Review

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Finite element analysis of natural fibers composites: A review

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.

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

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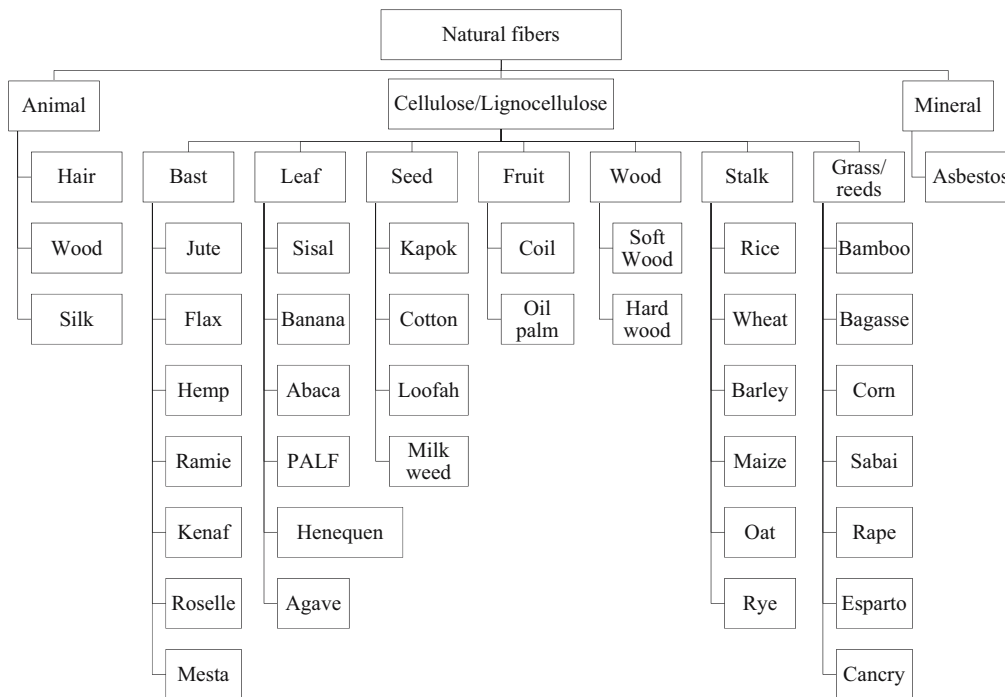
Figure 1: Classification of NF [33].

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
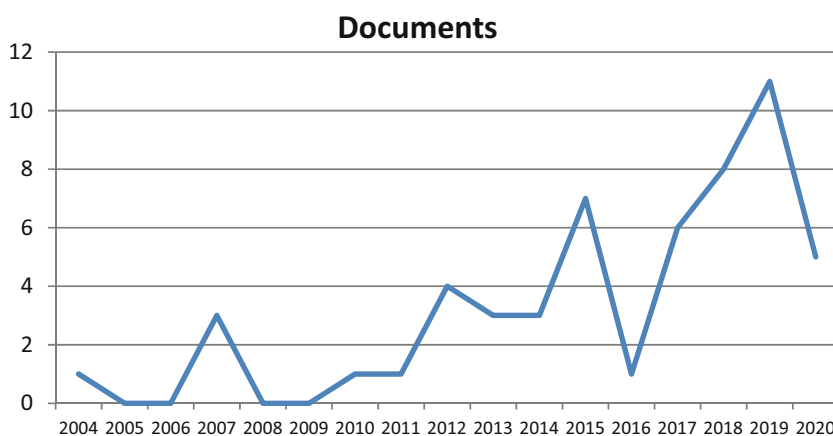

Figure 2: Statistic from Scopus database in Published documents per year search keywords: (TITLE-ABS-KEY ("Natural fiber composites" and "FEA") (Scopus – Sources, 08/06/2020).
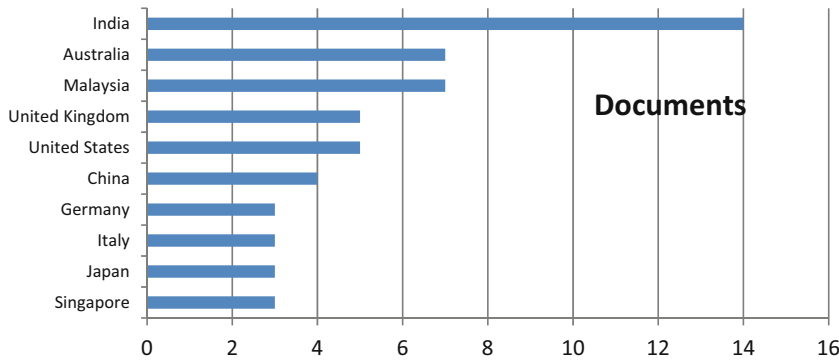
Figure 3: Statistic from Scopus database in Published documents by country search keywords: (TITLE-ABS-KEY ("Natural fiber composites" and "FEA") (Scopus – Sources, 08/06/2020).

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].
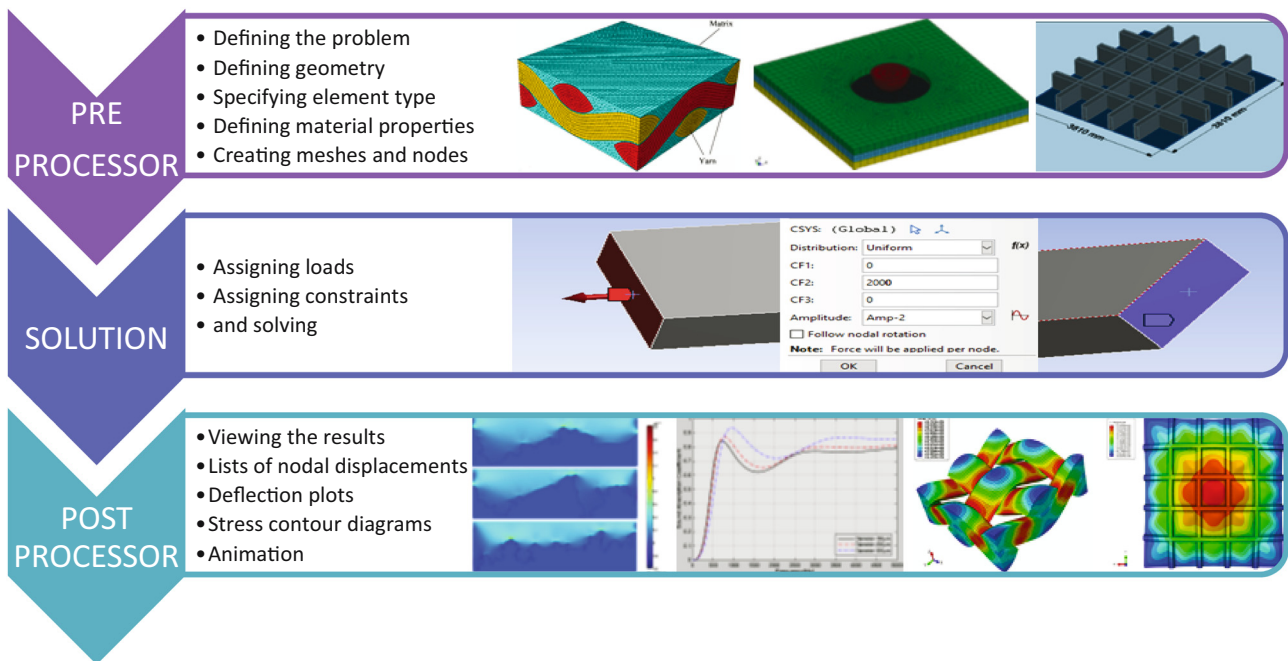
Figure 4: Overview of FEA adapted from [68].

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

only [88]. 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 [89]. 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 [91], for example, in mechanical loadings, the direction of applied forces indicates if this analysis is tensile, shear, flexural, impact, and so on [92].

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 [67]. When PBC is selected, the simulation outputs characterize a macro-structure 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 [93]. 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 [94]. Currently, various tools like EasyPBC in ABAQUS and material designer in ANSYS are being utilized to study the RVE of NFCs [95]. 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.) [96], such as parametric, genetic algorithm, TOPSIS, ANSYS parametric design language (APDL), and fuzzy logic [97]. 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 PLANE182	SOLID45 SOLID185	SHELL63 SHELL181	BEAM3/44 BEAM188
Quadratic	PLANE82/183 PLANE2	SOLID95/186 SOLID92/187	SHELL93	BEAM189

Figure 5: Elements type [90].

Table 1: Summary of research that involved analytical methods to study NFCs

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	Ref.
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	[98]
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	[99]
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) • Standard micromechanical models can be applied to natural fiber systems with mixed success	[57]
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 $i = N$)	• Tensile, flexural, and thermal • Once the model was corrected, it predicted very well the temperatures in the mold	[100]
Flax+51/–52°	Epoxy	Tsai–Hill, Tsai–Wu, Hashin, and Puck failure theories	Stiffness, strength and interaction	Matlab	Failure criteria	• Parametric optimization • Tension and compression • Hashin and Puck failure theories are recommended because they have the smallest error compared to experimental data	[101]
Flax laminates	Epoxy	Mesoscale damage theory	Mechanical response, stiffness degradation, and inelasticity			• Cost-function minimizing optimization • Tensile • The damage model and flax-specific parameters can be combined with user-defined material characteristics	[102]
Coconut coir and rice husk	Granular materials	Johnson–Champoux–Allard	Sound absorption	Matlab	Acoustic	• Impedance tube	[103]

Table 1: Continued

Fiber type, size and orientation	Epoxy/hardener	Analytical	Platform	Analysis type/ boundary conditions	Objective of the study	Optimization algorithms/physical experiments and validation/key findings and remarks	Ref.
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)		Matlab		Wear rate and surface coating	• Fuzzy logic Optimization • Wear test and SEM • Fuzzy approach performed better assessment on surface coating quality	[96]
Jute woven	PU	Hirsch, Cox, Halpin T-sai, and mass fraction (MFS)	Matlab	Mechanical	Tensile strength and Young's modulus	• Tensile • Cox, Hirsch's, and H.T-sai models are reliable and predictable models (for mechanical properties)	[58]
B & Jute	Recycled high density polyethylene/ polypropylene	Variable order creep model	Matlab	Mechanical	Creep behavior	• 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 numerally 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

Table 2: Numerical M&S of thermal, acoustic, and vibration properties of NFCs

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	Ref.
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 • Finite element analyses reveal the success of L-lysine templated coatings	[107]
Flax	PE		Wave FEA	Dispersion curves	ANSYS		Lamb waves	• Genetic algorithm • Tensile • Wave FEA is more convenient for such analysis types	[108]
FlaxCar Hood	Vinyl ester		FEA	Aerodynamic	Nastran/ Patran		Aerodynamic	• Full-scale static structural test • FEA and experimental results showed high agreement	[109]
Hemp car mirror	Acrylic	Nonlinear transient heat transfer	FEA	Curing Behavior	COMSOL	Neumann boundary conditions	Thermal	• Heat compression molding • Simulation procedure is numerically valid and stable and provides reasonably accurate predictions	[110]
Hemp sandwich	Bio-epoxy		FEA	Sound transmission loss	ANSYS		Acoustic	• Shear, compression, and Tensile • FEA and experimental results were in high agreement	[81]
Hemp & e-glass electronic rack in helicopter	Epoxy	Life cycle analysis	Static and dynamic FEA	Design	Nastran			• Results are promising from the structural point of view	[111]
Jute and ramie plies	Polyester	Halpin–Tsai	FEA	Free undamped vibration	ANSYS	Simply supported	Vibration		[112]

Table 2: Continued

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	Ref.
						edges, free edges, and clamped edges		• SEM, tensile, water absorption, and swelling thickness • Ramie, jute, and ramie/jute mode shapes as well dimensionless frequency agreed with the literature	
Bamboo, jute, coir & sisal bricks	Clay		FEA	Thermal conductivity	ANSYS		Thermal	• Porosity, bulk density, water absorption, and thermal conductivity • The model is applicable as highest variance between FEA and experimental was 7.8%	[113]
Agave	Epoxy and hardener	Fick's law	FEA	Moisture diffusion	Abaqus		Moisture diffusion	• Water absorption and SEM • Results showed that mass diffusion appeared to follow Fick's diffusion performance in composite specimens	[114]
Maise	Polyester		FEA	Deflection and stress properties	ANSYS			• SEM and X-ray diffractometer • FEA values are acceptable with proper assumptions	[115]
Rice husk window frame	PE		Injection molding	Design	Moldflow			• Further work is required to enhance the precision analyses of the rice husk/ PE NFC	[116]
Areca sheath 25, 27 & 29 mm	Epoxy		FEA	Effect of fiber length	ANSYS		Dynamic frequency response	• Fast Fourier technique • FEA results highly agreed with were experimental findings	[51]
B-Boron	Epoxy	Hamiltonian system and Symplectic	FEA	Critical buckling loads, fundamental frequencies and	ANSYS	Simply supported edges, Free	Buckling and Vibration	• Analytical and FEA results were in high agreement	[117]

Table 2: Continued

| 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	Ref.
Luffa	Epoxy	superposition method Hamilton's principle	FEA	corresponding mode shapes Deflection and frequency	MATLAB	edges, and clamped edges		• Dynamic structural behavior (frequency responses), flexural strength (central deflection), shear modulus, and Young's modulus • Findings are highly accurate for both parameters, layers' number, and modular ratio	[118]
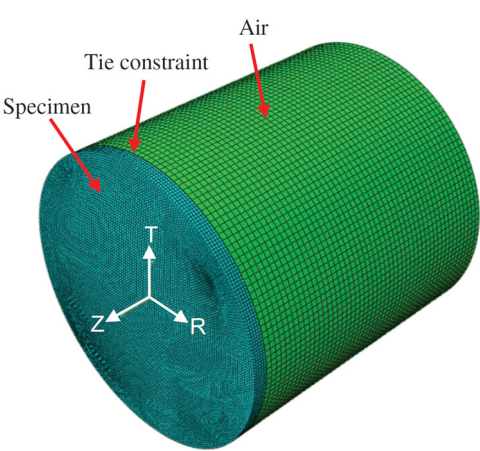
Figure 6: Mesh of STL specimen with air [50].

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.
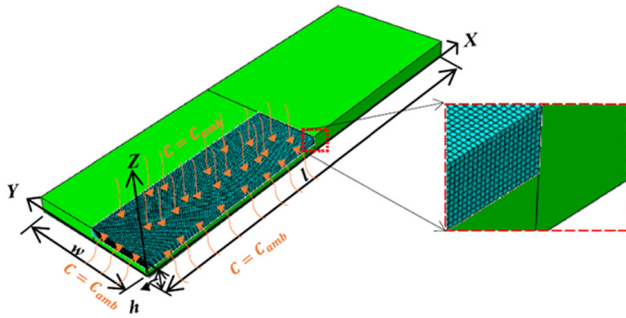
Figure 7: Moisture diffusion model and its mesh [114].

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 mesco-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].

Table 3: Numerical M&S of tensile and elastic behavior 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	Ref.
Flax 46.2 WT%	POM		FEA RVE (homogenized)			PBCs	• Tensile, SEM • Results obtained from RVE and FEA models significantly agreed with experimental results	[121]
Flax one by one top-hat stiffened composite plate	Epoxy	Grillage	FEA	Stresses & strain	Abaqus	Simply supported boundary conditions	• 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 • FLC and MSF criteria can accurately predict failure regions in all specimens	[123]
HempNaca cowling of an acrobatic ultra-light airplane	Epoxy	Maximum strain and Tsai–Wu	FEA	Mechanical properties	Fluent and ANSYS)		• Tensile, three-point bending and SEM • FEA and experimental results were different	[124]
Hemp 30 WT%	PP		FEA (RVE)	Mass fraction, tensile	Kebir simulation platform		• Tensile • PF approach could be considered as a complementary technique to micro-mechanical approaches	[125]
Hemp/Jute Hybrid30°,45° & 90°	Epoxy & Polyester			Mechanical properties	ANSYS		• Tensile, flexural, impact, specific gravity, water test, and hardness tests • High agreement was exhibited between FEA and experimental results	[126]
Jute 45°–90°	Epoxy		FEA	Tensile behavior	Siemens PLM NX 10.0		• Tensile testing and SEM • Simulation outputs significantly agreed with tensile testing 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		• Bulk tensile • Trapezoidal law reproduces the experimental behavior with a reasonable level of accuracy	[128]
Jute	Epoxy	Rule of mixiture, Weibull distribution	FEA	Tensile, strain, and elastic modulus	MENTAT & MARC		• Predicting failure stress and tensile strength were	[129]

Table 3: Continued

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.
							significantly improved by updating fibers' strength with accordance to their length postfailure.	
Jute/banana hybrid	Cashew nut shell resin		FEA	Strength	Solidworks, ANSYS & Minitab		• Tensile • FEA and experimental results are close	[105]
Banana	Polystyrene	Chamis model, Nielsen elastic model, Halpin–Tsai model, and the ROM	FEA (RVE)	Elastic properties	ABAQUS	PBCs	• The phenomenological analytical model estimations highly agreed with FEA results	[95]
Sisal and banana	Epoxy	ROM and Halpin–Tsai	FEA	Elastic Properties	ANSYS		• Tensile and SEM • The FEA combined with the micromechanical analysis had the ability to describe the interface state of the NFC phases	[130]
Sisal/coir hybrid	Epoxy		FEA (RVE)	Mechanical properties	ANSYS		• Tensile • Significant agreement between FEA and experimental results	[131]
Agave	Epoxy	Linear elastic orthotropic model	FEA	Effect of joint geometry on the strength	ANSYS		• Tension • Tensile strength of lap shear joints was extremely lower than plain NFC, dissimilar to intermingled fiber joints and laminated fiber joints	[132]
Nettle & grewia optiva	Polylactic acid and polypropylene		FEA	Joint strength	COMSOL		• 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	[133]
Pineapple	Epoxy	ROMs, modified rule of mixtures (MROMs), chamis model,	FEA (RVE)	Mechanical properties	ANSYS & Matlab	$x, y, z = 0$	• Electronic tensometer and single fiber pull-out	[134]

Table 3: Continued

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.
		Halpin–Tsai model, Hashin and Rosen model					• MROM as well as Chamis model showed high accuracy	
Pulp ellipsoidal	Poly lactic acid		FEA	Dimensions and orientation of fiber agglomerates	ANSYS		• Tensile test, SEM • The predicted strength using the stress concentration factor theory disagreed with experimental findings	[135]
Henequen laminates	PE	Photoelastic	FEA	Fiber curvature effect on the tensile properties	NISA		• Tensile test • Much better agreement was obtained after decreasing the fiber efficiency by using an average length value to compensate for the fiber curvature in the strength properties	[136]
Wood 60 WT%	18% PE and 12% PP		FEA	Joint strength	Yamada-Sun failure criterion in ABAQUS	Simply supported	• Tension • Predicted and experimental results are in high agreement	[137]
Wheat straw four fiber lengths	PP		FEA	Microstructural behavior and microcellular-voided	AutoCAD and Abaqus		• Tensile and SEM • The FEA curves are well matched in general to the experiments	[138]

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	Ref.
Flax	Vinyl ester		FEA	Impact			• Impact and compression • The structural design and test showed that the designed bonnet structure is acceptable	[140]
FlaxHoneycomb	Thermoplastic resin		FEA	Impact	Abaqus		• Impact • Agreement between numerical results and experimental data	[53]
FlaxLaminates	PP		FEA	Flexural property	.Patran/Nastran		• Numerical results agreed with experimental results	[141]
Flax	PE	Experimental modal analysis	FEA	Mechanical	Matlab	Free boundary conditions	• Classical static tests • Authors had to change the mechanical characteristics assigned for Finite element model due to the discrepancies between FEA and experimental results	[142]
Basalt & Flax (Vf 60%) high-pressure vessel	Epoxy		FEA	Burst pressure	CATIA V5 & ANSYS		• 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 • Experimental ultimate moment capacities were predicted using the numerical models with a variation mean of 0.99 and coefficient of 0.06	[144]
Hemp lass fibers2–4.5 mm < 30 WT%	PP		FEA	Impact	LS-DYNA		• Tensile • FEA results and macro-cracks agreed with experimental results	[145]
Hybrid kenaf/glass	Epoxy		FEA (Impact)	Deflection, strain energy, and the rib possibility	Catia and Abaqus		• TOPSIS • Experimental work should be done to validate the results	[146]
Ramie triangular structure	PMI foam	Solid model method, beam model method, and simplified method (SM)	FEA	Load-carrying capacity	ANSYS		• APDL • Four point bending • SM and BMM have lower accuracy than SMM	[147]
Wood	PVC	Classical beam theory	FEA	Flexural strength	ABAQUS	Simply supported	• Compression, tensile, and flexural	[148]

Table 4: Continued

| 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.
						boundary condition	• FEA results exhibited higher accuracy compared to analytical findings	[149]
Wood pallet	RPP		FEA	Static deformation	SolidWorks and CosmosWorks		• Shadow moire • Simulation and deflection results showed highest agreement at the pallet center	
Rice husk, radiata pine, and poplar wood ply	HDPE		FEA	Flexural strength	ABAQUS		• Optical micrograph, impact, flexural, creep, and thermal expansion • FEA findings indicates that the NFCs comprise orthotropic flexural characteristics that rely on the angle of fiber orientation	[82]
Wood3D printing	Tango plus	ROM		Mechanical properties	ANSYS		• Compression • Simulations results agreed with and experimental results	[150]
Human hair			FEA	Stress distribution	ANSYS		• Some of the properties of proteins in hair cannot be fed into the material properties and the provision is lacking, the accuracy may not be high	[151]
Oil palm	Polyethylene		FEA	Fiber pull-out resistance	MATLAB and ABAQUS		• SEM, X-ray microtomography, and degree of grafting • FEA model proved that the addition of silica bodies improves the performance of the NFC	[152]
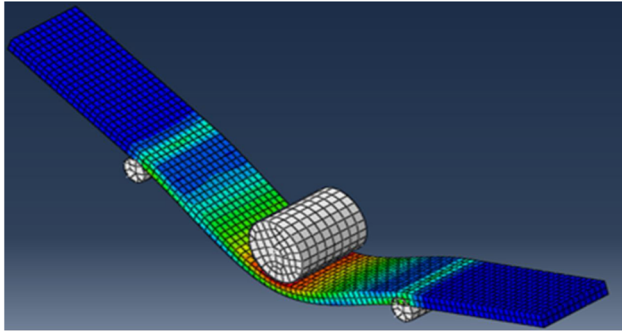
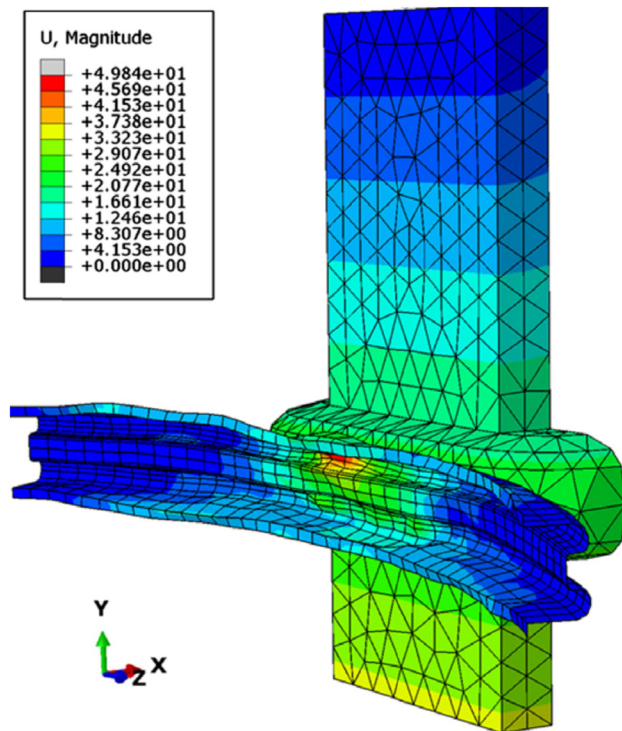**Figure 8:** Agave NFC bending analysis [153].

Figure 9: Displacement profile of double hat profile after impact [146].

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.

Conflict of interest: The authors declare no conflict of interest regarding the publication of this paper.

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