition of 20%, the MOR exhibits a non-linear relationship with temperature. The highest MOR value is obtained in N3 (190°C), in contrast to the trend observed in the 10% filler group. This indicates that, at higher filler loading, elevated temperature enhances filler dispersion and matrix consolidation, thereby improving interfacial adhesion. Conversely, N2 presents the lowest MOR value, which may be attributed to suboptimal curing at 180°C for the 20% filler composition.

At a filler composition of 30%, the MOR generally increases with increasing hot press temperature, with the highest value recorded in O3 (190°C). This phenomenon is associated with the higher filler fraction, which necessitates elevated temperatures to achieve improved mechanical interlocking, enhanced structural densification, and better matrix flow to fill interparticle voids. Therefore, higher processing temperatures exhibit a beneficial effect at higher filler contents.

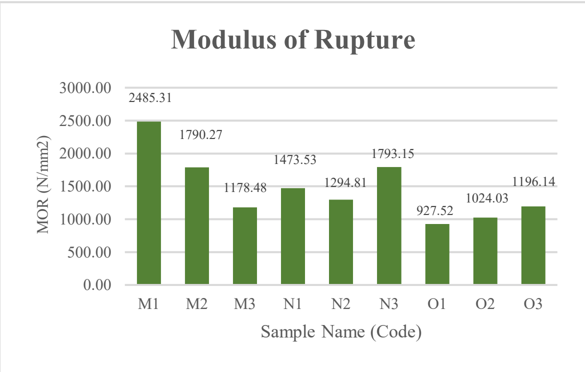



Figure 3. Modulus of Rupture

### *3.2 Modulus of Elasticity*

The Modulus of Elasticity (MOE), or elastic modulus, is a fundamental mechanical parameter that characterizes the stiffness of a material under applied load. In essence, MOE quantifies the extent to which a material undergoes elastic deformation (temporary shape change) when subjected to a given stress. In the context of biocomposites, MOE is used to evaluate the effectiveness of both the filler and the matrix in contributing to structural stiffness, making it a critical parameter in determining material performance under structural or flexural loading conditions [20, 21].

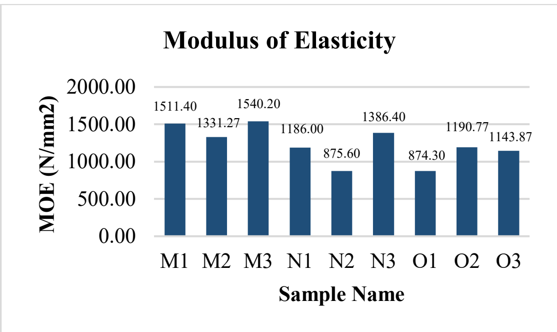



Figure 4. Modulus of Elasticity

In general, the MOE values exhibit a clear trend in which composites with 10% filler content (series M) demonstrate the highest stiffness compared to those with 20% (series N) and 30% (series O). Within the 10% filler group, M3 (1540.20 N/mm²) exhibits the highest stiffness, followed by M1 (1511.40 N/mm²) and M2 (1331.27 N/mm²). This indicates that at low filler content, the material structure is more homogeneous, and the interaction between the liquid natural rubber matrix and the eggshell/crumb rubber fillers is more effective, resulting in a higher modulus of elasticity.

For the 20% filler composition (series N), the MOE decreases significantly. For instance, N2 reaches only 875.60 N/mm², representing the lowest value among all samples. The increase in filler content to 20% tends to promote particle agglomeration and less uniform mixing, which reduces material stiffness. However, sample N3 (1386.40 N/mm²) still exhibits a relatively high value, indicating that a temperature of 190°C enhances interfacial bonding despite the higher filler content.

At 30% filler content (series O), the MOE values remain lower than those of series M but are slightly higher than some samples in series N. The highest value in this series is observed in O2 (1190.77 N/mm²), suggesting that 180°C provides the most favorable condition for achieving adequate bonding between the high filler content and the matrix. Meanwhile, O1 (874.30 N/mm²) shows the lowest value in this group, indicating that 170°C is not optimal for higher filler loadings.

Overall, composites with 10% filler exhibit the highest and most stable modulus of elasticity, with minimal variation. Increasing the filler content to 20% and 30% tends to reduce MOE due to decreased structural homogeneity. Nevertheless, the hot press temperature plays a critical role in governing the mechanical performance of the material.

### *3.3. Strain*

Strain is a mechanical parameter that describes the extent to which a material undergoes a change in length when subjected to tensile loading. It is

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defined as the ratio of the change in length to the original length of the material and is therefore commonly expressed as a percentage (%) [22]. This parameter reflects the material's flexibility, where a higher strain value indicates a greater ability to elongate prior to failure. In tensile testing, strain serves as a critical indicator for evaluating the deformation capability of biocomposites before fracture. The following presents the strain results obtained from the tensile tests conducted.

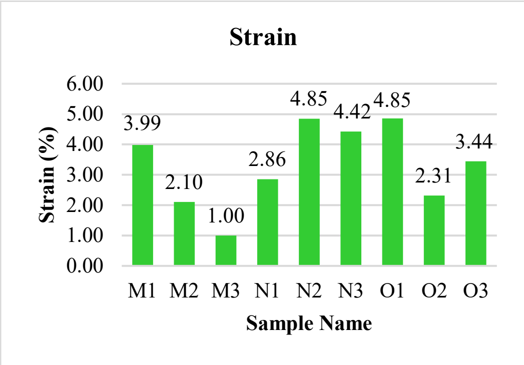


Figure 5. Strain

The M series specimens exhibit the lowest strain values, indicating that composites with 10% filler possess the highest stiffness. Sample M1 shows the highest strain within this group, as the matrix remains relatively ductile at 170°C. However, the strain decreases significantly in M2 and particularly in M3, reflecting increased stiffness due to higher hot press temperatures. The relatively small error bars observed in M2 and M3 suggest a more uniform material structure at elevated temperatures. The N series specimens exhibit the highest strain values overall, indicating that a 20% filler composition provides the most favorable balance between stiffness and flexibility. Samples N2 and N3 demonstrate high strain values, likely due to improved interfacial bonding and more homogeneous material consolidation at temperatures of 180–190°C. However, the larger error bars in this series indicate greater internal variability among the samples, suggesting that while the composite is more flexible, its structure is less uniform.

In contrast, the O series displays a fluctuating strain pattern due to the dominance of high filler content. Sample O1 exhibits relatively high strain, but a significant decrease is observed in O2, indicating increased brittleness at 180°C. Sample O3 shows a subsequent increase in strain, as the higher temperature of 190°C promotes structural densification, although the overall behavior remains less stable.

### *3.4. DOE (Design of Experiment) Analysis – Taguchi*

The Design of Experiment (DOE) method with the Taguchi approach was employed to analyze the effect of each process parameter on the mechanical properties of the resulting biocomposite material. The Taguchi method was selected due to its capability to identify the optimal combination of factor levels with a minimal number of experimental runs, while also evaluating system sensitivity through the calculation of the Signal-to-Noise (S/N) ratio.

The factors investigated in this study include variations in filler composition (10%, 20%, and 30%) and hot press temperature (170°C, 180°C, and 190°C), both of which have been shown to significantly influence interfacial bonding mechanisms and the tensile performance of the composite. By utilizing main effects plot analysis, the Taguchi method facilitates the determination of optimal factor levels that yield the highest tensile strength while simultaneously minimizing variability or noise in the experimental results.

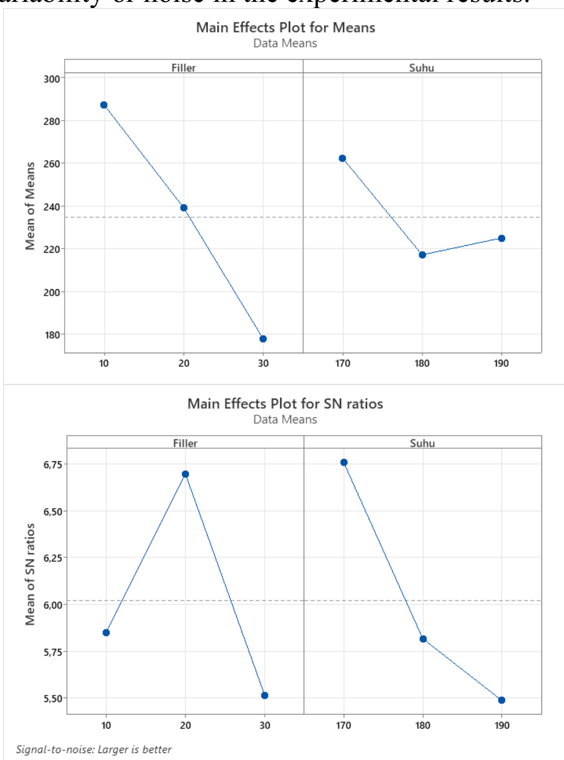


Figure 6. Optimal Factor Level Data for Tensile Testing

The Main Effects Plot analysis reveals a conflict between absolute performance optimization (Data Means) and stability optimization (S/N Ratios). For the temperature factor, the 170°C level consistently emerges as optimal, as it yields the highest average response (approximately 262) and the highest S/N ratio (6.75), indicating strong and robust performance (i.e., stable against variability).
However, for the filler factor, a trade-off is observed: a 10% filler provides the highest absolute mean response (288), whereas a 20% filler yields the highest S/N ratio (6.7), making it the most stable level. Within the Taguchi methodology, since the primary objective is to achieve robustness in production, the most optimal process combination for this composite is 20% filler and a temperature of 170°C. This selection prioritizes consistent quality over peak but less stable performance.

## 4. CONCLUSION

This study demonstrates that variations in eggshell and crumb rubber filler content, as well as changes in hot press temperature, exert a significant influence on the mechanical properties of biocomposites, particularly in terms of Modulus of Rupture (MOR), Modulus of Elasticity (MOE), and strain. A low filler composition (10%) yields the highest stiffness and mechanical stability, whereas a 20% filler composition results in the highest strain and provides an optimal balance between strength and flexibility. In contrast, a 30% filler composition exhibits less stable performance, primarily due to non-uniform particle distribution.

From a processing standpoint, a temperature of 170°C is identified as the most favorable condition for achieving stable mechanical responses, while 190°C proves to be more beneficial for higher filler loadings. Based on the Taguchi method analysis, the optimal parameter combination is determined to be 20% filler and a temperature of 170°C (N1), yielding MOR, MOE, and strain values of 1473.53 MPa, 1186 MPa, and 2.86%, respectively. This combination is considered optimal as it provides the most robust performance with respect to process variability.

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