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Mathematical Modeling and MOPSO-Based Simulation of Natural Fiber Reinforced Polypropylene Composites for Damping Performance Validation

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Abstract

Polymer composites reinforced with natural fibers are increasingly being used due to their environmental friendliness, cost-effectiveness and superior damping properties. But the task of determining the best balance between stiffness and vibration damping presents a complex multi-objective problem. In this paper, a mathematical modeling and Multi-Objective Particle Swarm Optimization (MOPSO)-driven simulation approach is proposed to determine the optimal composition of Polypropylene (PP) composites reinforced with Jute, Sisal and Banana natural fibers. The developed model assesses the effects of different weight fractions on two contradictory objectives, Young's modulus and damping. The MOPSO algorithm is used to obtain a diversified set of Pareto-optimal solutions to determine the best compromise between stiffness and damping. The outcomes reveal that polypropylene plays a crucial role in improving the stiffness of the structure while the natural fibres, especially Jute and Banana, improve the damping factor as they dissipate energy, and Sisal contributes to both. Convergence studies and particle movements validate the stability, robustness and effectiveness of the optimization process. The results underline the role of hybrid composite design and multi-objective optimization in the development of composite materials with desired properties for engineered systems. The methodology offers a robust and scalable process for the development of sustainable and high-performance composites for vibration control and other applications.

Keywords: Natural Fiber Reinforced Composites; Polypropylene (PP); Multi-Objective Particle Swarm Optimization (MOPSO); Damping Performance; Mathematical Modeling

1. Introduction

There is a recent trend towards the use of low-cost, lightweight and ecologically friendly materials in various engineering applications, including automotive, aerospace and structural. Traditional synthetic fiber composites, although strong and stiff, are expensive, non-biodegradable and environmentally unfriendly [1]. Consequently, natural fiber reinforced polymer (NFRP) composites have gained attention for their renewable nature, low density, biodegradability and damping properties [2]. Polypropylene (PP) is a commonly used matrix for its good processability, resistance to chemicals and good mechanical properties, and is suitable for hybrid composites.

In many applications, a high stiffness and good vibration damping are desirable mechanical properties. Unfortunately, the two are mutually exclusive [3]. High stiffness materials usually have low energy dissipation, and vice versa [4]. Natural reinforcing materials such as Jute, Sisal and Banana have different mechanical and viscoelastic characteristics, which affect the viscoelastic properties of the composite material when mixed with a polymer matrix. As a result, predicting the right proportion of these materials to obtain a desired performance is challenging.

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Traditional design strategies are based on trial-and-error or single-objective optimization, which can be inefficient and overlook the trade-offs between different performance objectives. However, multi-objective optimization methods offer a more systematic means to determine a range of solutions, called the Pareto front, where further improvement in one objective results in deterioration in another objective. One such technique, the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm, has emerged as a simple, efficient and diverse solution approach [5].

In this work, a mathematical model is developed to predict the mechanical (Young's modulus) and damping characteristics of natural fiber reinforced polypropylene composites as a function of material weight fractions. The developed model is combined with the MOPSO algorithm for multi-objective optimization to simultaneously enhance both the stiffness and damping of the composites. This method allows the identification of Pareto-optimal solutions for the material formulations, offering insights into the PP and natural fiber interactions. The contributions of this paper are the creation of a model for predicting the stiffness and damping of hybrid natural fiber reinforced polypropylene composites. Furthermore, the research uses the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to determine the optimal material weight fractions by taking into account multiple, conflicting objectives. The study also includes an extensive analysis of the Pareto fronts, convergence behavior, and contribution analysis. Additionally, the study highlights the best composite compositions that have the potential to effectively improve damping performance without compromising stiffness, thus offering a well-rounded and efficient design solution for advanced engineering design.

2. Literature Review

The growing need for eco-friendly and lightweight composites has motivated research on natural fiber reinforced polymer (NFRP) composites. Jute, sisal and banana natural fibers are of particular interest for their low density, sustainability, low cost and good mechanical properties compared to man-made fibers [1]. These have been extensively used in automobile, construction and structural applications where vibration damping and sound absorption are critical. There are numerous studies on the dynamic and mechanical properties of natural fiber composites [2]. Studies of hybrid composites containing jute, sisal and banana fibers have shown that fiber hybridization leads to improved tensile, flexural, and dynamic mechanical properties [3]. For example, one study found that the interlaminar strength and viscoelastic properties were improved with the optimum blend of natural fibers, demonstrating the significance of hybridization in composite systems [4]. Likewise, experimental studies on sisal and banana fiber composites demonstrated that higher fiber content results in higher stiffness and damping, but this enhancement is contingent on fiber dispersion and bonding [7].

Polypropylene (PP) is a popular matrix material known for its good processability, chemical stability and mechanical properties. Research on sisal fiber composites with polypropylene matrix reveals that the addition of natural fibers results in a considerable improvement in storage modulus and stiffness, but the effect on damping can be different depending on the type of fiber treatment and loading conditions [5,6]. Moreover, hybrid PP composites using different types of natural fibers demonstrate enhanced mechanical properties and impact strength, validating the concept of fiber hybridization. However, there are still some issues to be addressed. A critical aspect is the fiber–matrix interface, which governs the stress transfer between the fiber and matrix, thus affecting the composite performance [7]. The hydrophilic nature of natural fibers and the hydrophobic nature of polymer matrices can result in weak bonding, affecting the mechanical performance [8,9]. Several studies have shown that chemical treatments and coupling agents play an important role in enhancing interfacial bonding and composite performance. Furthermore, the properties of natural fiber composites are affected by various factors including fiber length, orientation, weight fraction and processing conditions, complicating the design process.

Another critical property is dynamic loading and damping of composites. Although numerous experimental studies have shown that natural fiber composites have higher damping than synthetic fiber composites, detailed modeling and optimization studies are rare. The majority of research has been conducted using single-objective optimization or experimental studies, with a relatively understated focus on multi-objective optimization of conflicting properties such as stiffness and damping. To overcome these challenges, there has been a growing interest in computational optimization methods such as evolutionary algorithms and swarm intelligence [10]. Multi-objective optimization techniques, like Particle Swarm Optimization (PSO) and its variants, have demonstrated high potential in addressing complex engineering problems because of their rapid convergence and capability to produce a diverse set of Pareto-optimal solutions. But the use of Multi-Objective Particle Swarm Optimization (MOPSO) in natural fiber reinforced composites, especially for simultaneous optimization of mechanical and damping properties, has not been widely studied.

Based on the literature reviewed, it has become clear that while considerable research has been done in the mechanical and damping properties of natural fiber composites, there is still a need for integrated approaches that simultaneously incorporate mathematical modeling of composite properties, multi-objective optimization of the composite composition, and an analysis of the relationship between stiffness and damping. In this paper, an integrated strategy is presented, involving mathematical modeling and a simulation framework based on Multi-Objective Particle Swarm Optimization (MOPSO). This approach seeks to improve the damping properties of composites without detrimentally affecting their stiffness, by optimizing the weight fraction of polypropylene (PP), jute, sisal and banana fiber, offering a more effective composite design approach.

3. Methodology

The approach combines mathematical expressions for composite properties with a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to calculate the optimal weight ratios of polypropylene (PP), jute, sisal and banana fiber. The goal is to achieve a composite material with optimal Young's modulus (stiffness) and damping factor.

3.1. Problem Formulation

The composite is considered as a four-phase material system, consisting of one matrix (PP) and three reinforcing natural fibers (Jute, Sisal, and Banana). The design variables are the weight fractions of each constituent:

$$W = [w_{PP}, w_J, w_S, w_B]$$

subject to the constraint:

$$w_{PP} + w_J + w_S + w_B = 1$$

and

$$0 \leq w_i \leq 1, i \in \{PP, J, S, B\}$$

The optimization problem is defined as:

- Maximize: Young's Modulus (E)
- Maximize: Damping Factor (η)

3.2. Mathematical Modeling of Composite Properties

3.2.1. Young's Modulus (Stiffness Model)

The effective Young's modulus of the composite is estimated using the rule of mixtures, expressed as:

$$E_c = w_{PP}E_{PP} + w_J E_J + w_S E_S + w_B E_B$$

where:

E_c= composite Young's modulus

E_{PP}, E_J, E_S, E_B= Young's modulus of PP, Jute, Sisal, and Banana fibers respectively

This linear approximation assumes uniform distribution and perfect bonding among constituents.

3.2.2. Damping Factor Model

The overall damping factor of the composite is modeled as a weighted contribution of individual materials:

$$\eta_c = w_{PP}\eta_{PP} + w_J\eta_J + w_S\eta_S + w_B\eta_B$$

where:

η_c= composite damping factor

$\eta_{PP}, \eta_J, \eta_S, \eta_B$= damping coefficients of individual materials

This model captures the energy dissipation characteristics of each constituent.

3.3. Multi-Objective Optimization Using MOPSO

To solve the formulated problem, the Multi-Objective Particle Swarm Optimization (MOPSO) algorithm is employed. MOPSO is an extension of PSO that generates a set of Pareto-optimal solutions instead of a single optimal solution.

3.3.1. Particle Representation

Each particle represents a candidate solution:

$$X_i = [w_{PP}, w_J, w_S, w_B]$$

with corresponding velocity:

$$V_i = [v_{PP}, v_J, v_S, v_B]$$

3.3.2. Velocity and Position Update

The velocity and position of each particle are updated using:

$$V_i^{t+1} = \omega V_i^t + c_1 r_1 (P_i - X_i^t) + c_2 r_2 (G_i - X_i^t)$$
$$X_i^{t+1} = X_i^t + V_i^{t+1}$$

where:

- ω= inertia weight
- c_1, c_2= cognitive and social coefficients
- r_1, r_2= random numbers in [0, 1]
- P_i= personal best position
- G_i= global best (selected from repository)

3.3.3. Pareto Dominance and Repository Management

A solution $A$is said to dominate solution Bif:

$$A \prec B \iff (f_1(A) \geq f_1(B) \text{ and } f_2(A) \geq f_2(B)) \text{ with at least one strict inequality}$$

where $f_1$and $f_2$represent stiffness and damping objectives.

A repository (archive) is maintained to store non-dominated solutions, ensuring diversity using techniques such as crowding distance or grid-based selection.

3.3.4. Constraint Handling

After each iteration, constraints are enforced:

- Normalize weight fractions:

$$w_i = \frac{w_i}{\sum w_i}$$

- Ensure bounds:

$$0 \leq w_i \leq 1$$

3.4. Performance Evaluation Metrics

The performance of the optimization is measured by:

- Pareto front distribution
- Convergence behavior of objectives
- Diversity of solutions in repository
- Stability of material weight fractions

The developed approach offers a rigorous and scalable design process for composite materials. The combination of mathematical modeling and MOPSO enables efficient exploration of the trade-off between stiffness and damping to discover the best hybrid materials.

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4. Algorithm: Multi-Objective Particle Swarm Optimization (MOPSO)

MOPSO algorithm is employed to find the optimum weight percentage of polypropylene (PP), jute, sisal, and banana fibers to achieve high Young's modulus and damping factor.

4.1. Algorithm Steps

Input:

- Population size N
- Maximum iterations T
- Inertia weight ω
- Cognitive coefficient c_1, social coefficient c_2
- Material properties: E_i, η_i for $i \in \{PP, J, S, B\}$

Output:

- Pareto-optimal set of weight fractions $W = [w_{PP}, w_J, w_S, w_B]$

Step 1: Initialization

1. Initialize particle positions randomly:

$$X_i = [w_{PP}, w_J, w_S, w_B], \forall i = 1,2,\ldots,N$$

2. Normalize weights such that:

$$\sum w_i = 1$$

3. Initialize velocities V_i randomly
4. Evaluate objective functions:
   - $f_1 = E_c$ (Young's modulus)
   - $f_2 = \eta_c$ (damping factor)
5. Set personal best $P_i = X_i$
6. Initialize repository R with non-dominated solutions

Step 2: Iterative Optimization
For $t = 1$ to T do

1. Select Global Best (gbest):
   - Choose G_i randomly from repository R using crowding distance/grid method
2. Update Velocity:

$$V_i^{t+1} = \omega V_i^t + c_1 r_1 (P_i - X_i^t) + c_2 r_2 (G_i - X_i^t)$$

3. Update Position:

$$X_i^{t+1} = X_i^t + V_i^{t+1}$$

4. Apply Constraints:
   - Ensure $0 \le w_i \le 1$
   - Normalize:

$$w_i = \frac{w_i}{\sum w_i}$$

5. Evaluate Objectives:
    - Compute E_c and η_c
6. Update Personal Best (pbest):
    - If X_i^{t+1} dominates P_i, then update $P_i = X_i^{t+1}$
7. Update Repository (Pareto Set):
    - Add non-dominated solutions
    - Remove dominated solutions
    - Maintain repository size using crowding distance

   End For

Step 3: Output Results
- Return repository R containing Pareto-optimal solutions
- Extract optimal weight fractions for different trade-offs

5. Results and Discussion

The findings of the mathematical modelling and Multi-Objective Particle Swarm Optimization (MOPSO) simulation give insight into the mechanical properties and damping characteristics of natural fiber reinforced polypropylene composites. The study compares the relationship between Young's modulus (stiffness) and the damping factor, which are competing objectives. The Pareto fronts, convergence behavior and weight fraction trends demonstrate the success of the optimization approach. The assessment of individual material contributions, weight fraction convergence, and particle distribution of Jute, Sisal and Banana reveal the interaction of the natural fibers with Polypropylene and their impact on the performance. The next sub-sections provide a detailed discussion of the results, with specific reference to optimization strategy, material interactions and solution stability.

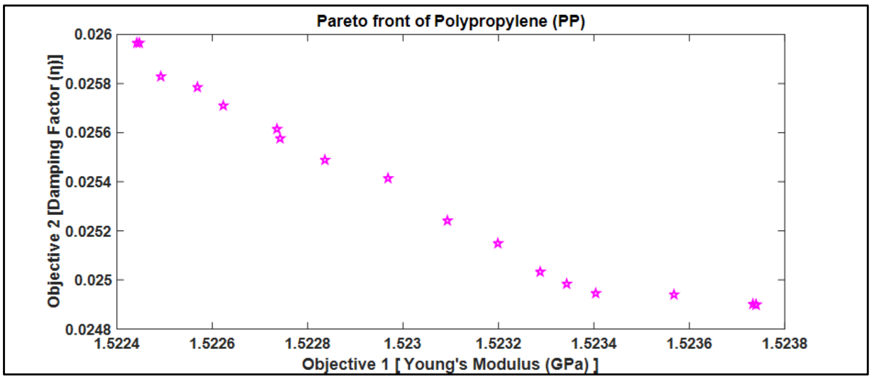

Figure 1 Pareto front of Polypropylene (PP)

Figure 1 shows the Pareto front for Polypropylene (PP) which is a trade-off between Young's modulus (stiffness) and damping factor. The spread of solutions suggests that a trade-off exists between the two objectives. Increasing the content of PP results in an improvement of the stiffness of the composite (due to the structural properties of PP); but also leads to a deterioration of the damping property (as PP has a limited ability to dissipate energy). The distribution of the Pareto solutions shows that there exists no single solution that could optimise both of the objectives, thus confirming the need for multi-objective optimisation with MOPSO. The continuous and evenly spaced front also indicates that the MOPSO algorithm performs a good search of the feasible solution space, and does not get trapped in local minima. The knee of the curve defines the best compromise solutions; an intermediate PP fraction offers a combination of stiffness and damping, which is desirable for engineering applications that need a combination of these properties.

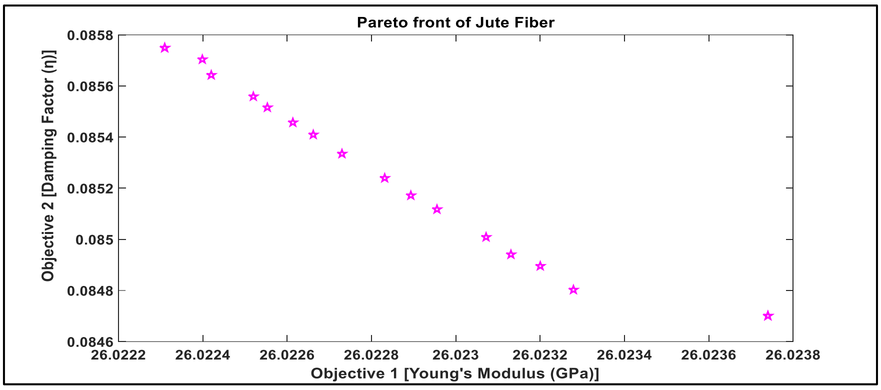

Figure 2 Pareto front of Jute Fiber

Figure 2 shows the Pareto curve for Jute fiber reinforced composites. Jute fiber plays a crucial role in improving the damping properties compared to PP, thanks to its fiber structure and friction. The Pareto curve illustrates that a higher Jute content results in enhanced damping but with a trade-off in terms of stiffness when compared to the synthetic matrix. The Pareto front is relatively broad, suggesting that Jute fiber offers more design options for different combinations of performance. This implies that Jute is very useful in vibration control and energy absorption applications. The spread of multiple non-dominated solutions demonstrates the capability of MOPSO to capture a range of optimal solutions, allowing designers to choose among designs with a preference for certain performance objectives.

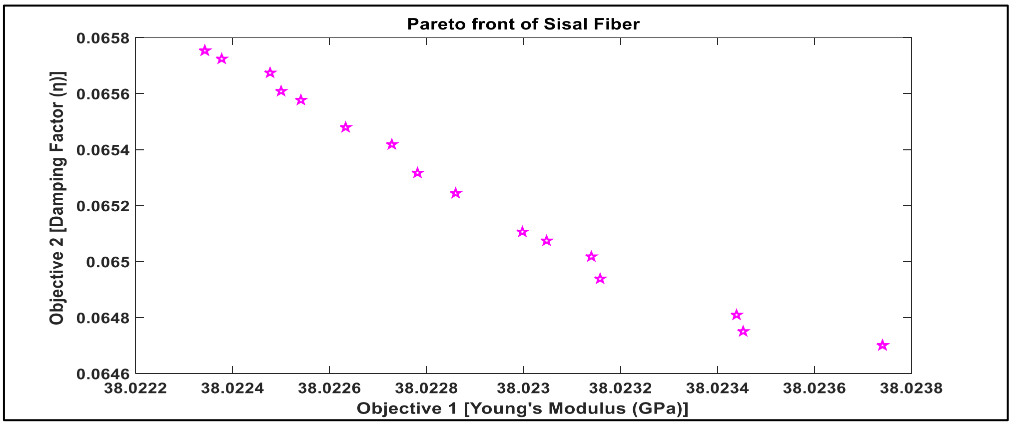

Figure 3 Pareto front of Sisak Fiber

Figure 3 illustrates the Pareto front for Sisal fiber, which exhibits a moderate effect on both stiffness and damping. Sisal fiber has lower damping and higher stiffness than Jute, which results in a Pareto front that is between the extremes of PP and Jute. The curve is more linear, suggesting that Sisal fiber can be used as a middle ground reinforcement. The concentration of solutions in some parts of the Pareto front indicates the robustness of the optimal solutions, suggesting that slight changes in Sisal fiber content have minimal influence on performance. This makes Sisal a suitable option for applications where consistent mechanical properties with adequate damping are desired.

The Pareto front for Banana fiber is shown in Figure 4, which is strongly biased towards damping. As a natural lignocellulosic fiber, Banana fiber promotes energy absorption through its porous and fibrous nature. The Pareto solutions show that the addition of Banana fiber increases the damping performance, but could decrease the stiffness of the composite when compared to synthetic and some other natural fibers (Sisal). The Pareto front is slightly curved, suggesting interactions between Banana fiber content and composite response. The spread of solutions indicates that Banana fiber is an ideal choice for vibration and acoustic insulation, rather than stiffness. The ability of MOPSO to identify these nonlinear relationships confirms its suitability for composite design.

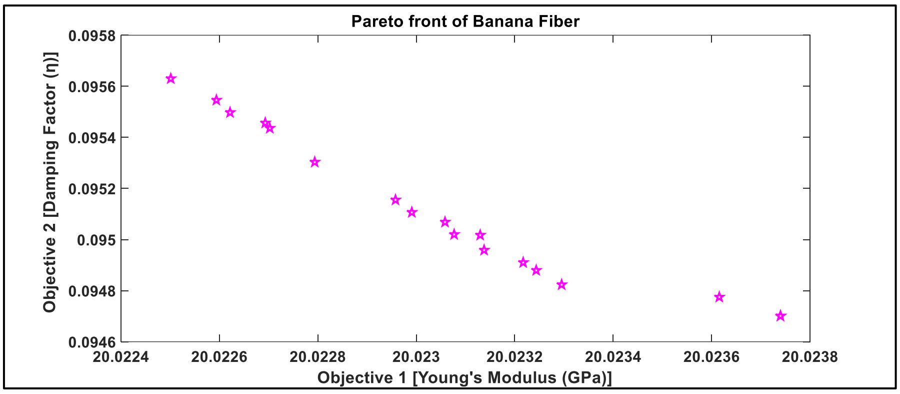

Figure 4 Pareti front of Banana Fiber

As a whole, the Pareto fronts of PP, Jute, Sisal and Banana fibers demonstrate the multi-material trade-offs in designing composites. Polypropylene (PP) increases stiffness, whereas the natural fibers (particularly Jute and Banana) increase damping. Sisal offers a compromise. The findings highlight the need to hybridize materials to get the best of both mechanical and damping properties.

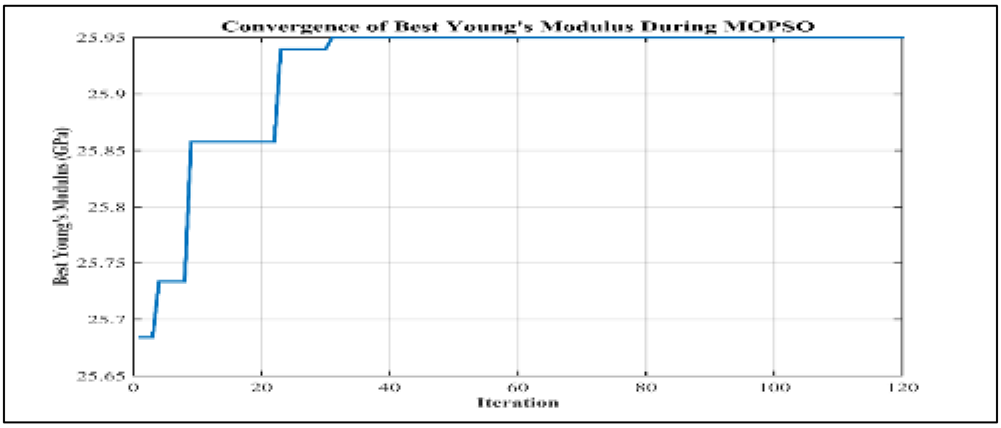

Figure 5 Convergence of Best Youngs, Module During MOPSO

The convergence of the best Young's modulus value found by MOPSO is shown in figure 5. The curve starts with a steep rise, suggesting that the MOPSO algorithm quickly finds promising areas in the search space that have higher Young's modulus values. This is the exploration stage of MOPSO where different particle positions help in finding better solutions. Over time, the curve levels off, showing a decrease in the rate of improvement. It suggests the algorithm is switching from exploration to exploitation of the best solution. The steady value to which the curve converges indicates that the optimization algorithm successfully finds the optimal or near-optimal stiffness configuration. The lack of significant fluctuations also indicates the algorithm's stability and robustness, leading to consistent optimization results.

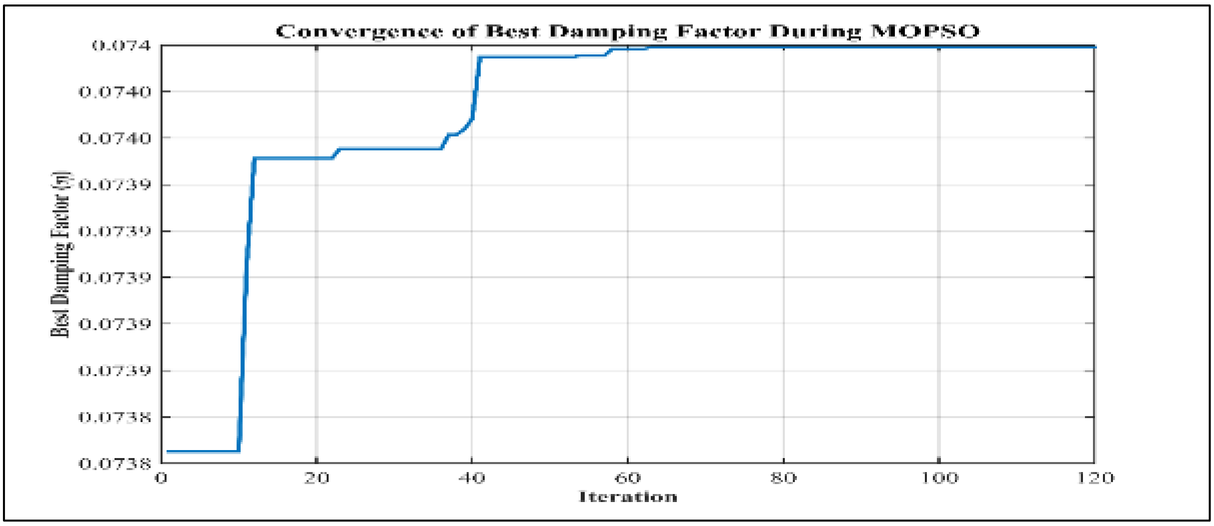

Figure 6 Convergence of Best Damping Factor During MOPSO

The convergence trend of the best damping factor is shown in Figure 6. The pattern for the best damping factor is similar to that of the best Young's modulus, showing a rapid improvement at the very beginning of the optimization process, thus showing the capability of MOPSO in finding good solutions in the early stages. But unlike stiffness convergence, the damping convergence curve may be less smooth before settling, as the damping properties of composite materials are inherently complex and nonlinear. This is a result of the conflicting effect of different types of fibers. Finally, the curve reaches a steady maximum value, suggesting that the algorithm successfully optimises the energy dissipation performance of natural fiber composites by finding a balance between different fiber components.

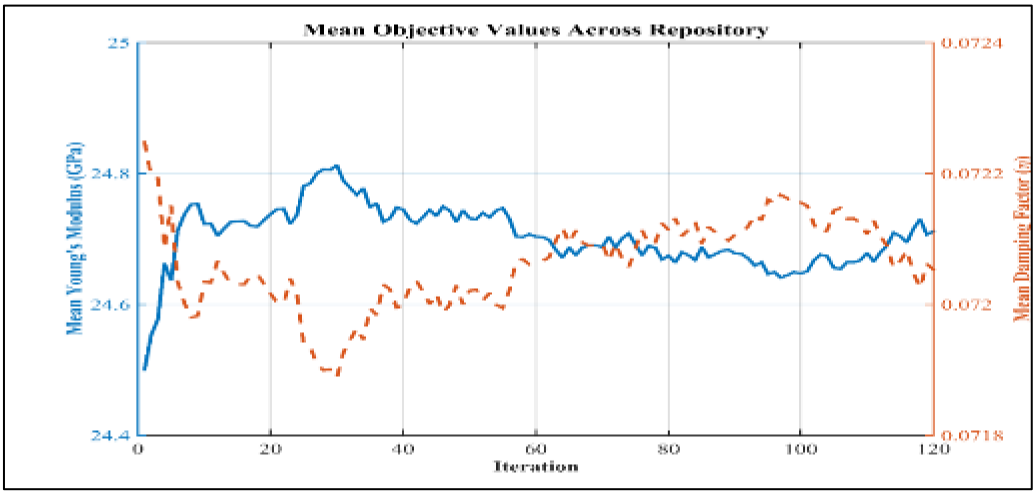

Figure 7 Mean Objective Values Across Repository

Figure 7 illustrates the changes in mean objective values of solutions in the MOPSO repository across iterations. This plot gives an idea of the quality of the Pareto-optimal solutions rather than the best solution. The steady improvement of mean values suggests that the repository is steadily collecting more fit non-dominated solutions. The smooth convergence of the mean objective values indicates that MOPSO maintains a well-distributed Pareto front, which results in diversity of solutions while achieving convergence. Further, the plateauing in mean values of objective functions indicates that the repository has converged and that additional iterations will not significantly improve the solution set. This indicates that the repository update strategies have maintained the best trade-off between the stiffness and damping.

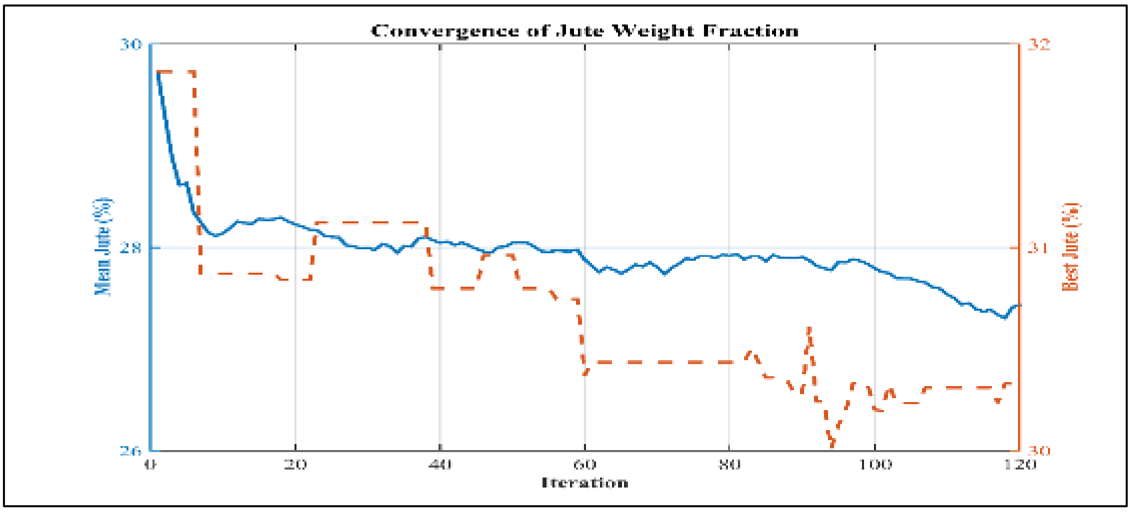

Figure 8 Convergence of Jute Weight Fraction

In Figure 8, the convergence of Jute fiber weight fraction is illustrated. The initial weight fraction may fluctuate due to the random initialization and exploration stage of MOPSO. At this point, the algorithm is exploring the design space for promising regions. Over time, the Jute weight fraction converges towards an optimal value, suggesting that the algorithm has recognised its crucial role in enhancing damping. The stabilization behavior shows that Jute fiber is always part of the solution, indicating its critical role in improving energy absorption and vibration damping. The converged value implies that Jute fiber is incorporated in an optimal fraction in the composite, without overloading the composite and compromising its stiffness. This trend confirms the importance of Jute as a reinforcing agent in meeting MOPSO objectives.

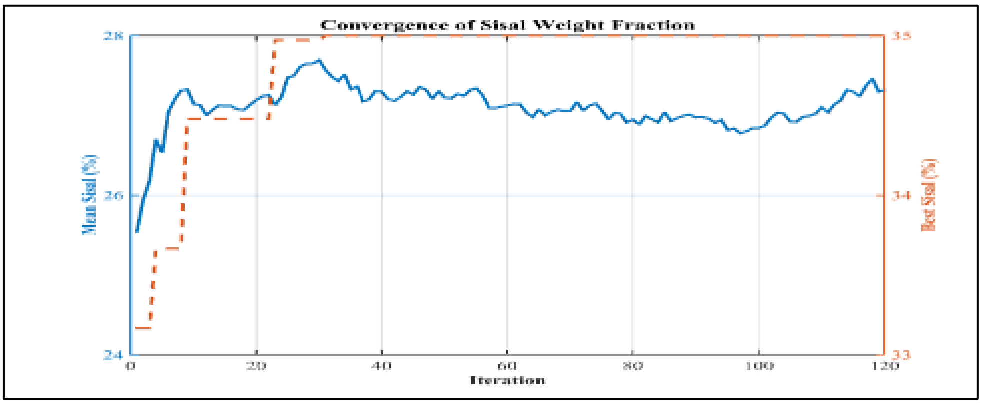

Figure 9 Convergence of Sisal Weight Fraction

Figure 9 shows the convergence of the Sisal fiber weight fraction in MOPSO optimization. During the early iterations, the Sisal fraction shows large variations, which correspond to the initial exploration stage where the particles explore a broad range of possible composite fiber combinations. Over time, the curve smooths out, suggesting that the algorithm converges towards an optimal fraction of Sisal fiber that provides sufficient stiffness and damping. Unlike Jute, Sisal has a more balanced impact, resulting in a more stable convergence curve with reduced fluctuations in the final iterations. The converged value indicates that Sisal fiber in the composite serves a stabilising role, maintaining consistent structural performance and contributes to the damping. This makes it a valuable intermediate reinforcement material in hybrid composites.

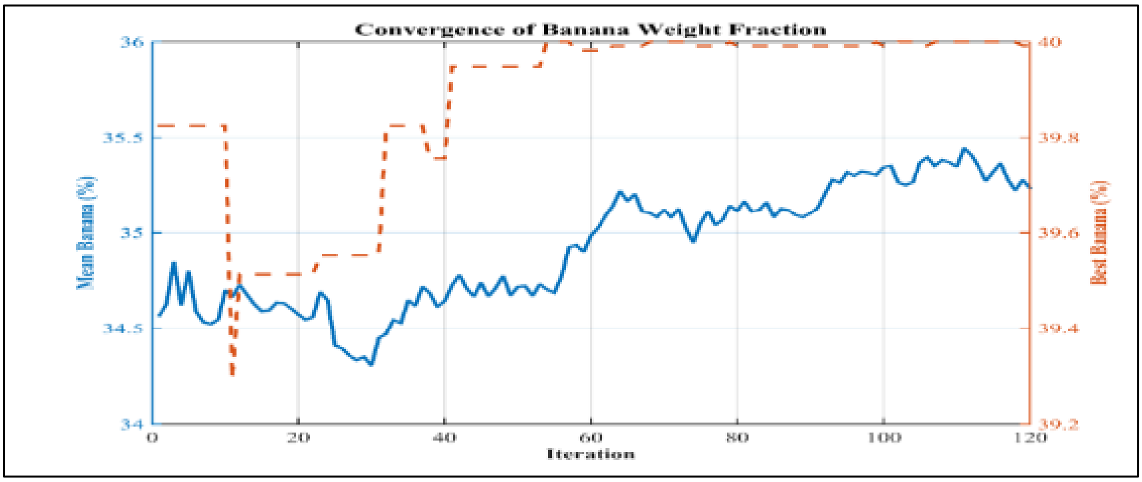

Figure 10 Convergence of Banana Weight Fraction

The convergence of the Banana weight fraction is illustrated in Figure 10, which is different from other fiber types. The fraction fluctuates greatly at the beginning to explore different configurations, as MOPSO is a stochastic algorithm. The fraction gradually stabilises at a relatively higher level as iterations progress, suggesting the significant role of Banana fiber in enhancing damping. The convergence curve may exhibit slight fluctuations before settling down, due to the complex interaction between Banana fiber and the other components. The last curve confirms the Banana fiber is always chosen in the optimal solution for vibration response; hence, it is an important material for improved vibration control. Its weight fraction is controlled to prevent excessive stiffness decrease.

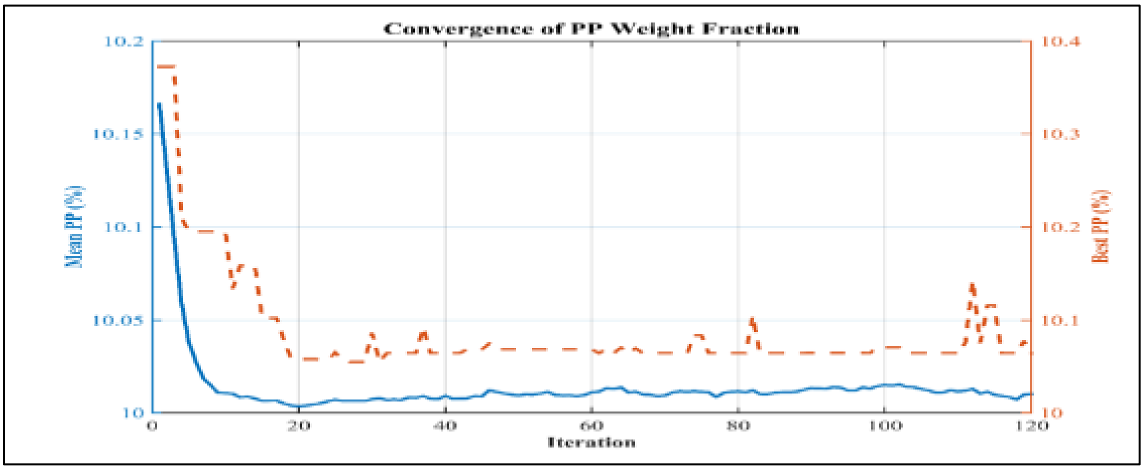

Figure 11 Convergence of PP Weight Fraction

The convergence of the weight fraction of Polypropylene (PP) is shown in Figure 11. Initially, the PP weight fraction fluctuates, as the algorithm explores different combinations of matrix and fiber content. Then, the PP weight fraction stabilises, implying that an optimal matrix weight fraction has been identified, which offers sufficient mechanical properties while enabling the use of natural fibers. The convergence highlights the role of PP as a matrix, providing stiffness and stress transfer in the composite. PP is not dominant, but rather compliments the natural fibers. The last value suggests an optimal matrix-to-fiber ratio where the composite can have both stiffness and damping.

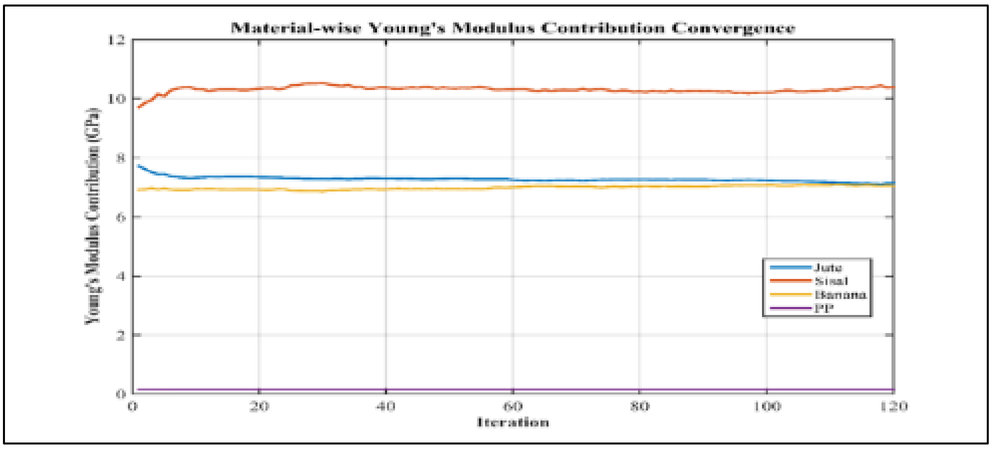

Figure 12 Material-wise Youngs Module Contribution Convergence

Figure 12 shows the convergence of the contribution of individual materials to the Youngs Module of the composite. It shows the contribution of each material - PP, Jute, Sisal and Banana - to the stiffness during the optimization. In the beginning, the contributions are spread, reflecting the random initialization of the MOPSO particles. As the iterations continue, the contributions converge, suggesting that MOPSO effectively finds the right material combination for high stiffness. PP is likely to have a significant contribution to Young's modulus due to its higher stiffness compared to natural fibers. Sisal might have a relatively higher contribution than other fibers because of its balanced properties, while Jute and Banana, though less stiff, also contribute to the stiffness. This convergence indicates that the algorithm has achieved an effective balance in the material properties to result in a synergistic increase in composite stiffness. This confirms the adequacy of the modeling and optimization approach to account for material interactions.

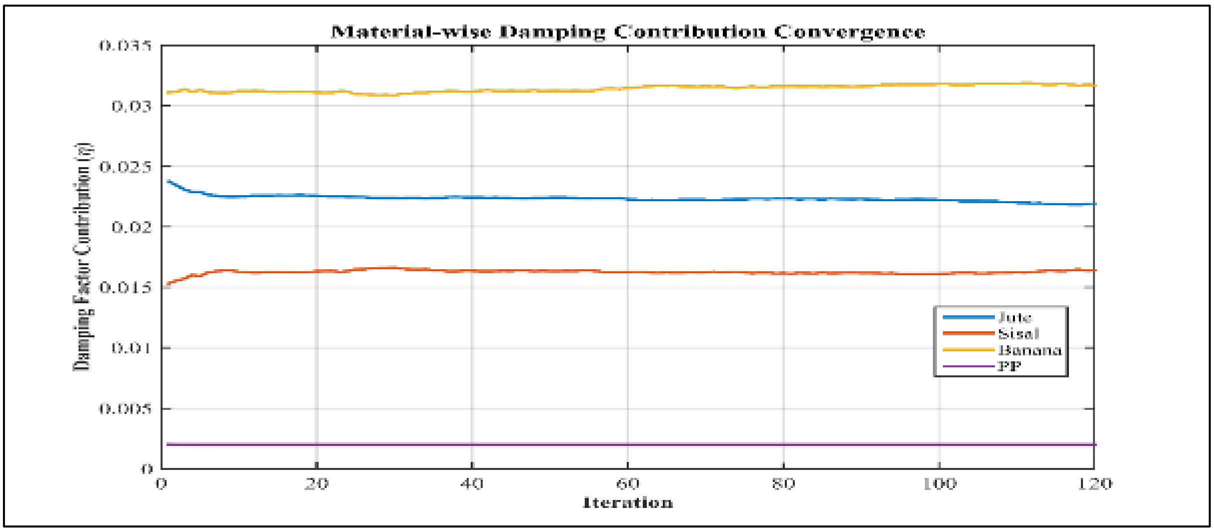

Figure 13 Material-wise Damping Contribution Convergence

Figure 13 shows the convergence of the damping contribution of each material towards the composite's overall damping performance during MOPSO optimization. Early in the optimization process, the contributions of PP, Jute, Sisal and Banana fibers fluctuate due to the random search and initial exploration of the solution space. Over time, the contributions converge, suggesting that MOPSO has found an optimal material distribution for energy dissipation. The viscoelastic and porous properties of the natural fibers, Jute and Banana, make them the major contributors to damping within the constituents. By comparison, PP plays a lesser role in damping, given its role as a matrix material that supports the structure. The convergence trends show that the algorithm effectively balances the choice of constituents to ensure that high damping efficiency is achieved while maintaining the composite's structural integrity. This confirms the ability of the multi-objective damping optimization framework to account for the specific damping properties of materials.

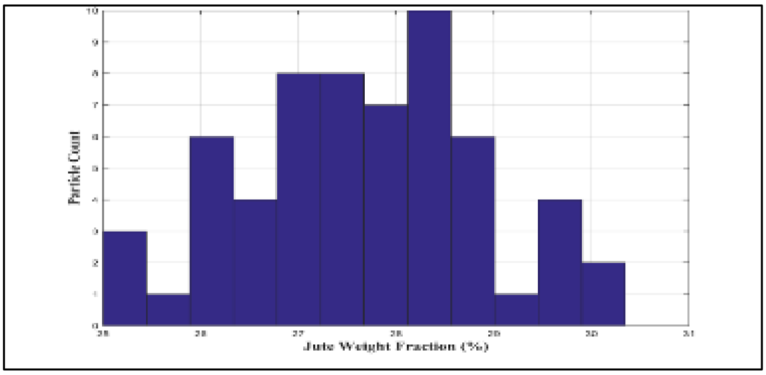

Figure 14 Particle Position Distribution of Jute

This figure illustrates the distribution of Jute fiber weight fraction of particles in the search space. This distribution shows the spread and convergence of particles (solutions) towards optimal areas. In the early stages, the particles are spread out, showing a broad exploration of Jute content values. Over time, the distribution narrows around a particular range, reflecting solution convergence towards an optimal Jute content. Particle concentration indicates that Jute consistently occurs within a preferred range in Pareto-optimal solutions, confirming the role of Jute in improving damping behaviour. The lack of extreme dispersion towards the end suggests stability and robustness of the algorithm, which ensures reliable convergence to the solutions.

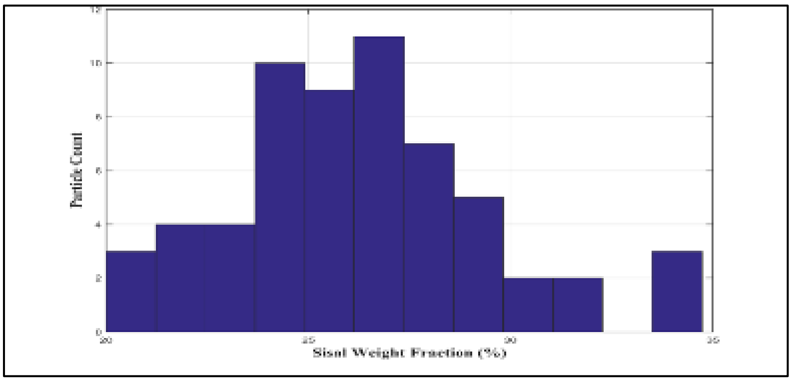

Figure 15 Particle Position Distribution of Sisal

The distribution of particles for Sisal fiber weight fraction is presented in Figure 15 and illustrates the search space exploration for this material. In the initial stages, the distribution is more spread out, indicating exploration. As iterations progress, the particles start to converge into a tighter area, which suggests that MOPSO determines an optimal Sisal fiber weight fraction that is effective in increasing stiffness and damping. The clustering for Sisal might seem more stable and concentrated compared to Jute, implying that the optimal proportion is less variable. This is an indication that Sisal fiber is a reliable and stable component in the composite. The particle position distribution shows the algorithm effectively narrows the search for optimal material proportions and confirms the accuracy of the solution.

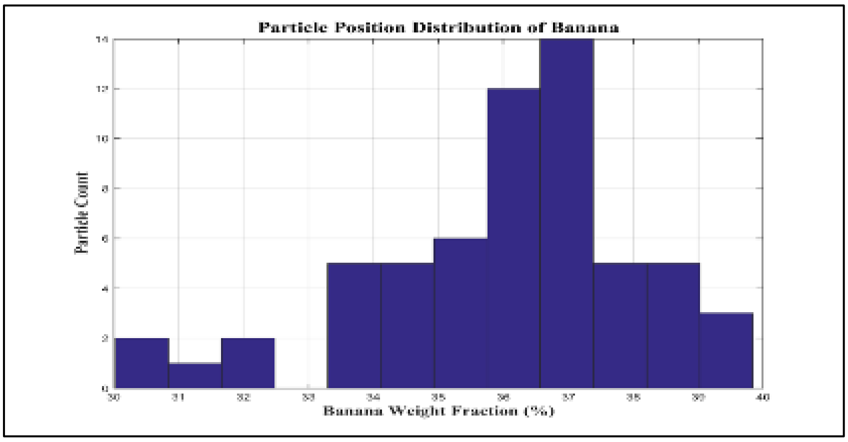

Figure 16 Particle Position Distribution of Banana

Figure 16 shows the particle position distribution of Banana fiber weight fraction. Like other materials, the starting distribution is broad, suggesting a large search space for initial compositions. Over time, the particles tend to cluster around a region with increased Banana fiber content, suggesting its high impact on vibration suppression. The grouping patterns may be slightly less focused than Sisal, suggesting that Banana fiber is more sensitive and has a more complex interaction with other materials. The final clustering pattern suggests that Banana fiber is always present in optimum solutions with considerable weight fraction, which indicates its strong vibration suppression ability. The convergence pattern also indicates that MOPSO is able to account for the complex role of Banana fiber in multi-objective composite design.

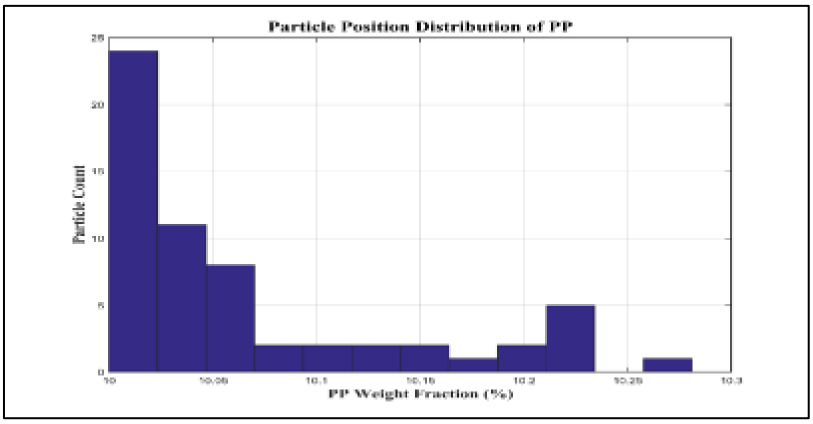

Figure 17 Particle Position Distribution of PP

Figure 17 shows the distribution of particles for the weight fraction of Polypropylene (PP) during MOPSO optimization. Initially, the particles are spread out over the search domain, suggesting exploration of various PP weight fractions. Over time, the particles start to concentrate in a smaller area, reflecting the optimal weight fraction of PP for achieving a compromise between stiffness and damping properties. Unlike natural fiber composites, the PP distribution appears to have a more limited clustering, as the matrix material must maintain a structurally sound weight fraction in the composite. The cluster behaviour confirms that PP does not overwhelm the optimization process but is adjusted to work in harmony with the fiber fillers. The clustered distribution at the end suggests that MOPSO successfully finds an optimal matrix weight fraction that facilitates load transfer and maintains structural integrity of the composite while allowing for the damping benefits of the fibers.

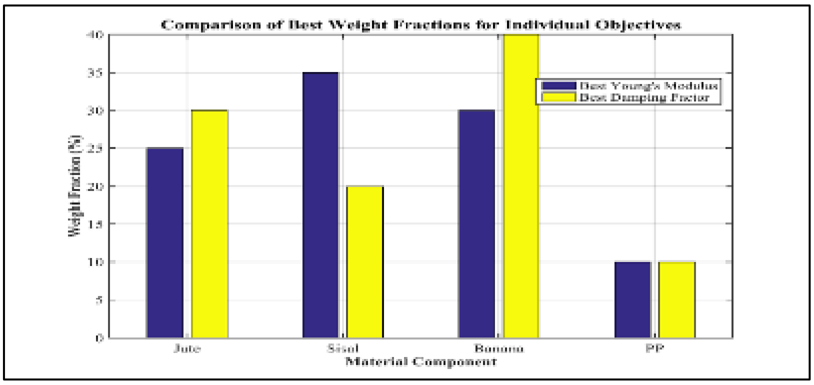

Figure 18 Comparison of Best Weight Fraction for Individual Objectives

Figure 18 compares the optimal compositions (weight fractions of materials) for the different objectives, i.e. maximum Young's modulus and maximum damping factor. The diagram illustrates the differences in the optimal material composition based on the priority of the objective function. When the objective is to maximise stiffness, the weight fraction composition is skewed towards higher PP and stiffer fibers (Sisal) to achieve higher load bearing capacity. For maximum damping, the optimal composition tends to have more of the natural fibers, such as Jute and Banana, which have better energy absorption properties. This is a clear indication of the conflicting nature of the objectives, justifying the use of multi-objective optimization. It also suggests that it is not possible to achieve optimal properties in both directions for the same composition, hence the use of the Pareto front concept in MOPSO and other approaches to identify compromises.

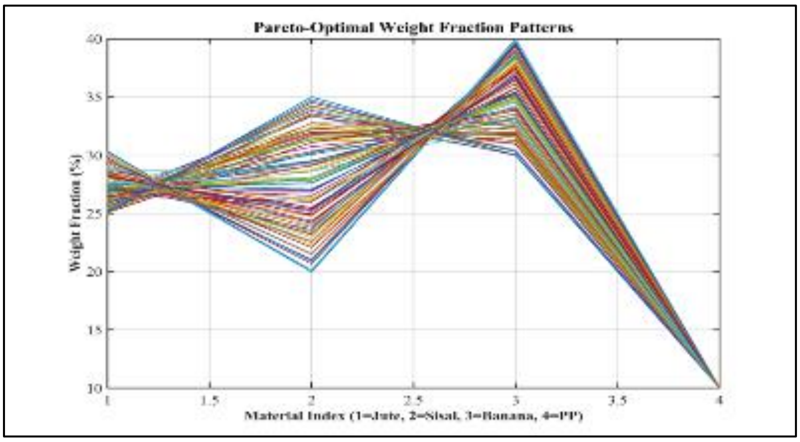

Figure 19 Pareto-Optimal Wight Fraction Paterns

Figure 19 shows the patterns of weight fractions for Pareto optimal solutions, offering an overall perspective of variation in material compositions along the Pareto front. This figure shows the variety of optimal solutions, each offering a different balance of stiffness and damping. These patterns show that PP consistently constitutes a minimum portion in most of these solutions, contributing to the required structural stiffness, whereas the ratios of Jute, Sisal and Banana fibers are highly variable to control the performance. Solutions with a higher proportion of damping generally have a higher proportion of natural fibers, while solutions with a higher proportion of stiffness typically have a higher proportion of PP and Sisal. These patterns also demonstrate that MOPSO is capable of finding a well-distributed Pareto front, providing multiple design options. This allows designers to choose material configurations that meet design criteria, such as damping or stiffness, or a combination of both.

In summary, the findings show that the suggested MOPSO-based multi-objective optimization framework successfully finds Pareto-optimal solutions that combine stiffness and damping characteristics in hybrid composite materials. Convergence curves, Pareto fronts and particle distributions demonstrate the effectiveness, stability and diversity of the solutions. It's clear that while polypropylene is critical for providing structural support, natural fibers, especially Jute and Banana improve the vibration damping properties, with Sisal providing a more balanced effect. The research highlights the significance of hybridisation and multi-objective optimisation in developing composite materials with desired properties for engineering applications. The findings of this study offer valuable insights for the design and development of advanced, sustainable composite materials, especially where a balance between mechanical properties and damping is desired.

6. Conclusion

In this paper, a mathematical model and Multi-Objective Particle Swarm Optimization (MOPSO) technique-based approach was developed for designing and optimising natural fiber reinforced polypropylene (PP) composites for improved damping characteristics. The research tackled the complex problem of optimizing a number of competing objectives, including Young's modulus (stiffness) and damping factor, to determine a set of Pareto-optimal solutions. The findings showed that the proposed method successfully characterizes the compromise between stiffness and damping, resulting in a variety of optimal designs for the composite material. The study show that polypropylene plays a major role in increasing the structural stiffness and the natural fibers, especially Jute and Banana, increase the damping performance, owing to their energy absorption capabilities. Sisal fiber was identified as having an intermediate effect, and can be used in applications where both structural stiffness and damping are required. The convergence trends, Pareto front distribution and particle positions validated the high stability, efficiency and effectiveness of the MOPSO algorithm in searching the solution space and preventing stagnation. The findings also demonstrate the role of material hybridization and the selection of appropriate weight fraction in the design of composite materials. In conclusion, the developed approach offers a reliable and scalable approach to the design of high-performance, environmentally sustainable composite materials, especially for vibration mitigation and structural health monitoring applications. Future work can explore the inclusion of nonlinear and experimental models, such as fibre orientation, length and bonding effects. Moreover, the application of new machine learning methods and hybrid optimization algorithms could be used to further improve prediction and optimization results. The validation of optimal composite designs through experimentation is also encouraged to translate the results into practical applications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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