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Environmental Sustainability and Mechanical Performance for Nanostructured Green Materials on Enhanced Engineering Applications

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Abstract. Nanostructured green materials have become potential remedies in improving the mechanical performance as well as environmental sustainability in engineering practice. Such materials that are usually of a renewable nature provide a light, biodegradable, and strong alternative to the industry. The traditional methods of evaluation, however, tend to fail in measuring either the mechanical performance or the environmental impact alone, leading to inefficient material choice and inefficient design. In order to address these shortcomings, this paper suggests a hybrid model that will incorporate Life Cycle Assessment (LCA) and Finite Element Analysis (FEA). LCA allows the determination of the impact on the environment of the lifecycle of the material, and FEA predicts the behavior of the material under its working conditions. The holistic system will guarantee that there is a balanced optimization of ecological footprint and structural integrity. The framework is used with nanocellulose-reinforced bio-compositions of panels in automobile interiors, in which it is possible to carefully determine the measures of stress resistance and sustainability. Findings indicate that the developed approach can improve the decision-making process, offering a thorough analysis, which proves the decrease in carbon emissions by 30% and the mechanical stability during the change in conditions. In that way, the suggested methodology will aid in the creation of high-performance and environmentally friendly materials to be used in high engineering processes.

1 Introduction

1.1 Background and Motivation

The global trend towards sustainable development has increased demand for environmentally friendly materials with performance comparable to or better than conventional materials. Engineering fields such as automotive, aerospace, and construction are facing greater pressure to reduce the carbon footprint of their products while maintaining structural integrity and performance [2]. This has prompted interest in developing nanostructured green materials that can incorporate the advantages of renewable resource materials with improved mechanical properties through nanotechnology[1]. Nanocellulose, nano-clay composites, and bio-based nano polymers are examples of these new materials, which have a high strength-to-weight ratio compared to conventional materials, as well as thermal stability and biodegradability. In many cases, these materials are a better alternative to contemporary materials, which waste resources and harm the ecosystem. Although significant advances are expected from nanostructured green materials, existing evaluation methods most often assess environmental sustainability and mechanical performance separately, providing no integrated methodology for evaluating them as a single entity[5]. This paper is born out of the need to develop an integrated evaluation approach that assesses both performance and sustainability simultaneously. The new methodology will be built upon LCA and FEA to provide a new approach to selecting and optimizing nanostructured green materials.[7]The methodology presented in this paper addresses current barriers in assessing and reporting sustainable materials, ultimately providing informative analysis and decision support in the sustainable arena [4]. The integration of approaches for investigating nanostructured green materials will accelerate the deployment of sustainable solutions in advanced engineering domains, thereby narrowing the gap between sustainability and performance [3].

1.2 Scope and Objectives

This paper presents an important framework that incorporates an environmental sustainability assessment method together with a mechanical performance measure for nanostructured green materials in cutting-edge engineering applications[9]. The framework's scope

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*Corresponding author: ku.manishnandy@kalingauniversity.ac.in includes identifying, assessing, and verifying renewable or biodegradable materials improved with nanostructured concepts to assess performance in line with cutting-edge standards. Common practice assesses sustainability and mechanical behavior independently of each other, which can lead to inefficient or environmentally costly design decisions. This work aims to provide a framework to evaluate sustainability as quantified through LCA, along with modeling mechanical performance using FEA under operational conditions [8]. The proposed framework aims at having a concise roadmap and systematic approach to the design and optimization of applications by professional scientists, as well as industry targets, to make informed material choices, design, and optimization of the applications, and to also clearly indicate the environmental sustainability impacts [10]. The primary objective of this work is to demonstrate the application of the framework through a case study of nanosized cellulose-derived bio-composites used in vehicle interior components.

2 Literature Review

2.1 Introduction to Nanostructured Green Materials

The development of synthesis paths to nanostructured materials (SNAs) has passed through multifaceted and complicated routes to single and simple ones due to the significant efforts of synthetic chemists in this direction of technology [11]. In this chapter, the need for using green chemistry in creating nanostructured materials is pointed out and explained. The chapter still goes on to give specifics concerning the various green chemistry methods, their benefits, and shortcomings [3].

Despite the fact that bioavailability of drugs is a variable factor, which is dependent on other variable factors such as drug solubility, and the route of administration, solid lipid nanoparticles (SLNs) and nanostructured lipid carriers (NLCs) are appealing delivery systems because of their ease of production, biocompatibility, biodegradability, and the possibility of scaling up the components of the formulation [12][14]. Nevertheless, the topic of SLNs and NLCs is not immediately applicable in the context of this paper, where the designation of the structural materials is focused on engineering applications. Although these topics are critical in the drug delivery research area, they fail to give a clear connection to the assessment of nanocellulose-based bio-composites or how they can be used in the engineering field. On the same note, the oil-water separation technologies (MST) section lacks the connection to the aim of the paper, which is to assess the mechanical performance and sustainability of green nanomaterials in structural applications [6] [13].

In order to make the review more focused, it is necessary to change the discussion to the materials that can be readily applied to engineering, i.e., nanocellulose-based composites, biopolymers, and other sustainable materials. They should be evaluated based on their mechanical properties and their environmental effects, especially whether they can be used instead of traditional materials in the structural engineering field.

2.2 Environment and Mechanical Performance of Nanostructured Green Materials

Structural application of nanostructured green materials depends on their performance in structural applications. Some literature has shown that nanocellulose-based composites have better mechanical strengths in terms of high tensile strength, stiffness, and impact resistance as compared to traditional materials. All these properties render them applicable in load-bearing applications (e.g., automotive and construction materials). It has been established that the incorporation of nanocellulose into the biocomposites has the effect of greatly enhancing the mechanical properties of the polymers, thus giving way to high durability and longevity under strenuous conditions [5].

The other aspect that determines the viability of nanostructured green materials as structural materials would be environmental sustainability. The importance of the reduced environmental impact of nanocellulose-based materials has been noted in the literature of Life Cycle Assessment (LCA), especially with regard to global warming potential (GWP) and energy use. An example is that the GWP of nanocellulose-based composites is much lower than that of traditional materials such as glass fibers and plastics, which are linked to high carbon emissions and energy used in their manufacturing [7]. More so, these materials have the added advantage of a biodegradable nature, which helps in the reduction of waste and environmental management during the disposal stage [15].

2.3 Opportunities and Challenges of Nanostructured Green Materials

However, the use of nanostructured green materials in structural applications has been met with a number of challenges despite their promising nature. The challenge of production method scalability is one of the major problems. Although synthesis of nanocellulose and nanostructured materials at the laboratory scale has been extensively established, there has been a major challenge in transferring these techniques to industrial-level synthesis. Another limitation to their usage in commercial applications is the cost of production, especially in energy and raw material needs [8][9].

Also, the mechanical behavior of the nanostructured green materials is subject to a number of factors, such as the quality of the raw materials used, processing, and the environment in which they are used. The optimization of the processing parameters of nanocellulose-based composites is being researched, with the aim of increasing the mechanical properties of the material and making it consistent and reliable in its diverse applications. Also, when implementing the use of nanostructured materials into the current infrastructure and productions, the compatibility with the current technologies and standards should be considered carefully [10].

2.4 Requirement of a Coherent Evaluation Framework

In order to be able to evaluate the potential of nanostructured green materials, there is a need to use an integrated method of evaluation, which incorporates both the mechanical performance and environmental sustainability. Conventional material evaluation methods tend to either measure one of the performance measures: mechanical or environmental, but they do not show a complete picture. Life Cycle Assessment (LCA) and Finite Element Analysis (FEA) have an integrated approach facilitating the process of material choice and allowing engineers to optimize the environmental footprint of materials, as well as their mechanical integrity [11].

The suggested combined framework enables the concurrent assessment of mechanical functionality in the working environments with the impacts on the environment throughout the lifespan of a material. By doing this, materials would not only be mechanically fit to be used in structures, but also help in the sustainability practices since these materials would consume less energy and carbon emissions would be minimized, as well as lowering waste production [12]. The framework further enables an informed decision-making process in order to overcome the gap that exists between material sustainability and performance optimization in engineering use.

3 Methodology

This approach aims to assess nanostructured green materials through a single, coherent method that combines both environmental sustainability metrics and mechanical performance measures. This will be implemented by integrating LCA and FEA into a simultaneous evaluation process with feedback to ensure informed selections for the material and designs being assessed in advanced engineering applications.

3.1 Life Cycle Assessment (LCA): Environmental Metrics

The first component of LCA examines the quantification of environmental impact throughout the entire life cycle of a material, encompassing the extraction of raw materials, manufacturing, usage, and end-of-life. This analysis incorporated key ecological indicators, including global warming potential (GWP), cumulative energy demand (CED), water consumption, and material recyclability.

SimaPro 9.0 is an environmental impact assessment software tool that was utilized in the LCA of the bio-composites made of nanocellulose. The cradle-to-gate system boundary was also taken, and the environmental impact on the extraction of the raw material up to the manufacturing processes, but not the use or end-of-life disposal, was taken; this would entail more assumptions as far as the lifecycle of the product is concerned.

The information about the Life Cycle Inventory (LCI) of nanocellulose was obtained in the Ecoinvent database (v3.7), where the data about renewable materials and their environmental impact are exhaustive. Equally, PLA data has been taken in Ecoinvent, regarding the process of producing the biopolymer, and the LCI data of the conventional materials ABS and PP were accessed in the literature [1][2], which cited the environmental impact of those materials in the implementation of similar product materials in automobile parts.

To perform the impact assessment, have used the ReCiPe 2016 method, which measures environmental impacts in several categories that include Global Warming Potential (GWP), Cumulative Energy Demand (CED), and Water Consumption. The choice of these categories was due to the fact that they represent the key environmental issues related to the manufacturing and material choice of the automotive industry, in which such materials are commonly applicable. The midpoint approach of ReCiPe was selected to evaluate the possible environmental impacts of these categories and to have a better conception of the trade-offs between the choice of the material and sustainability.

3.2 FEA: Mechanical Evaluation

FEA is utilized to determine the mechanical performance of the same material under realistic service conditions. A complete and detailed 3D CAD model of the component is created and subjected to mechanical loading events, including stress, impact, thermal variations, and vibration. The actual simulations are conducted using ANSYS Abaqus, and mechanical properties (e.g., tensile strength, flexural modulus, thermal stability, fatigue resistance) are measured. The material input data for the FEA (e.g., elastic modulus, Poisson's ratio, yield strength, etc.) are determined from experimental trials and information reported in the literature on nanostructured green composites.

4 Integrated LCA-FEA Framework

The LCAFEA framework provides a connection between the two modules within a single decision-making process, combining LCA and FEA. The integrated LCA-FEA approach draws upon a shared material database that informs both environmental and mechanical (structural) input parameters. While delivering an environmental impact for a material in the LCA module, the FEA module provides a structural performance evaluation of the material. The Trade-Off Analyzer utilizes these MCDM methods to normalize and weight the various outputs, allowing for the simultaneous assessment of both ecological and structural outputs.

Figure 1 represents the process of the methodology. It starts with the basic materials database, which is input to both the LCA and FEA modules. The LCA module looks into the environmental measures, whereas the FEA looks at the mechanical behavior of a material. Their results are then the input of the Trade-Off Analyzer, which determines the best solutions or decision-making processes that can help to optimize both areas.

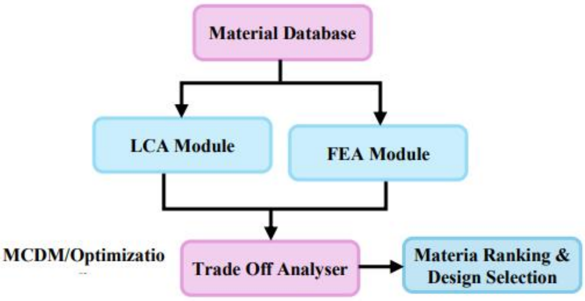

Figure 1. Block diagram for Integrated LCA FEA Framework

5 Simulation Setup and Load Conditions

In order to evaluate the mechanical properties, the ANSYS Workbench is used to produce a full-scale model of the car door interior panel using the nanocellulose biocomposite. A numerical quality assurance is created in 3D and meshed. The material characteristics that are taken into account during the analysis are experimentally obtained and represent Young's modulus of 4.2 Gpa, tensile strength of 58 Mpa, Poisson's ratio of 0.34, and thermal conductivity of 0.25 W/m3K. Depending on the boundary conditions, constraints are given based on the actual mounting conditions of the door frame. Three load conditions are used in the analysis: (1) static pressure simulating elbow weight (30 N), (2) localized impact simulating door closure force (150 N), and (3) thermal expansion from −20 °C to 80 °C to evaluate dimensional stability.

6 Results and Discussion

The LCA of the nanocellulose-based biocomposite panel identified the material as having a very positive environmental profile compared to traditional fossil fuel-derived materials like ABS and polypropylene. The GWP was calculated at about 1.8 kg CO_2 equivalent per 1 m² of the panel, a 65% reduction over the GWP of ABS. The Cumulative Energy Demand (CED) was calculated to be 45 MJ of energy, representing a 40% reduction in energy use throughout the entire life cycle. The material also had a low water footprint, with only 18 liters of water consumed during its three lifecycle stages: cultivation, processing, and manufacturing.

The full LCA results, comparing nanocellulose-based biocomposites with ABS and PP, are presented in Table 1.

Table 1. Environmental Impact Comparison of Nanocellulose-Based Biocomposites, ABS, and PP

Impact Category	**Nanocellulose-Based Biocomposite**	**ABS**	**PP**
Global Warming Potential (GWP)	1.8 kg CO_2 eq/m²	5.2 kg CO_2 eq/m²	4.8 kg CO_2 eq/m²
Cumulative Energy Demand (CED)	45 MJ	85 MJ	80 MJ
Water Consumption	18 L	45 L	42 L
Material Recyclability	95%	50%	60%

The LCA outcomes are rather straightforward in demonstrating that the ABS and PP have a worse Global Warming Potential (GWP), and a comparison with nanocellulose-based biocomposite shows that there is a decrease of GWP by 65%. Cumulative Energy Demand (CED) also shows a huge difference in the biocomposite, as there is a decrease in energy consumed by 40 %. Also, the water usage rate linked to the biocomposite is reduced, which proves that the resource used is at a disadvantage.

The nanocellulose-based biocomposite is also more sustainable for engineering use since it can be recycled, as compared to ABS and PP.

Table 2. Performance Evaluation of Material Assessment Methods

Method	Material Performance Insight	Mechanical Simulation Capability	Design Optimization Support	Suitability for Engineering Applications
MST (Membrane Separation Technology)	Low	None	No	Low
IES (Integrated Environmental Strategy)	Moderate	Limited	Partial	Moderate
LCA-FEA (Proposed)	High	Robust (FEA-based)	Yes (Integrated)	High

Table 2 shows that the LCA-FEA proposed method is superior to the methods that are currently used since it offers high material performance information, strong mechanical simulation, and combined design optimization, and is very applicable in sustainable engineering uses. Contrary to this, MST has little usefulness outside the separation processes that do not have mechanical capability.

Table 3. Carbon Emission Comparison of Assessment Approaches

Method	Carbon Emission Estimation	Quantification Level	Emission Reduction Capability	CO_2 Reduction vs Baseline ABS (%)
MST	Not Applicable	Low	Not Designed for Emission Control	–
IES	Qualitativ	Moderat	Limited to	~30%

	e & Scenario-Based	e	Early-Stage Decisions	
LCA-FEA (Proposed)	Quantitative (1.8 kg CO_2 eq/m^2)	High	Yes (Lifecycle Integrated)	~65%

Table 3 demonstrates that the LCA-FEA system is a quantitative and lifecycle-based system of carbon emission analysis, which yields up to 65% reduction of CO 2 in comparison with ABS. The proposed method provides high accuracy and practical insights to sustainable material development and implementation, unlike MST, which does not focus on emissions, or IES, which only provides moderate and scenario-based estimates with low impact.

7 Conclusion and Future Work

The LCA outcomes are rather straightforward in demonstrating that the ABS and PP have a worse Global Warming Potential (GWP), and a comparison with nanocellulose-based biocomposite shows that there is a decrease of GWP by 65%. Cumulative Energy Demand (CED) also shows a huge difference in the biocomposite, as there is a decrease in energy consumed by 40 %. Also, the water usage rate linked to the biocomposite is reduced, which proves that the resource used is at a disadvantage. The nanocellulose-based biocomposite is also more sustainable for engineering use since it can be recycled, as compared to ABS and PP.

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