Humanities Horizon

Vol 2 No 2 (2025) pp 77-86
DOI: 10.63373/3047-8014/34

Low-cost plantain fiber composite as an alternative material for auto body fenders: A performance and manufacturing cost comparison

Obiafudo Obiora Jeremiah, Ofochebe Sunday Madubueze, Anyaora Sunday Chimezie, Godspower Onyekachukwu Ekwueme

Nnamdi Azikiwe University, Along Enugu-Onitsha Express Way, PMB 5025, Anambra State, Nigeria.

Correspondence should be addressed to Ofochebe Sunday Madubueze; sm.ofochebe@unizik.edu.ng

Paper received: 02-03-2025; revised: 15-05-2025; accepted: 06-06-2025; published: 10-06-2025

Abstract

High density polyethylene composite reinforced with natural plantain fiber was produced using injection moulding technique. The production process utilized the popular L18 Taguchi experimental design to investigate the effects of the major process variables such as barrel temperature, mold temperature, injection pressure, holding pressure, back pressure, clamping force and shaft speed in the final mechanical property of the composite material. The mechanical tests conducted on the new material reveal that fiber volume fraction of 0.1 combined with particle size of 75 μm and compactibilizer mass of 0.00024 kg gives a high-quality composite material suitable for auto body fender application, at reduced manufacturing cost of ₦1454/kg of the composite. The composite material produced at optimized process condition was found to have tensile strength of 87.44 MPa, yield strength of 76.6 MPa, flexural strength of 77.03 J, Rockwell hardness strength of 756.99, Impact strength of 16.21 J and density of 993 kg/m^3. The result shows that the auto body fender produced based on the compactibilized plantain fiber reinforced high-density polyethylene composite has an advantage of low density and reduced production cost compared to conventional/alternative materials.

Keywords: plantain fiber; composite material; manufacturing cost modeling.

Introduction

The body-in-white (BIW) structure and associated closure panels typically account for around 26 per cent of vehicle mass (Jambor & Beyer, 1997). Conventional metallic processes have evolved in recent years and there is now increased usage of lightweight steel technologies (International news, 1996) and aluminum (Carle & Blount, 1999). Existing composite materials technology in the form of glass-based sheet molding compounds can offer weight reductions for semi structural applications at low cost. Plantain fiber-based composites can provide greater weight savings (greater than 40 per cent) and the potential for structural part applications. Natural fiber thermoplastic components in the automotive industry can afford the advantages of weight/cost

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

reduction, recyclability, abrasiveness and biodegradability compared to conventional materials. Handling of natural fibers in automotive exterior and interior components are essential to recover eco-efficiency and renewability. Natural fibers have recently become affordable to automotive industry as an alternative reinforcement to glass fiber reinforced thermoplastics. The best way to boost fuel efficiency without sacrificing safety is to employ fiber reinforced composite materials in the body of the cars so that weight reduction can be achieved.

The main advantages of using the annual-growth natural plantain fibers in thermoplastics along with polyethylene are improved mechanical/thermal properties and recyclability (Sanadi et al., 1994). Plantains are plants producing fruits that remain starchy at maturity (Robinson, 1996) and need processing before consumption. Plantain production in Africa is estimated at more than 50% of worldwide production (FAO, 1990). Nigeria is one of the largest plantain producing countries in the world (FAO, 2006). The custom of the plantain fiber reinforced plastics can be extended up to the fender, bumper beams, front end modules, instrument panel carrier, door modules and under body shields of the automobiles. They have an edge over traditional materials such as steel and aluminum due to their high specific strength, good damping capacity, simple manufacturing process and corrosion resistance (Cheon et al., 1995). The efficiency of the natural fiber reinforced composites depends on the fiber to matrix interface and the capability to adhesion over the matrix to the fiber. This can be maximized by increasing the bonding between fiber and matrix. Influence of fiber length and fiber distribution having more impact while developing natural fiber thermoplastics composites using injection molding or extrusion process (Davoodi et al., 2008). The present work confirms that significant weight savings over existing BIW closure steel fenders can be achieved using plantain fiber-polymer composites solutions, and that the composite solution can be cost effective for small and mid-volume production levels.

Method

The high-density polyethylene resin labeled HBG00356 manufactured by Indorama Eleme Petrochemicals Limited with density of about 0.96 g/cm^3, purchased from Onitsha, Anambra state was used as the matrix. The plantain fiber used as reinforcement was obtained from a local plantation in Awka, Anambra State. Sodium Hydroxide, Acetic Acid and Acetic Anhydride used for the chemical treatment of plantain fiber was purchased from Dantex Chemical Ltd, Onitsha, Anambra State. The Compactibilizer, Maleic Anhydride Grafted PE(MAPE) was imported from China.

Plantain Pseudo Stem Fiber was obtained by immersing the Plantain stems in water for 28 days for rotting process to occur. The fibers were distinct from pectins, hemicellulose and other impurities and finally dried to constant weight in an ovum for 150 minutes at an oven temperature of 80°C.

Chemical treatment of plantain fibers at 2% solution of sodium hydroxide at optimum 2:30 hours remove the moisture content from the fibers, thereby increasing its strength. 1% acetic acid was applied to neutralize the sodium hydroxide solution. The fibers were thoroughly washed until a PH of 7 was obtained and finally dried to constant weight in an oven at 80°C. The mercerized and dried fibers were treated with acetic anhydride solution at 10% with optimally derived soaking time of 1 hour to stabilize the cell walls against moisture, environmental degradation and improve dimensional stability. The fibers were thoroughly washed to neutrality. The compactibilizer, Malaeic Anhydride Grafted PE(MAPE) was employed at 1.5% to increase compatibility between fiber and matrix and to decrease hyrophilicity of fibers.

The Treated fibers were ground to a fine powder using Electric Milling Machine and finally sieved unto a set of sieves of 75-micron meter (ASTM 200) and 150-micron meter (ASTM100) arranged in descending order of fineness using Sieve Shaker. Employing Taguchi L18 Design of Experiment, the samples were cast in a collapsible mild steel mould in accordance with ASTM standard D638-10 for Tensile tests, ASTM D790-10 for Flexural, ASTM A370 for Charpy Impact and ASTM E10-12 for Hardness using injection molding process. In accordance with ASTM (American Society for Testing and Materials) standards, Tensile strength, Flexural strength were tested using Universal Testing Machine while Impact strength was carried out using Charpy impact tester and Hardness strength using Hardness Tester.

The expected mechanical test response is estimated using the optimum control factor setting from the main effect plots (Radharamanan & Ansuri, 2001) by employing the response table for mean, the expected response model is as in Equation (1).

$$EV = AVR + (A_{opt} - AVR) + (B_{opt} - AVR) + (C_{opt} - AVR) + \ldots + ({n^{th}}_{opt} - AVR) \quad (1)$$

Where:

EV = expected response

AVR = average response

A_{opt} = mean value of response at optimum setting of factor A

B_{opt} = mean value of response at optimum setting of factor B

C_{opt} = mean value of response at optimum setting of factor C

Technical Cost modeling

Cost-modeling tools are widely used to anticipate the production costs of preproduction parts and are recognized as an essential part of design for manufacture. Basic models typically utilize an assessment of part complexity to capture the manufacturing costs of the part in question and knowledge of material costs to generate a final part cost. Such cost models do not reflect actual manufacturing costs (Bao and Samareh, 2000) and have been largely superseded by process-based models (Gutowski et al.,1994; Northrop Corporation, 1976). Process-based models aim to simulate the manufacturing process by splitting it into several steps and assigning materials and labour input at that step together with relevant tooling and capital equipment.

A generic parametric event-driven technical cost model has been used, which allows analysis of virtual candidate parts for comparison with other materials and processes or existing parts. Various levels of automation can also be examined and, thus, processes can be cost optimized at various projected production levels. Sensitivity analysis is a powerful feature of such a model and allows assessment of varying material, labour and tooling costs as well as comparison of process alternatives such as level of automation.

The cost for a given part consisting of i events is given by Equation (2).

$$\text{Cost} = \sum_0^i (raw \text{ material cost } + \text{ labour } + \text{ energy cost } + \text{ overhead charges}) \quad (2)$$

Where,

Raw material cost per part (₦) = part area(m^2) x material cost (₦/m^2) (3)

Labour Cost = Salary per hour x Number of working hours in a day x Number of days taken to finish the job (4)

Energy Cost = Kw/hr x amount per Kw x number of hours (5)

Overhead Charges =2:1 of direct labour (6)

Manufacturing Cost Analysis

The manufacturing cost (P) of the studied PFRHDPE composite was evaluated as a function of the volume fraction/particle size of fiber and the compactibilizer mass. The major contributors to the total manufacturing cost include material cost (MC) that is the joint cost of the fiber, the matrix and the compactibilizer), the labor cost (LC), processing (PC), treatment cost and other fixed cost (FC).

The cost analysis involves evaluation of the production cost/kg of composite produced for the various mechanical test schedule. There are no existing cost model(s) in literature for prediction of manufacturing cost of composites in terms of these indentified cost variables.

Thus, statistical investigation of the cost variability with respect to the three control factors (including volume fraction (Vf_r), particle sieve size (S_s) and compactibilizer mass (C_m) was conceived and conducted as a novel contribution of this study. An experimental design based on the classical Box-Behnken was considered appropriate for the study (Table 1). The typical range of the input (design) variables found in literature was employed for the experimental design.

Table 1. Box-Behnken Design for Manufacturing Cost Analysis

				Manufacturing cost of composite (₦/kg)			
S/N	Vf_r	$P_s(\mu m)$	$C_m(kg)$	*Tensile*	*Flexural*	*Hardness*	*Impact*
1	0.1	75	0.00012	1465	2865	4172	4732
2	0.1	225	0.00012	1465	2865	4172	4732
3	0.5	75	0.00012	2310	4567	6633	7497
4	0.5	225	0.00012	2310	4567	6633	7497
5	0.1	150	0	1469	2895	4243	4827
6	0.1	150	0.00024	1454	2824	4085	4621
7	0.5	150	0	2327	4655	6834	7759
8	0.5	150	0.00024	2283	4464	6417	7221
9	0.3	75	0	1781	3568	5234	5951
10	0.3	75	0.00024	1757	3458	4991	5636
11	0.3	225	0	1781	3568	5234	5951
12	0.3	225	0.00024	1757	3458	4991	5636
13	0.3	150	0.00012	1772	3520	5121	5802
14	0.3	150	0.00012	1772	3520	5121	5802
15	0.3	150	0.00012	1772	3520	5121	5802

Setting the three-design variable at three levels with three repetitions at the center point results in fifteen experimental iterations of the injection molding process presented in Table 4.35. The production costs/kg (P) of the various test specimens were estimated based on Equation (7) and recorded for the fifteen data sets.

$$Cost/kg\ of\ a\ sample = \frac{Average\ production\ cost\ of\ a\ sample}{mass\ of\ sample} \tag{7}$$

Modeling of Manufacturing Cost

Since there is no known model(s) for production cost to account for the effects of the three identified cost variables, a usual alternative approach which involves conducting regression analysis on the experimental data using some standard approximation functions was adopted. As a trial function a quadratic model of the general form, Equation (8), was fitted to the experimental data.

$$f(x_j, x_j) = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j\, x_j + \sum_{j>} \sum_{i=1}^{k} \beta_{ij} x_i x_j + \varepsilon \tag{8}$$

$f(x_j, x_j)$ is the objective function (that is the cost/kg of composite), β_0 is the model intercept, k is the number of design variables, x_j, $x_j x_j$ and $x_i x_j$ represent the first-order term(s) and the second-order term(s) and the interaction terms of the model respectively in coded notation. β_j, β_{jj} and β_{ij} are the respective coefficients of the model terms while ε is the random error.

The unknown coefficients of the fitted model were then determined through regression analysis implemented on Model-Based Calibration toolbox (MBC 3.5) found in MATLAB (R2008b). In the computation steps, the predicted error sum of squares (PRESS) was minimized to obtain the final predictive model for the manufacturing cost/kg composites corresponding to the various test specimens, as shown in Equations (9), (10), (11), and (12).

$$P_{tensile} = 1399.14 + 417.74Vf_r + 2873.31Vf_r^2 - 152370950.65C_m^2 - 259167.80Vf_rC_m \tag{9}$$

$$P_{flexural} = 2693.20 + 1460.95Vf_r + 4905.76Vf_r^2 - 505317135.94C_m^2 - 1265837.87Vf_rC_m \tag{10}$$

$$P_{hardness} = 3925.52 + 2275.15Vf_r + 7037.07Vf_r^2 - 971418029.06C_m^2 - 2868897.59Vf_rC_m \tag{11}$$

$$P_{impact} = 4475.88 + 2624.64Vf_r - 393750C_m + 7840.18Vf_r^2 - 3458333.33Vf_rC_m \tag{12}$$

The adequacy of the predictive models was verified using standard numerical criteria (including $PRESS\ RMSE$, $RMSE$, R^2, $Adj. R^2$, and $PRESS\ R^2$). The summary of the statistics is presented in Table 2.

Table 2. Model Summary Statistics

Specimen	Obs.	Parameters	Box-cox	PRESS RMSE	RMSE	R^2	$R^2 Adj.$	$R^2 PRESS$
Tensile	15	5	1	2.568	1.761	0.99	0.99	0.99
Flexural	15	5	1	7.729	4.739	0.99	0.99	0.99
Hardness	15	5	1	18.311	10.964	0.99	0.99	0.99
Impact	15	5	1	23.078	13.643	0.99	0.99	0.99

The adequacy assessment of the model presented above shows that the predictive models (4.4-4.7) have high prediction accuracy. The resulting model $R^2 = 0.99$, $Adj. R^2 = 0.99$ and $PRESS\ R^2 = 0.99$ all indicate that up to 99% of the overall variability of the manufacturing cost/kg of the composite could be explained using the predictive models, confirming high performance of the models. With the manufacturing cost model fully characterized in terms of the three identified cost variables, it becomes more straightforward to predict analytically the expected cost of a known fender volume.

Results and Discussion

Fiber particle volume fraction (Vf_r)/sieve size (S_s) and the compactibilizer mass (C_m) were studied as the major factors that determine the quality (grade) and of course the cost/kg of composite produced. From the results recorded it seems that the most significant variable in terms of contribution to the total manufacturing cost/kg of composite is the volume fraction of fiber. The details to the effect of this variable are compiled in Figure 1.

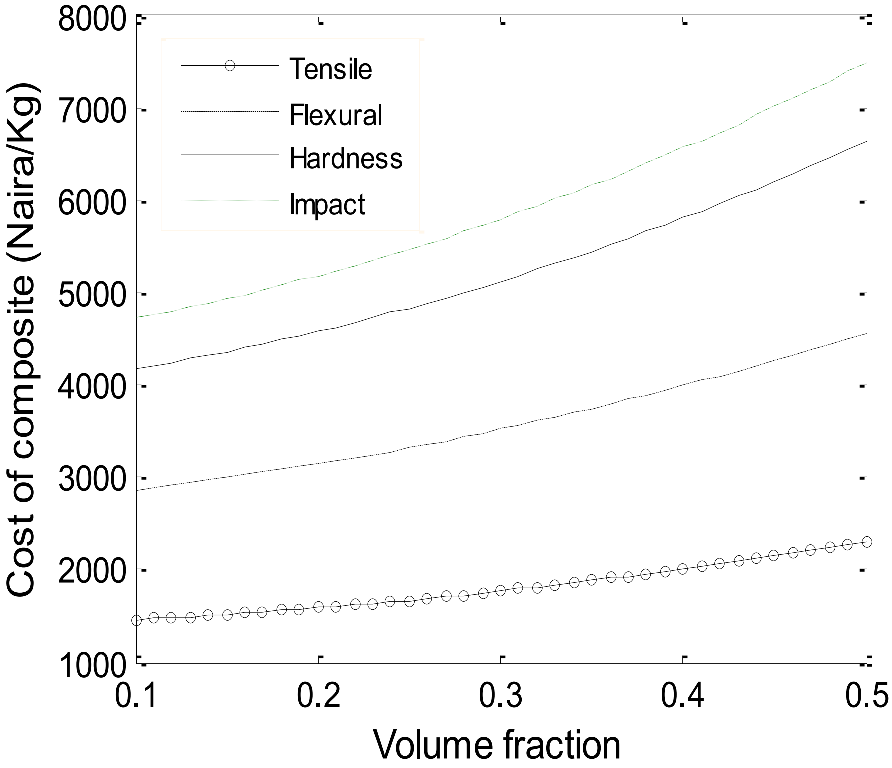

Figure 1. Effects of Volume Fraction on Manufacturing Cost/kg of Composite

In Figure 1, the effect of adjusting the fiber volume fraction on the manufacturing cost/kg of composite within the sampled space was monitored while the two other variables were set to their mean values. The specimen for the tensile test yields the overall minimum cost/kg composite in the various test samples. However, it should be noted that this result does not translate directly to the overall minimum cost of the samples which rather depends on the mass of composites in the samples. The low cost/kg of composite recorded for the tensile specimen, especially at the lower volume fraction range, may be attributed to the high weight/volume ratio noticed in this parameter range. Similar overall cost variability was noticed in all the test specimens. The volume fraction has a noticeable quadratic (curvature) effect on the recoded manufacturing cost/kg of composite with its minimum point tending towards the lowest volume fraction.

Moreover, the application of compactibilizer was found to have a significant one-directional effect of increasing the weight of a fixed volume of composite with a negligible rise in average production cost of sample. These results correspond to the decreasing manufacturing cost/kg of composites illustrated in Figure 2.

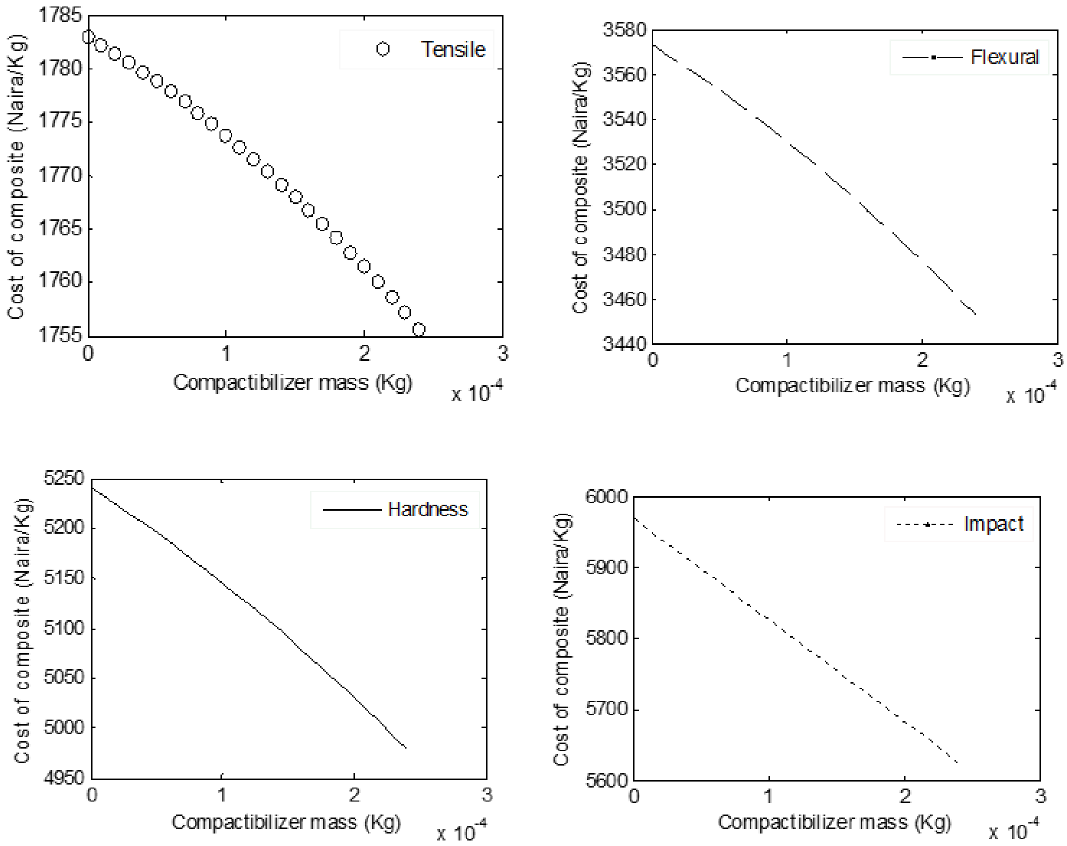

Figure 2. Effects of Compactibilizer Mass on Manufacturing Cost/kg of Composite

By and large the effect of fiber particle sieve size was found insignificant and excluded from the models. In summary, the overall effects of the cost variables suggest that the most cost-efficient production could be achieved using reduced fiber volume fraction, increased compactibilizer mass and increased volume of mould (as in tensile specimen).

Optimal Cost Analysis

The optimization study could be carried out using the models resulting in manufacturing cost analysis. A constrained optimization problem was formulated considering minimization of manufacturing cost/kg of composite as the objective function. The optimization problem was solved using genetic algorithm (GA). Genetic algorithms are an evolutionary optimization method developed from the principle of natural selection. The algorithm begins with a population of random solutions in some structured array. This is followed by number of operations intended to achieve convergence. The development of the GA follows some steps such as initialization of solution population identified as chromosomes, fitness computation based on objective function, selection of best chromosomes, and genetic propagation of chosen parent chromosomes by genetic operators like crossover and mutation. Crossover and mutation are implemented to produce a new and better population of chromosomes. GA was selected as an appropriate optimization search algorithm for the current problem. GA implementation procedures were found in GA toolbox stored in MatLabR2008b. The problem constraints and the boundary condition were specified accordingly. Since production based on the schedule for tensile test gave the best cost efficiency, which describes the cost behavior based on tensile specimen was applied as the objective function. It is quite reasonable that any deduction resulting from studies based on such a high-volume test specimen would give the most realistic comparison with that of a real fender volume. The optimization study reveals that optimum manufacturing cost of ₦1454/kg of the composite could be achieved with 0.1 volume fraction of fiber and 0.00024 kg compactibilizer. This literally means that optimal cost/kg of composite was achieved with minimum volume fraction of fiber and maximum compactibilizer mass within the studied range of the cost variables.

Table 3 shows a comparison of the cost and weight values of PFRHDPEC with alternative materials for auto body fender. Significant weight savings over existing BIW closure steel fenders can be achieved by the use of plantain fiber–polymer composites solutions, and the composite solution can be cost effective for small- and mid-volume production levels.

Table 3. Comparing Cost and Weight Values of PFRHDPEC with Alternative Materials for Auto Body Fender

S/N	Material	Density(kg/m^3)	Cost(₦/kg)	Fender Volume(m^3)	Total Cost((₦)	Fender Weight(kg)
1	GFRP	1550	3129	0.002	9700	3.1
2	CFRP	1800	15646		56326	3.6
3	AA	2710	452		2450	5.42
4	MCS	7860	139		2185	15.72
5	SS	8000	1391		22256	16
6	PFRHDPEC	993	1454		2887	1.986

Table 4 shows the Optimal setting of control factors and expected Optimum strength of composites. The tensile strength and the young's modulus of the compactibilized particle size 2 fibers were higher than compactibilized particle size 1 fibers and uncompactibilized particle size fibers. This is due to the good adhesion and bonding between the fibers/matrix interfaces in the material. Under a tensile load, the improved adhesion results in a more efficient stress transfer from the matrix to the reinforced fibers.

Table 4. Optimal Setting of Control Factors and Expected Optimum Strength of Composites

Mechanical Test	Control	Particle size 1	Particle size 2
Tensile (MP$_a$)	64.68	80.26	87.44
Flexural (J)	-	65.32	77.03
Rockwell Hardness	747.1	601.15	756.99
Charpy Impact(J)	6.14	10.47	16.21

The compactibilized particle size 2 fibers shows challenging values in flexural strength compared to the compactibilized particle size 1 fibers and uncompactibilized particle size fibers. This implies that the compactibilized partcle size 2 fibers had better strength, and the fiber distribution is good.

While comparing the Charpy Impact test results, it is proven that the compactibilized paritcle size 2 fibers has demanding strength to compactibilized particle size 1 fibers and uncompactibilized particle size fibers. The fender materials should have higher impact strength to absorb heavy shock loads during collision. Rockwell hardness strength in compactibilized particle size 2 fibers was higher than compactibilized particle size 1 fibers and uncompactibilized particle size fibers.

Conclusions

In this study, the particle size analysis and mechanical tests carried out on the composite specimen developed showed that auto body fender can be improved significantly with Plantain fiber reinforced high density polyethylene composite. The compactibilized particle size 2 fibers composite which is fabricated by injection moulding process, presents a superior mechanical property and cost effectiveness when compared with uncompatibilized composites and alternative materials for Auto body Fender. The overall result suggests that natural plantain fiber reinforced composites could be utilized in automotive structural components such as fenders, bumper beams, front end modules and also in interiors of automobiles.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

All authors in this publication declare no conflict of interest regarding the title, data, location, and results of the research.

Funding Statement

This research was conducted independently by the researcher without any financial support or funding from external institutions or organizations.

Acknowledgments

The author would like to thank all those who have helped in the preparation of this article.

Supplementary Materials

This study does not include any supplementary materials.

References

Bao, H., & Samareh, J. (2000, September). Affordable design-A methodology to implement process-based manufacturing cost models into the traditional performance-focused multidisciplinary design optimization. In *8th Symposium on Multidisciplinary Analysis and Optimization* (p. 4839).

Carle, D., & Blount, G. (1999). The suitability of aluminium as an alternative material for car bodies. *Materials & design*, *20*(5), 267–272.

Cheon, S. S., & Choi, J. H. (1995). Development of the composite bumper beam for passenger cars. *Composite structures*, *32*(1-4), 491–499.

Davoodi, M. M., Sapuan, S. M., & Yunus, R. (2008). Conceptual design of a polymer composite automotive bumper energy absorber. *Materials & Design*, *29*(7), 1447–1452.

Food and Agriculture Organization. (1990). Production Yearbook 1990. Rome: FAO, Rome.

Food And Agriculture Organization. (2006). Production Yearbook 2006. Rome: FAO, Rome.

Gutowski, T., Hoult, D., Dillon, G., Neoh, E. T., Muter, S., Kim, E., & Tse, M. (1994). Development of a theoretical cost model for advanced composite fabrication. *Composites manufacturing*, *5*(4), 231-239.

International news – ULSAB Consortium unveils the new look of ultralight steel auto body. Mater. Des., 1996, 17, 107–110.

Jambor, A., & Beyer, M. (1997). New cars—new materials. *Materials & design*, *18*(4-6), 203–209.

Joseph, S., Sreekala, M. S., & Thomas, S. (2002). Studies on resol matrix resin. *Composites*, *62*, 1857.

Northrop Corporation, Advanced composites cost estimating manual (ACCEM). (1976). *Technical report AFFDL-TR-76-87, Air Force Flight Dynamics Laboratory, Wright–Pattens Air Force Base Dayton, Ohio, August 1976*.

Okafor, C. E., Ihueze, C., & Ujam, A. J. (2017). Optimization of tensile strengths response of plantain fibres reinforced polyester composites (PFRP) applying Taguchi robust design. *Innovative Systems Design and Engineering ISSN*, 2222-1727.

Opbroek, E. (2013). *Ultralight steel: a global consortium changes the future of automotive steel*. Xlibris Corporation.

Robinson, J. C., & Saúco, V. G. (2010). *Bananas and plantains* (Vol. 19). Cabi.

Sanadi, A. R., Calufield, D. F., & Rowell, R. M. (1994). Reinforcing polypropylene with natural fibers. *Plastics Engineering(USA)*, *50*(4), 27–28.