Review

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Finite element analysis of natural fibers composites: A review

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Abstract: Natural fiber composites (NFCs) also termed as biocomposites offer an alternative to the existing synthetic fiber composites, due to their advantages such as abundance in nature, relatively low cost, lightweight, high strength-to-weight ratio, and most importantly their environmental aspects such as biodegradability, renewability, recyclability, and sustainability. Researchers are investigating in depth the properties of NFC to identify their reliability and accessibility for being involved in aircrafts, automotive, marine, sports’ equipment, and other engineering fields. Modeling and simulation (M&S) of NFCs is a valuable method that contributes in enhancing the design and performance of natural fibers composite. Recently many researchers have applied finite element analysis to analyze NFCs’ characteristics. This article aims to present a comprehensive review on recent developments in M&S of NFCs through classifying the research according to the analysis type, NFC type, model type, simulation platform and parameters, and research outcomes, shedding the light on the main applicable theories and methods in this area, aiming to let more experts know the current research status and also provide some guidance for relevant researches.

Keywords: natural fiber composite, finite element analysis, modeling and simulation, optimization, representative volume element

1 Introduction

Increasing awareness of environmental concerns evidenced the importance of developing biodegradable [1,2], recyclable [3], and environment-friendly composite materials [4]. Natural fibers like kenaf, ramie, jute, palm, leaf spring, sisal, flax, and hemp have the prospect of substituting glass fibers, carbon fibers, and other typical reinforcements in composite materials due to their attractive range of characteristics [5–10]. These fibers have some significant properties such as strength [11,12], toughness, flexibility, and stiffness [13–17]. Moreover, they have high availability [18], as well as they are sustainable and renewable [19]. It is worthy to mention some of their advantages, such as low density, negligible cost, remarkable energy recovery, vibration damping, less skin and respiratory irritation [20], and less equipment abrasion [21]. Recently, there was an increase in natural plant fibers selection as a reinforcement in composite materials development [22], and several matrices were chosen with these fibers like vinyl-ester, epoxy, polyester, polypropylene, and so on [23,24]. These natural fibers were utilized for different purposes, such as bandage, house hold appliances, roofing, and ropes [25–29]. Natural fiber composites (NFC) replaced many synthetic fiber-reinforced polymers for building materials, aerospace composite materials, and automotive.

Fibers are similar to hair structure (separate outstretched parts or continuous strings), and they may be turned into ropes, threads, or filaments [28,30,31]. Fibers can be involved in composite materials development. Fibers have two main categories: synthetic and natural fibers [14,32]. Natural fibers classification is shown in Figure 1.

Natural fibers comprise those obtained from minerals, animals, and plants. Hence, their classification is related to their source of extraction. Traditional manufacturing techniques used for composite materials with thermosetting and thermoplastics are implemented...
in NFCs [34], for example, injection molding, vacuum infusion hand layup, resin transfer molding, compression molding, and direct extrusion [4]. Several natural fibers were selected as a reinforcement with various polymeric matrixes, such as sisal, jute, kenaf, bamboo, jowar, sugar palm, date palm, coir, pineapple leaf, hemp, flax, rice husk, cotton, and so on [35–37].

Published documents from 2004 to 2020 regarding NFC and FEA have been gathered from the Scopus database (Figure 2), which shows a building momentum in the trend of research interest of NFC specifically to FEA. Modeling and simulation (M&S) of NFC began in 2004 and remained between 0 and 3 researches per year until 2011, where this topic brought attention to researchers, and the number of published articles increased and reached a peak of 11 papers in 2019. Figure 3 shows that India is most active in research on FEA of the NFC field.

The growing utilization of NFC highlighted the essentiality of effectively designing and developing NFC for optimum performance [38]. Since testing all aspects of research interest of NFC specifically to FEA. Modeling and simulation (M&S) of NFC began in 2004 and remained between 0 and 3 researches per year until 2011, where this topic brought attention to researchers, and the number of published articles increased and reached a peak of 11 papers in 2019. Figure 3 shows that India is most active in research on FEA of the NFC field.

The growing utilization of NFC highlighted the essentiality of effectively designing and developing NFC for optimum performance [38]. Since testing all aspects
of an NFC are expensive, scientists and engineers are involving computational techniques to simulate the thermal, physical, and mechanical properties of their developed materials, thereby validating their findings experimentally [39,40]. The application of analytical and numerical methods is profusely increasing in the natural fibers modeling and the design of NFCs [41–44]. Yet there are various methods, approaches, and models that can predict multiple properties of natural fibers and NFCs [45–49]. M&S methods applied for defining the mechanical characteristics of NFCs exhibited high efficacy. This review article focuses on the recent research on M&S of NFCs, aiming to highlight the key available approaches/techniques that can be implemented to analytically and numerically investigate the properties of NFCs, taking into account the reliability of each model and the efficiency of the applied methods. Information from several studies have been gathered and compared, including natural fiber and matrix types [50,51], model type, analysis type, simulation parameters and platform, and accuracy of the model/method [8,52–56].

2 Analytical models

Analytical models are able to mathematically compute specific properties of the end composite material through assigning characteristics of matrix and reinforcement as input, for example, in some basic micromechanics theories, main inputs including volume fraction, shear modulus, Poisson’s ratio, and elastic modulus of each component in the considered composite. Further parameters might be required in some models, such as fiber orientation, aspect ratio, density, orthographic properties, viscoelastic behavior, and so on. Predicting properties of woven fiber composites are much complex compared to continuous fibers composites. The wide variety of theoretical models includes rule of mixtures (ROM), which is the easiest existing method to analyze the elastic properties of a fiber-reinforced composite [57], and ROMs are used only on continuous and unidirectional fiber. Similarly, Halpin and Tsai equations are mostly implemented to predict elastic properties of composite materials [58]. Cox’s model is an ancient analytical model used to determine the impact of short fibers on the modulus and the strength of composite materials [58].

3 Finite element analysis (FEA)

The FEA is a M&S tool widely used in academia and industry, as any material model, boundary conditions, and complex shape structures can be solved by FEA easily [59–62]. FEA is a tool where an experiment is conducted virtually; hence, the graphs obtained can be read and analyzed easily [63]. Highly accurate and optimized results can be obtained by conducting several iterations, so that the product development down time will be reduced and its lifetime will be enhanced [64–66]. Figure 4 shows the steps of the FEA [67].

The preprocessing of the FEA is a very important step. It determines the quality of the simulation and hence the accuracy of the results. It consists of geometry preparation, material definition, element, and mesh selections. Then, loads and constraints are assigned based on the considered analysis type [69].
3.1 FEA of NFC

In M&S, a range of properties can be predicted, and a diversity of analysis methods can be utilized, namely, multi-physics analysis, electrical analysis, buckling analysis, electromagnetic analysis, heat transfer analysis, fluid analysis, thermal analysis, structural analysis, and acoustic. Mostly in M&S of NFC, researches focused on mechanical properties [52,70–73], while few investigated the acoustic and thermal properties [74,75]. Analytically, a model can be studied from one dimension up to three dimensions. But for accurate results, three-dimensional models are recommended for NFC analysis, especially when loads are applied in the out-of-plane direction [76]. The model preparation is rather easy since the imported geometry is usually three dimensional [77].

The characteristics of matrix and natural fibers are specified in M&S based on the type of analysis [78,79], for example, studying the mechanical properties requires Poisson’s ratio, young’s modulus, elongation at break, shear strength, and density. However, analyzing the thermal behavior of a natural fiber composite (NFC) needs to assign the thermal conductivity values (K) of both components. However, inspecting the sound absorption coefficient requires orthotropic mechanical characteristics [80,81]. As it is hard to define the exact orthotropic properties of a newly developed NFC, some researchers considered their materials as isotropic, where a material behaves similarly in all force directions, unlike orthotropic materials that exhibit dissimilar properties on different load directions [82,83], where it is simpler to assign a single value for young’s modulus and Poisson’s ratio [84–86].

FEA has become a valuable engineering tool. Commercially available FEA Software’s are ANSYS, SDRC/IDEAS, NASTRAN/PATRAN, HYPERMESH, LS DYNA, ABAQUS, SIEMENS PLM NX, NISA, COMSOL, KEBIR, and so on. Matlab has been used for modeling and optimization (using fmincon solver). ABAQUS capabilities for geometry modeling are quite general (cables, trusses, shells, 2D and 3D continua, and so on) and include a wide range of materials, limited support, and reasonable control in meshing [20]. However, ANSYS workbench is vastly automated and very flexible for users to modify according to application/analysis type. Its materials library consists of reactive material, creep, viscoelasticity, elasticity, plasticity, and linear materials. Moreover, ANSYS includes thin-sweep meshing and automatic meshing (hexa-dominant, swept hex, hex-core, tetrahedral, and surface meshing) [87]. Furthermore, based on the geometry shape and dimensions in NFC studies, elements’ numbers ranged between 15,000 and 1,80,000 with the element size from 20 to 70 µm. Solid models involve typical solid elements where the material is assigned to all regions of the model, while shell models consider the external shell of the model.
Researchers utilized diverse solid and shell elements in ANSYS such as Solid 20 Node 186, Solid 95, Solid 46, Shell 281, shell 181, and Shell 99. Numerous element types were used in ABAQUS, such as hexahedral elements (C3D8R), tetrahedral elements (C3D6), tetrahedron (TET10 or C3D10), and eight-node hexahedron (HEX8). Figure 5 illustrates the main element types involved in the FEA.

Hence, the load applied depends on the analysis type of NFCs (acoustic, fatigue load, buckling load, thermal load, and structural load), so that this load indicates which property of the NFC is examined. For example, in mechanical loadings, the direction of applied forces indicates if this analysis is tensile, shear, flexural, impact, and so on.

### 3.2 Representative volume element (RVE)

RVE comprises investigating the performance of an NFC or a composite material’s unit cell at nano-scale, micro-scale, or macro-scale. Main three-dimensional RVE boundary conditions are periodic boundary condition (PBC), homogeneous boundary condition (HBC), and displacement boundary condition. When PBC is selected, the simulation outputs characterize a macrostructure containing repeated periodical cells. However, by selecting HBC, the simulation outcomes will deem that the RVE itself is the macrostructure and take into consideration its microcomponents. However, in another NFC analysis type, the boundary conditions of the electrical conductivity problem included an applied voltage on one face and a ground on the opposing face. This generated some current density within the RVE model, and that current density was used along with Ohm’s law and the dimensions of the RVE to calculate the overall conductivity of the composite. Currently, various tools like EasyPBC in ABAQUS and material designer in ANSYS are being utilized to study the RVE of NFCs. These tools require materials’ properties, fiber size, and volume fraction as inputs, thereby it can automatically define the corresponding RVE dimensions, most convenient mesh size, and type, and finally, it solves the RVE model.

### 3.3 Design of experiment and optimization

Several optimization techniques are implemented in natural fiber composite studies to find the best parameters combination or optimal value of a particular property (strength, stiffness, etc.) such as parametric, genetic algorithm, TOPSIS, ANSYS parametric design language (APDL), and fuzzy logic. Thus, diverse design of experiment approaches can be adapted to define the least/efficient number of specimens needed for results’ experimental validation.

### 4 Discussion

NFC analytical studies investigated models in one and three dimensions, but 2D was mostly considered. Mostly, hemp fiber was selected in the analytical NFC research. However, a range of analytical theories were involved in the analysis of mechanical, thermal and acoustic properties of NFC, for example, ROM, Puck failure theories, Halpin, Tsai–Wu, Tsai–Hill, Nairn Shear-lag, Mendels et al. stress transfer, fatigue–life (S–N) curves, and Hirsch were utilized for studying stiffness, elastic modulus, strength, and fatigue–life response.

| Element Order | 2D Solid | 3D Solid | 3D Shell | Line Elements |
|---------------|----------|----------|----------|---------------|
| Linear        | PLANE42  | SOLID45  | SHELL63  | BEAM3/44      |
|               | PLANE182 | SOLID185 | SHELL181 | BEAM188       |
| Quadratic     | PLANE82/183 | SOLID95/186 | SHELL93 | BEAM189 |
|               | PLANE2   | SOLID92/187 |        |               |

Figure 5: Elements type [90].
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Objective of the study | Platform | Analysis type/ boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks |
|--------------------------------|---------------|------------|------------------------|----------|-----------------------------------|-----------------------------------------------------------------------------------|
| Hemp 20–40 wt%                | HDPE          | Fatigue-life (S-N) curves | Fatigue-life response |          |                                   | • Tensile, (monotonic and cycle tests) & SEM |
|                                |               |            |                        |          |                                   | • The fatigue model utilized was able to predict the fatigue behavior of the experimentally tested NFC upon different values of stress ratios and volume fractions with considering moisture uptake |
| Manila Hemp                    | Poly lactic acid | Square arrayed pipe filament | Transverse thermal conductivity |          |                                   | • Fiber volume fraction, thermal conductivity ratio, and geometrical ratio affect the dimensionless effective transverse thermal conductivity of NF |
| Hemp, hardwood, rice hulls, E-glass 10–60 wt% | HDPE          | ROM, Halpin–Tsai, Nairn shear-lag analysis and Mendels et al. stress transfer | Stiffness & Young's modulus correction | Micromechanical |                                   | • E-glass fibers (tensile, composite density and SEM) |
| Hemp/kenaf hybrid up to 20.6 wt% | Polyester    | Fourier's heat conduction equation | Temperature variation and cure | Thermal/Temperatures at the wall ($i = 1$ and $i = N$) |                                   | • Standard micromechanical models can be applied to natural fiber systems with mixed success |
| Flax+51/–52°                  | Epoxy         | Tsai–Hill, Tsai–Wu, Hashin, and Puck failure theories | Stiffness, strength and interaction | Matlab | Failure criteria | • Tensile, flexural, and thermal |
| Flax laminates                | Epoxy         | Mesoscale damage theory | Mechanical response, stiffness degradation, and inelasticity | Matlab | Acoustic | • Once the model was corrected, it predicted very well the temperatures in the mold |
| Coconut coir and rice husk    | Granular materials | Johnson–Champoux–Allard | Sound absorption | Matlab | Acoustic | • Parametric optimization |
|                                |               |            |                        |          |                                   | • Tension and compression |
|                                |               |            |                        |          |                                   | • Hashin and Puck failure theories are recommended because they have the smallest error compared to experimental data |
|                                |               |            |                        |          |                                   | • Cost-function minimizing optimization |
|                                |               |            |                        |          |                                   | • Tensile |
|                                |               |            |                        |          |                                   | • The damage model and flax-specific parameters can be combined with user-defined material characteristics |
|                                |               |            |                        |          |                                   | • Impedance tube |

Ref. [98], [99], [57], [100], [101], [102], [103]
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Objective of the study | Platform | Analysis type/ boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks |
|--------------------------------|---------------|------------|------------------------|----------|----------------------------------|--------------------------------------------------------------------------------|
| Four sample thicknesses (20–50 mm) | | | | | | **A promising agreement of the acoustic absorption performances was observed between the experimental and analytical outcomes** |
| Coconut coir Sandwich | Polyester and polyurethane (coating) | Wear rate and surface coating | Matlab | | **Fuzzy logic Optimization** | [96] |
| Jute woven | PU | Hirsch, Cox, Halpin T-sai, and mass fraction (MFS) | Tensile strength and Young’s modulus | Matlab | Mechanical | **Wear test and SEM** |
| | | | | | | **Fuzzy approach performed better assessment on surface coating quality** |
| | | | | | | **Tensile** |
| | | | | | | **Cox, Hirsch’s, and H.T-sai models are reliable and predictable models (for mechanical properties)** |
| B & Jute | Recycled high density polyethylene/polypropylene | Variable order creep model | Creep behavior | Matlab | Mechanical | **The variable order creep model showed high results accuracy compared to experimental results** | [104] |
Johnson–Champoux–Allard was utilized for inspecting the sound absorption of coconut coir and rice husk NFC (Table 1).

Moreover, several analytical models contribute for calculating the mechanical properties of woven fibers composites, such as Halpin–Tsai, Hirsch’s, and Cox [58]. However, Fourier’s heat conduction equation was utilized to study the temperature variation of hemp/kenaf/epoxy hybrid NFC. The mesoscale damage theory was also used for calculating the mechanical response, inelasticity, and stiffness degradation of Flax NFC [58,96,101–103]. Furthermore, Cox and Halpin–Tsai models has an adequate accuracy in predicting the tensile strength. Similarly Hirsch’s model is able to calculate the elastic modulus [58]. Hence, less error was revealed while computing the elastic modulus using Halpin–Tsai approach compared to rule of mixture, Nairn shear lag analysis, and stress transfer [57]. Comparing with Tsai-Wu and Tsai-Hill theories, Puck and Hashin exhibit higher accuracy in predicting failure criteria of NFC [101]. However, the ROM- and Tsai-based rules were commonly used. Hence, Halpin–Tsai approach can be considered as the best approach in predicting micromechanical properties. In terms of woven NFC, Hirsch’s model was the best analytical technique for predicting young’s modulus, yet Cox and Halpin–Tsai models exhibited analogous remarkable accuracy in calculating the tensile strength. Johnson–Champoux–Allard model was most accurate model for analyzing the sound absorption of NFC; Fourier’s heat conduction equation was significantly convenient to predict the thermal behavior of NFC; and Hashin’s model was notably reliable in predicting the fatigue criteria. Only few researches implemented optimization theories and design of experiments.

In the NFC numerical analysis, most researches tend toward using the FEA and RVEs due to the high accuracy of this method in predicting the properties of composites. Some studies involved analytical theories besides the numerical methods, such as ROM, Chamis model, Fick’s law, Hamilton’s principle, Halpin–Tsai model, and Hashin and Rosen model. Numerically analyzing the mechanical properties of NFC was the major focus of a notable number of studies. Major natural fiber selected was flax fiber, and epoxy matrices were mostly chosen. While several researches involved more than one type of natural fibers to develop a hybrid natural fibers composite, NFCs were hybridized with synthetic fibers like E-glass. Despite the fact that composites and NFCs are orthotropic, materials were mostly considered as isotropic in M&S of NFC studies, apparently, due to the lack of data about these newly developed materials.

Various boundary conditions were assigned like clamped, free, and simply supported boundary conditions, as well as PBCs in RVE [67,71,93]. Diverse boundaries were taken into account, such as topologies, material properties, weight, cost, mass, cost, easy manufacturing, mesh density, element order, microwave exposure time, and location of specimen in the microwave. ANSYS was mostly utilized as a simulation platform. Also, several element types were used, such as wedge elements (C3D6), linear hexahedral elements (C3D8R), quadratic tetrahedral elements (C3D10), SHELL 181, Solid 95, Solid 185, Solid 186, and Solid 187, yet most studies analyzed NFC as a 3D solid model. Some optimization algorithms were applied, namely, genetic algorithm, Topsis, parametric optimization, and APDL, regardless of the distinct aspects optimized through the aforementioned algorithms, and the implementation of these techniques proved its reliability and effectiveness. Very few studies included the design of experiment by using the Taguchi method (ANOVA) for selecting the combination of parameters that gives maximum load enduring capacity at failure, for instance, Parsad et al. considered three factors, namely, three fiber lengths, three CNSL percentages (5, 10, and 15%), and three fiber-to-matrix ratios (20, 30, and 40 wt%) and then utilized Taguchi (Design of experiments [DOE]) method to obtain the analysis number [105]. A significant number of researches indicated that predicted and experimental findings were in strong agreement. Table 2 presents the summary of research on numerical M&S of thermal, acoustic, moisture diffusion, deflection, and aerodynamic properties of NFCs.

To date, simulation of various NFC properties are still limited, i.e. thermal, aerodynamic, acoustic, vibration, moisture absorption (Table 2). However, the sound transmission loss of few NFC was numerically studied using the finite element analysis in ANSYS and ABAQUS. However, FEA of thermal behavior considered hemp/ acrylic NFC and NF bricks made from bamboo, jute, coir, and sisal fibers. FEA of aerodynamical properties focused on Flax/vinyl-ester NFC.

For instance, Haris et al. [50] inspected the noise reduction ability of Flax/Carbon/polypropylene hybrid NFC, experimentally conducted the sound transmission loss test, and numerically used Abaqus software, where eight-node acoustic brick elements (AC3D8) were utilized to mesh the air volume and eight-node continuum brick elements (C3D8R) were used for meshing the specimen. Flax/carbon/PP and Flax/PP were considered
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Numerical analysis | Objective of the study | Platform | Boundary conditions | Analysis type (macromechanic/micromechanical/thermal) | Optimization algorithms/physical experiments and validation/key findings and remarks |
|---------------------------------|----------------|------------|-------------------|------------------------|----------|-------------------|--------------------------------------------------|--------------------------------------------------------------------------------|
| Flax bundle                     | Fourier expansion | Numerical simulation | MATLAB             |                        |          |                   |                                                  | • The model was sufficiently relevant to render the morphometric factors of the observed fibers in a statistical sense [106] |
| Flax                            | Styrene butadiene rubber | Cartesian coordinate | FEA                | Crystal structure      |          |                   |                                                  | • XRD, FTIR, Flexural, nanoindentation [107] |
| Flax                            | PE              | Wave FEA   | Dispersion curves | ANSYS                 |          |                   | [Lamb waves]                                    | • Finite element analyses reveal the success of L-lysine templated coatings [108] |
| FlaxCar Hood                    | Vinyl ester     | FEA        | Aerodynamic       | Nastran/Patran         | Aerodynamic |                   |                                                  | • Genetic algorithm [109] |
| Hemp car mirror                | Acrylic         | FEA        | Curing Behavior   | COMSOL                | Neumann boundary conditions | Thermal |                                  | • Full-scale static structural test [109] |
| Hemp sandwich                  | Bio-epoxy       | FEA        | Sound transmission loss | ANSYS                |          |                   | Acoustic                                         | • FEA and experimental results showed high agreement [110] |
| Hemp & e-glass electronic rack | Epoxy           | Life cycle analysis | Static and dynamic FEA | Design                | Nastran  |                   |                                                  | • Heat compression molding [110] |
| in helicopter                  |                 |            |                    |                        |          |                   |                                                  | • Simulation procedure is numerically valid and stable and provides reasonably accurate predictions [81] |
| Jute and ramie plies           | Polyester       | FEA        | Free undamped vibration | ANSYS                |          | Simply supported | Vibration                                         | • Shear, compression, and Tensile [111] |
|                                 |                 |            |                    |                        |          |                   |                                                  | • FEA and experimental results were in high agreement [111] |
|                                 |                 |            |                    |                        |          |                   |                                                  | • Results are promising from the structural point of view [112] |
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Numerical analysis | Objective of the study | Platform | Boundary conditions | Analysis type (macromechanical/micromechanical/thermal) | Optimization algorithms/physical experiments and validation/key findings and remarks |
|---------------------------------|----------------|------------|--------------------|-----------------------|----------|-------------------|------------------------------------------------|-----------------------------------------------------------------|
| Bamboo, jute, coir & sisal bricks | Clay | FEA | Thermal conductivity | ANSYS | Thermal | edges, free edges, and clamped edges | • SEM, tensile, water absorption, and swelling thickness |
| Agave | Epoxy and hardener | FEA | Moisture diffusion | Abaqus | Moisture diffusion | | • Ramie, jute, and ramie/jute mode shapes as well dimensionless frequency agreed with the literature |
| Maise | Polyester | FEA | Deflection and stress properties | ANSYS | | | • Porosity, bulk density, water absorption, and thermal conductivity |
| Rice husk window frame | PE | Injection molding | Design | Moldflow | | | • The model is applicable as highest variance between FEA and experimental was 7.8% |
| Areca sheath 25, 27 & 29 mm | Epoxy | FEA | Effect of fiber length | ANSYS | Dynamic frequency response | | • Water absorption and SEM |
| B-Boron | Epoxy | Hamiltonian system and Symplectic | FEA | Critical buckling loads, fundamental frequencies and | ANSYS | Simply supported edges, Free | Buckling and Vibration | • Results showed that mass diffusion appeared to follow Fick's diffusion performance in composite specimens |
| | | | | | | | | • FEA values are acceptable with proper assumptions |
| | | | | | | | | • Further work is required to enhance the precision analyses of the rice husk/PE NFC |
| | | | | | | | | • Fast Fourier technique |
| | | | | | | | | • Analytical and FEA results were in high agreement |
as orthotropic materials, and NFC model dimensions were of 3.7 and 4.6 mm thickness with a diameter of 100 mm. The performed simulation proved its high reliability as it was in high accordance with the experimental findings. The aforementioned model is shown in Figure 6.

Similarly, only few studies investigated the moisture diffusion characteristics of NFC, for instance, Jain et al. [114] investigated the mass diffusion in Agave/epoxy NFC considering several environmental conditions and fibers were of an average length of 2.8 m and diameter between 100 and 150 µm; moreover the aforementioned fibers were assumed as homogeneous and isotropic. Regarding concentration profiles of moisture of Agave NFC treated with sodium hydroxide and cleaned with water at 75°C, an increase in moisture absorption was observed by increasing the time. The results of the FEA were in high accordance with bond graph results; as the moisture diffusion analysis exhibited similar moisture ingress trends, the 3D model created in Abaqus verified the model studied in the bond graph [119]. Figure 7 shows whole-body model with a small meshed region.

Few researches numerically studied the vibration properties of NFC using ANSYS while involving some analytical approaches like Halpin–Tsai, Hamiltonian system, and Symplectic superposition method. Furthermore, Waddar et al. [120] investigated the buckling and vibration behavior of syntactic foam core sandwich beam that has sisal fabric/epoxy outer layers, and the model was represented as a 210 mm × 12.5 mm rectangle using Shell 181 in ANSYS. The utilized model evidenced its ability of predicting vibration and buckling behavior by revealing results that significantly agreed with the experimental results.
Majority of the researches focused on investigating the mechanical properties of NFC. Multiple simulation platforms were utilized, such as ANSYS, ABAQUS, MATLAB, LS-DYNA, Nastran/Patran, Siemens PLM NX 10.0, NISA, and so on. In addition, several analytical techniques were involved like experimental modal analysis, Newton–Raphson nonlinear, Maximum strain and Tsai–Wu, J-Integral, ROM, Weibull distribution, Chamis model, Nielsen Elastic model, and Halpin–Tsai model.

Table 3 presents the summary of research on numerical M&S of tensile strength, joint strength, and stress and strain characteristics of NFCs. Numerical M&Ss of NFCs were barely reported compared to glass and carbon composite materials. However, initial FEA steps consist of creating the model geometry followed by assigning the characteristics of the material. FEA that considers the mechanical behavior of an NFC requires specific failure criteria, which defines the failure initiation and propagation. It is worthy to mention that in terms of tensile properties, natural fibers behave in a different manner compared to synthetic fibers. Failure criteria of strong synthetic fibers are usually involved in NFC analyses, as the specific failure criteria of NF are not proposed. Thus, the aforementioned criteria contribute in predicting the ultimate tensile strength, yet it ignores other characteristics like nonlinear tensile response of a NF [139]. As given in Table 3, numerical M&S of NFC mostly focused on the tensile behavior compared to other mechanical properties. The tensile strength and stress/strain properties of numerous natural fibers were simulated, i.e., flax, hemp, jute, banana, sisal, wood, and so on. Several analytical approaches were considered along with the numerical techniques, such as maximum strain failure criterion, Tsai–Wu, Weibull distribution, Chamis model, Nielsen Elastic, Halpin–Tsai, rule of mixture, Hahsin, and Rosen. Different polymeric matrixes were selected, for example, epoxy, polypropylene, POM, polystyrene, and PLA.

Table 4 presents the summary of research on numerical M&S of impact, bending, burst pressure, and other properties of NFCs. As presented in Table 4, the FEA of impact property was mostly considered for flax fibers with diverse matrixes such as vinyl ester, PE, PP, and thermoplastic resin, as well as hemp hybrid NFC with polypropylene matrix. Several NFCs were analyzed through FEA to identify their flexural (Bending) characteristics such as flax, jute, wood, rice husk, and pine. Figure 8 shows an Agave NFC beam under bending load.

Thus, Petrone and Meruane [142] numerically analyzed the mechanical properties of flax/polyethylene laminate (250 × 15 × 1 mm) NFCs using structural dynamic toolbox in Matlab software, and the authors had to modify the mechanical properties assigned to the finite element model due to the discrepancies between FEA and experimental results. After two parameter’s update stages, it was observed that outcomes may be enhanced by including further information through the model update procedure like panel shape and thickness dimensions. Xiong et al. [121] studied the micromechanical characteristics of flax/polyoxymethylene NFCs using RVE micro-scale. The multiscale constitutive model was conducted in two stages: first, an orientation averaging technique was utilized to calculate micromechanical characteristics of the twisted yarn and then, the outputs of stage 1 were shifted into a meso-scale RVE of a single ply NFC to inspect its elastic behavior. Results showed that elastic properties of this NFC are highly affected by the twist angle of the yarn. The latter has a simultaneous effect on the distributed stress throughout the RVE.

Further mechanical performance has the potential to be inspected through the FEA at costs lower than experimental testing, for example, Davoodi et al. [146] numerically studied the impact properties of a car bumper made from hybrid kenaf/glass/epoxy using Catia and Abaqus platforms. Figure 9 illustrates the displacement profile of a car beam after applying an impact load. Usually, the variation between the results of experimental and FEA analyses is due to unconsidered material properties, and it is worthy to mention that natural fibers are orthotropic, as well as NFCs contain voids, discontinuity, and porosity [153]. To examine the sound transmission loss, it is conceivable to create a mechanical model in FEA using the data obtained from mechanical testing and assign identical boundary conditions imposed in the impedance tube [81].
| Fiber type, size and orientation | Epoxy/hardener       | Analytical | Numerical analysis     | Objective of the study | Platform         | Boundary conditions                                      | Optimization algorithms/physical experiments and validation/key findings and remarks |
|---------------------------------|----------------------|------------|------------------------|------------------------|-----------------|----------------------------------------------------------|---------------------------------------------------------------------------------|
| Flax 46.2 WT%                   | POM                  | FEA RVE    | (homogenized)          |                        | PBCs            | • Tensile, SEM                                           | [121]                                                                            |
|                                 |                      |            |                        |                        |                 | • Results obtained from RVE and FEA models significantly agreed with experimental results |                                                                                  |
| Flax one by one top-hat stiffened composite plate | Epoxy | Grillage | FEA                    | Stresses & strain      | Abaqus          | • Parametric study is 5% lower in accuracy compared to FEA | [122]                                                                            |
| Flax                            | PP                   | Maximum strain failure criterion | FEA | Strain | Abaqus | • Stamping and Aramis monitoring system     | [123]                                                                            |
| HempNaca cowling of an acrobatic ultra-light airplane | Epoxy | Maximum strain and Tsai–Wu | FEA | Mechanical properties | Fluent & ANSYS | • FLC and MSF criteria can accurately predict failure regions in all specimens | [124]                                                                            |
| Hemp 30 WT%                     | PP                   | FEA (RVE)  | Mass fraction, tensile | Kebir simulation platform |                | • Tensile, three-point bending and SEM               | [125]                                                                            |
| Hemp/Jute Hybrid 30°, 45° & 90° | Epoxy & Polyester | Mechanical properties | FEA | Tensile behavior | Siemens PLM NX 10.0 | • PF approach could be considered as a complementary technique to micro-mechanical approaches | [126]                                                                            |
| Jute 45°–90°                    | Epoxy                | FEA        | Tensile behavior       | Siemens PLM NX 10.0    |                 | • High agreement was exhibited between FEA and experimental results | [127]                                                                            |
| Jute                            | Epoxy and (PU joints) | J-Integral (compliance calibration method, cubic polynomial, and corrected beam theory) | FEA | Tensile fracture toughness of adhesive joints & CZM | Matlab subroutine | • Simulation outputs significantly agreed with tensile testing results | [128]                                                                            |
| Jute                            | Epoxy                | Rule of mixiture, Weibull distribution | FEA | Tensile, strain, and elastic modulus | MENTAT & MARC | • Trapezoidal law reproduces the experimental behavior with a reasonable level of accuracy | [129]                                                                            |
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Numerical analysis | Objective of the study | Platform | Boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks |
|---------------------------------|----------------|------------|--------------------|------------------------|----------|---------------------|----------------------------------------------------------------------------------|
| Jute/banana hybrid             | Cashew nut shell resin | FEA       | Strength            | Solidworks, ANSYS & Minitab | PBCs     |                     | significantly improved by updating fibers’ strength with accordance to their length postfailure. |
| Banana                          | Polystyrene     | FEA (RVE) | Elastic properties  | ABAQUS                 |          |                     | • Tensile and experimental results are close                                      |
| Sisal and banana               | Epoxy           | FEA       | Elastic Properties  | ANSYS                  |          |                     | • The phenomenological analytical model estimations highly agreed with FEA results |
| Sisal/coir hybrid              | Epoxy           | FEA (RVE) | Mechanical properties | ANSYS                |          |                     | • Tensile and SEM                                                                 |
| Agave                           | Epoxy           | FEA       | Effect of joint geometry on the strength | ANSYS                |          |                     | • Significant agreement between FEA and experimental results                    |
| Nettle & grewia optiva         | Polylactic acid and polypropylene | FEA     | Joint strength      | COMSOL                |          |                     | • Tensile                                                                 |
| Pineapple                      | Epoxy           | ROMs, modified rule of mixtures (MROMs), chamis model, FEA (RVE) | Mechanical properties | ANSYS & Matlab, x, y, z = 0 |          |                     | • Microwave heating and adhesive bonding                                          |
|                                 |                 |           |                    |                        |          |                     | • By considering experimental and numerical results, the proposed model may be utilized to study the joining performance of composite materials using microwave technology. |
|                                 |                 |           |                    |                        |          |                     | • Electronic tensometer and single fiber pull-out                                  |
| Fiber type, size and orientation | Epoxy/hardener | Analytical | Numerical analysis | Objective of the study | Platform | Boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks |
|---------------------------------|----------------|------------|--------------------|------------------------|----------|--------------------|----------------------------------------------------------------------------------|
| Pulp ellipsoidal                 | Poly lactic acid | FEA        | Dimensions and orientation of fiber agglomerates | ANSYS      |          |                    | • MROM as well as Chamis model showed high accuracy                               |
| Henequen laminates               | PE              | Photoelastic | Fiber curvature effect on the tensile properties | NISA       |          |                    | • Tensile test, SEM                                                               |
| Wood 60 WT%                     | 18% PE and 12% PP | FEA        | Joint strength     | Simply supported       |          |                    | • The predicted strength using the stress concentration factor theory disagreed with experimental findings |
| Wheat straw four fiber lengths   | PP              | FEA        | Microstructural behavior and microcellular-voided | AutoCAD and Abaqus |          |                    | • Tension                                                                      |
|                                 |                 |            |                    |                         |          |                    | • Predicted and experimental results are in high agreement                         |
|                                 |                 |            |                    |                         |          |                    | • Tensile and SEM                                                                |
|                                 |                 |            |                    |                         |          |                    | • The FEA curves are well matched in general to the experiments                    |
### Table 4: Numerical M&S of impact, flexural, and compression behaviors of NFCs

| Fiber type, size, and orientation | Epoxy/hardener | Analytical | Numerical analysis | objective of the study | Platform | Boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks |
|----------------------------------|----------------|------------|--------------------|------------------------|----------|---------------------|-----------------------------------------------------------------------------------|
| Flax                             | Vinyl ester    | FEA        | Impact             |                         |          |                     | • Impact and compression                                                            |
|                                  |                |            |                    |                        |          |                     | • The structural design and test showed that the designed bonnet structure is acceptable | [140] |
| Flax Honeycomb                   | Thermoplastic resin | FEA | Impact             |                         |          |                     | • Impact                                                                           | [53] |
|                                  |                |            |                    |                        |          |                     | • Agreement between numerical results and experimental data                      |                                                        |
| Flax Laminates                   | PP             | FEA        | Flexural property  |                         |          |                     | • Numerical results agreed with experimental results                              |                                                        |
|                                  |                |            |                    |                        |          |                     | • Classical static tests                                                           |                                                        |
|                                  |                |            |                    |                        |          |                     | • Authors had to change the mechanical characteristics assigned for finite element model due to the discrepancies between FEA and experimental results |                                                        |
| Basalt & Flax (VF 60%) high-pressure vessel | Epoxy         | FEA        | Burst pressure     |                         |          |                     | • Studying one-eighth of the tank is adequate, hence deduce the outputs on the remaining region of the tank by symmetry | [143] |
| Flax and jute channel            | Epoxy          | Newton–Raphson non-linear | FEA | Bending             | ANSYS    |                     | • Tension and four-point bending                                                  | [144] |
| Hemp lass fibers 2–4.5 mm < 30 WT% | PP             | FEA        | Impact             |                         |          |                     | • Experimental ultimate moment capacities were predicted using the numerical models with a variation mean of 0.99 and coefficient of 0.06 | [145] |
| Hybrid kenaf/glass               | Epoxy          | FEA (Impact) | Deflection, strain energy, and the rib possibility | Catia and Abaqus |          |                     | • Tensile                                                                         |                                                        |
|                                  |                |            |                    | Catia and Abaqus       |          |                     | • FEA results and macro-cracks agreed with experimental results                   |                                                        |
|                                  |                |            |                    |                        |          |                     | • TOPSIS                                                                          |                                                        |
| Ramie triangular structure       | PMI foam       | Solid model method, beam model method, and simplified method (SM) | FEA | Load-carrying capacity | ANSYS    |                     | • Experimental work should be done to validate the results                       |                                                        |
|                                  |                |            |                    |                        |          |                     | • APDL                                                                            |                                                        |
|                                  |                |            |                    |                        |          |                     | • Four point bending                                                              |                                                        |
| Wood                             | PVC            | Classical beam theory | FEA | Flexural strength | ABAQUS  | Simply supported     | • SM and BMM have lower accuracy than SMM                                        |                                                        |
|                                  |                |            |                    |                        |          |                     | • Compression, tensile, and flexural                                              | [148] |
| Fiber type, size, and orientation | Epoxy/hardener | Analytical | Numerical analysis | objective of the study | Platform | Boundary conditions | Optimization algorithms/physical experiments and validation/key findings and remarks | Ref. |
|---------------------------------|---------------|------------|-------------------|-----------------------|----------|---------------------|---------------------------------------------------------------------------------|------|
| Wood pallet                     | RPP           | FEA        | Static deformation| SolidWorks and CosmosWorks |          | boundary condition  | • FEA results exhibited higher accuracy compared to analytical findings          | [149]|
| Rice husk, radiata pine, and poplar wood ply | HDPE         | FEA        | Flexural strength | ABAQUS                |          |                     | • Shadow moire                                                                  | [82] |
| Wood3D printing                 | Tango plus    | ROM        | Mechanical properties | ANSYS                |          |                     | • Simulation and deflection results showed highest agreement at the pallet center | [150]|
| Human hair                      | FEA           |            | Stress distribution | ANSYS                |          |                     | • Optical micrograph, impact, flexural, creep, and thermal expansion             | [151]|
| Oil palm                        | Polyethylene  | FEA        | Fiber pull-out resistance | MATLAB and ABAQUS |          |                     | • FEA findings indicates that the NFCs comprise orthotropic flexural characteristics that rely on the angle of fiber orientation | [152]|

Finite element analysis of natural fiber composites
5 Conclusion

This article presents a comprehensive review and critical comparison of recent research on M&S of NFC. Considering both numerical and analytical studies, most researches focused on mechanical properties of NFCs like tensile, flexural, impact etc., while few researches considered moisture absorption, thermal, and acoustic properties. Most considered fiber for the theoretical analysis was hemp fiber, while flax and jute fibers attained higher interest in the numerical analysis studies. Several analytical approaches were utilized to predict thermal, mechanical, and acoustic properties of NFCs, such as Fourier’s heat conduction equation, rule of mixture, Tsai–Hill, Tsai–Wu, Halpin Tsai, and Johnson–Champoux–Allard. Halpin–Tsai theory exhibited higher accuracy compared to Nairn shear lag and rule of mixture. Moreover, findings obtained from Puck and Hashin approaches were in higher agreement with the experimental results compared to the ones obtained from Tsai–Wu and Tsai–Hill. However, most utilized approaches in analytical modeling were Tsai-based ROM. Hence, Halpin–Tsai approach exhibited highest accuracy in predicting the micromechanical characteristics of NFCs. In terms of NFC numerical researches, the FEA and RVEs were drastically utilized. Yet, few researches used analytical approaches along with the FEA. Thus, ANSYS is the most common FEA platform used for M&S of NFC, with solid and shell elements. Several boundary conditions were considered, such as simply supported, clamped, and free boundary conditions, as well as PBCs in RVE. As a future work agenda, thermal conductivity, sound absorption, and vibration of further NFC types made from palm, flax, Luffa, cotton have to be numerically analyzed, and thus, optimization algorithms can be implemented to determine the ideal fibers’ size and orientation on the corresponding property. Complex loading scenarios can be analyzed, and DOE can be employed for meta-modeling or Taguchi for the worst-case analysis. Major challenges in M&S of NFCs are defining accurate materials properties inputs, assigning a failure criteria specifically for NF, and analyzing the nonlinear stress/strain behavior of a natural fibers composite.

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