Composite Structures 275 (2021) 114392

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Damping behavior of plant fiber composites: A review

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ARTICLE INFO

Keywords:
Damping
Loss factor
Dynamic mechanical analysis
Plant fiber
Composites
Energy dissipation

ABSTRACT

This paper reviews the damping characteristics of plant fiber composites (PFCs) with particular attention regarding their performance with respect to that of synthetic fiber composites (SFCs). Indeed, PFCs have become increasingly popular in many application fields. Their specific characteristics when compared to those of synthetic fibers, such as glass fibers, make them good candidates to improve the damping behavior of composite materials and structures. The influences of mesoscale and microscale parameters as well as surrounding conditions are reviewed in the present paper. Contradictory reports are sometimes found, and the existing knowledge on the damping behavior of PFCs is sometimes deficient or ambiguous. Some key points, such as the variability, hierarchical aspects and sensitivity of mechanical properties, are thus discussed. This review provides a first reference for the factors that affect damping properties in PFCs to be used in engineering applications in various fields, including automotive parts, aerospace components, and musical instruments. It also highlights the current shortcomings of knowledge on the damping of PFCs. The Ashby diagram presented here, built from data available in the literature, constitutes a first tool for selecting materials considering the compromise between the loss factor and stiffness for engineering design considerations.

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https://doi.org/10.1016/j.compstruct.2021.114392
Received 28 August 2020; Revised 30 June 2021; Accepted 19 July 2021

1. Introduction

The invention of mechanical equipment accelerated the process of industrial development. Human requirements for machinery were not limited to high-efficiency characteristics but began to place greater value on comfort, performance and safety. Therefore, engineers began to look for different kinds of damping materials to reduce the effects of vibration and noise [1,2]. The use of damping materials improves people's living and working conditions and creates quiet and comfortable surroundings. With the development of the petrochemical industry, oil sources began to expand from the original fuel to byproducts [3–5]. Resins, asphalt, and rubber began to enter the field of large-scale industrial applications, especially for reducing vibration [6]. However, these materials cannot be used alone due to their low stiffness. In most cases, they are used together with wood or metal sheets in sandwich structures to compensate for the shortcomings of the individual components. A sandwich structure has characteristics of sound insulation and vibration damping properties that cannot be provided by a single material in addition to enhanced strength properties compared with those of pure wood board or metal plate [7–10]. With the development of high-strength fibers such as glass fibers and carbon fibers, attempts have been made to mix fibers and polymers in a specific ratio to manufacture fiber-reinforced composites [11]. This type of material has outstanding performance in terms of specific strength, specific modulus, fatigue strength, impact resistance, damping and devisable characteristics compared to that of pure metal materials or polymers [12,13]. In particular, it is currently desirable to reduce energy consumption by using lightweight materials, and the advantages of composite materials in this respect have led to a significant trend in their use to replace traditional materials, especially in the fields of aerospace, transportation, wind power, etc. [14–16]. When composite materials began to be of interest, many studies focused on increasing the strength, modulus, and crashworthiness of structural components [17]. At present, composite materials are also designed to improve the damping performance of structures while retaining other primary structural functions.

However, the large-scale application of petroleum-based compounds has also brought about some adverse effects. Engineers should now consider the environmental impact at each stage of the life cycle during the implementation of damping materials since petroleum-based products are difficult to degrade in nature [18]. Plant fibers have become increasingly considered because of their abundant reserves, renewability, low cost, quick acquisition and processing, degradability, light weight, relatively high specific modulus, and other advantages [3,18–20]. The properties of many plant fibers derived from hemp, flax, jute, ramie, kenaf, banana, agave, doum palm, pine cone, etc. have been investigated [21–24]. Plant fibers have become a sustainable material of choice in automotive parts, aerospace components, musical instruments, and other applications. In particular, plant fibers are used in automotive parts in ceilings, coat racks, seatbacks, and instrument panels [25,26]. To date, plant fiber-reinforced composites (PFCs) have been mainly used as a low-cost and sustainable solution to save mass. PFCs can also overcome the mechanical and physicochemical properties of conventional composite materials to a certain extent, and they can solve some critical problems that cannot be addressed by traditional materials in engineering structures. Some of their intrinsic properties, for instance, their natural damping, can be exploited to implement new and advanced functionalities in structures.

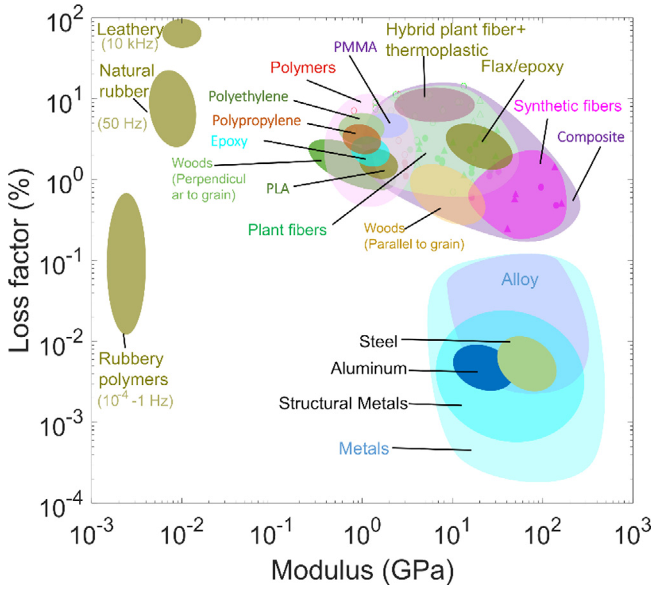

Fig. 1. Ashby diagram: loss factor vs. modulus (summarized from refs. [10,27–62]; triangles represent measurements obtained by modal tests in the first mode (approximately 10–200 Hz) and ambient temperature, and circles represent measurements obtained by DMA tests at 1 Hz and ambient temperature).

Indeed, the literature clearly notes that the loss factor of PFCs is generally much higher than that of synthetic fiber composites (SFCs). PFCs have loss factors between 0.7% and 14%, while the values typically range between 0.24% and 2.5% for SFCs. The loss factor and storage modulus (or Young's modulus) values at ambient temperature were collected from the literature and plotted in a stiffness-loss map as proposed by Lakes et al. [51,63] for different material families (Fig. 1). Due to their internal structures, metals exhibit high stiffness and a low loss factor. In contrast, the chemical composition of polymers results in low stiffness and a relatively high loss factor. The combination of components in composite materials is currently the best way to provide compromises between stiffness and loss factor. In this category, PFCs globally perform better than SFCs in terms of damping.

The sources of energy dissipation in fiber-reinforced polymer composites are quite well described and documented in the literature [12,64–67]. These sources mainly include (1) the viscoelastic nature of the matrix and/or fiber materials, (2) damping due to interphases, and (3) damping due to inelastic and irreversible behaviors such as damage and/or plasticity. In contrast, the damping behavior of PFCs, even if already documented [27,68], has not been fully elucidated. Furthermore, various effects on damping are observed when plant fibers are introduced into polymer matrices depending on the polymer nature, stiffness, textile architecture and yarn lengths [27]. The physics underlying the particular behavior of PFCs is not yet fully understood and requires additional research efforts. Additionally, the length scales corresponding to all dissipation mechanisms that may occur in these multiscale materials can result in damping occurring at various time (or frequency) scales. Therefore, this paper aims to review the current knowledge on the damping behavior of PFCs to outline the needs for future research activities and to evaluate the potential of composite materials to reach specific levels of damping. Throughout the paper, the term *damping* is used to describe the physical mechanisms corresponding to energy dissipation that occurs when materials are subjected to cyclic deformations, while the term *loss factor* refers to the ratio of the energy dissipated per cycle to the maximum strain energy stored in the material during the cycle, which is widely used to describe the damping performance of materials and structures.

In this paper, we review the existing studies on the damping behavior of PFCs. The classical experimental techniques used to characterize the damping behavior of composite materials are first discussed in Section 2. Section 3 reviews the studies available in the open literature. The analysis is performed using different key parameters at the mesoscale (including reinforcement type and stacking sequence), at the microscale (fiber, matrix, interface/interphase and porosity) and related to testing and environmental conditions (moisture and temperature). Section 4 discusses the current limitations of existing studies. Finally, conclusions are given in Section 5.

2. On the experimental techniques for the characterization of composite damping

In this section, the most widely used damping characterization techniques, such as dynamic mechanical analysis (DMA), modal analyses and wavenumber-based approaches, are briefly described.

2.1. Quasi-static and low frequency characterization: DMA

One of the most widely used nonresonance techniques for damping characterization is DMA. It is usually used to characterize viscoelastic materials with low stiffness, such as polymers or organic composite materials, and is widely used for the rheological analysis of polymers and elastomers, especially in the fields of chemistry and materials science [69]. In particular, the glass transition temperature can be identified through temperature sweep curves at different frequencies.

The storage modulus (E'), loss modulus (E'') and loss factor ($\tan\delta$) are usually identified from DMA tests to describe the viscoelastic properties of materials at various temperatures [28,33,69–72]. The temperature range of interest is generally investigated either through temperature ramps or temperature steps. In the latter case, isothermal conditions are often used with a stable-temperature stage of several minutes to ensure that the sample has reached a homogeneous temperature distribution [70,71,73]. The harmonic excitation is usually set between 0.01 Hz and 100 Hz in most existing studies since the DMA apparatus always exhibits mechanical resonances in the higher frequency range that affect the measurement [34,74–76]. Another essential factor that needs to be considered in DMA is the ratio of the stiffness of the sample to that of the apparatus: the stiffness of the sample should be much smaller than the stiffness of the system to obtain accurate test results, especially for the storage modulus [70]. Furthermore, the deformation of the sample should be kept in the linear viscoelastic range to meet the theoretical requirements [69]. Despite these limitations in terms of frequency, DMA remains a popular technique for the characterization of damping, in particular because the time–temperature superposition (TTS) principle, which is verified for a large set of polymers and composites, can be used to estimate damping and stiffness properties in the higher frequency range [69,70].

2.2. Low- to mid-frequency characterization: Modal analysis

Modal analysis is another common method for damping identification. The natural frequencies, damping ratios, and modal shapes of composite structures are estimated at certain resonances by using an external excitation source within a specific frequency range [10,77,78]. These methods are efficient for frequency ranges from the first eigenfrequency of the structure to mid-frequency range, which is typically reached when the -3 dB bandwidths of subsequent modes are superimposed on one another; hence, the results depend not only on the materials but also on the geometry and the boundary conditions. Several excitation signals and boundary conditions can be used for resonance testing. Techniques for damping measurement using the logarithmic decrement method (LDM) for free vibrations of beams have been reported [60,78–82]. The test configuration is important; several aspects are discussed in the literature, such as the location of the excitation, boundary conditions, accelerometer adhesion, and measurement interference[70,77,78,83,84]. Specific techniques for composite structures have been proposed for beams on complex shapes [85–88].

Since there is usually no heating or cooling device used in modal analysis tests, the samples are sometimes placed in a constant-temperature oven to maintain the required test temperature [7,89]. However, such a setup cannot generally be used to reach high temperatures because most instruments cannot tolerate excessive temperatures.

2.3. High-frequency characterization: Wavenumber-based approaches

Marchetti et al. reviewed several wavenumber-based approaches used for the characterization of the dynamic properties of composite structures in frequency ranges where modal analysis approaches become impractical because the increased modal density is too large [90,91]. The loss factor and storage modulus can be computed from the natural wavenumber obtained from high-frequency analysis.

However, this type of characterization has not been widely applied for PFCs at this time, so this frequency range is not addressed in this review paper. The works by Zhang et al. and Duval et al. represent first studies that remain to be completed in future research by the collection of additional data related to the damping properties of PFCs at high frequencies [48,92].

3. Review of studies on the damping behavior of PFCs

3.1. Mesoscale parameters

This section discusses the effects of mesoscale parameters (features of laminates) on damping given the issues of reinforcement architecture and stacking sequence.

3.1.1. Reinforcement type

Plant fibers can be processed into many kinds of reinforcements, such as short fibers, nonwoven fabrics, noncrimp fabrics, and woven fabrics. This variety of applications leads to composite mesostructures with significant differences. This section summarizes the effects of different kinds of reinforcement on damping performance.

Regarding short fiber composites, Senthil Kumar et al. [93] investigated the influence of fiber length and weight percentage on the free vibration characteristics. Their study concerned banana fiber and sisal fiber polyester composites. The results show that the fiber content influences the free vibration behavior more than the fiber length does. This result is attributed to the shear behavior at the fiber ends. The authors also claim that the damping of banana fiber is higher than that of sisal fiber owing to the smaller diameter of banana fiber and potential for a thicker interface, as reported by Bledzki et al. [94].

Sreenivasan et al. reported that the dynamic characteristics of *Sansevieria cylindrica* fiber-reinforced polyester matrix composites are significantly influenced by increases in fiber length and fiber loading but not by geometric progression [35]. In contrast, the loss factor of short SFCs is higher than that of long fiber composites because long fibers limit the movement of polymer molecules [95–97]. The fiber–matrix interface is considered a significant source of energy dissipation of discontinuous SFCs since short fibers increase the number of fiber ends and fiber–matrix interfaces [95]. However, comparisons of discontinuous, short and long PFCs under the same conditions have been rarely reported.

When woven reinforcements are considered, most authors report a reduction in damping level compared to unidirectional reinforcements (UD) in transverse direction such as tapes [27,47,98–100]. Among the different weave patterns investigated, the loss factor in huckaback-type woven composites is higher than that of plain, satin, twill, and basket woven composites because the performance depends on the interlacement between the warp and weft directions, which increases the interactions between the fiber and matrix [101]. Additionally, twisted yarns generally induce a decrease in Young's modulus because of the induced crimp but increase the damping through enhanced interyarn friction [102].

However, the existing reports have not found any significant effect of long fibers on damping compared to the effects of short fibers and continuous reinforcements [32,48]. Further research efforts focused on comparing the effects of these three types of reinforcement on damping performance are still required.

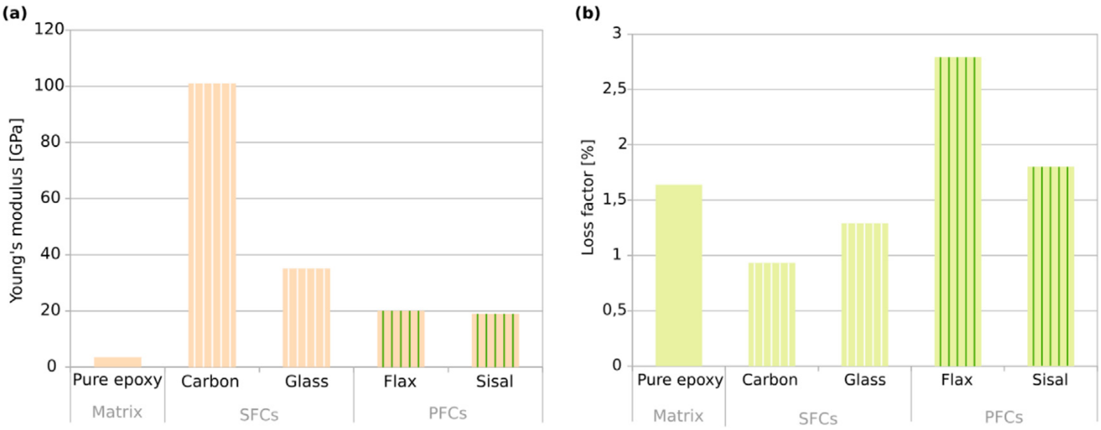

Fig. 2. (a) Young's modulus and (b) loss factor of UD fiber-reinforced epoxy composites in the longitudinal direction (measured by DMA tests at 1 Hz and ambient temperature), summarized from refs. [27,31,33]

3.1.2. Stacking sequence

The effect on damping of different stacking sequences using some common arrangements, such as 0°, 45°, and 90°, has been investigated by several authors. Regarding symmetric layups, composites often show a lower damping level in the longitudinal direction at 90° in the outer layer and the highest damping level at 0° in the outer layer [103]. The authors indicate that this pattern is related to the flexural properties of the composite structure. In particular, the shear effect is found to enhance resistance to fiber mobility and increase the effective load transfer between the fiber and matrix [104].

Stacking sequences with long UD fibers and randomly oriented short fibers have also been studied. The results show that the stacking sequence does not influence the dynamic mechanical properties (including storage modulus and loss factor) of the studied PFCs in the longitudinal direction [105].

Research on hybrid fibers (flax and E-glass fiber woven fabric) shows that the best damping performance is obtained in the longitudinal direction when flax fibers are distributed in the outer layer [47]. Y. Li et al. found that the damping properties in hybrid composites (flax and carbon fiber) are greatly influenced by the position of the flax fiber layers, which are supposed to dissipate more energy than those with synthetic fibers in fiber direction [45]. Contradictory results have also been reported in the latest literature [106] for hybrid composites made of basalt and flax woven fabrics (0/90 orientation). The authors observed that the maximum damping is obtained when basalt is in the outer layer [106,107].

3.2. Microscale parameters

This section discusses the effect of microscale parameters, such as fiber type, fiber orientation, fiber volume fraction and microstructure, on damping. Moreover, fiber treatment methods, the interface between fiber and matrix, and porosity are also discussed.

3.2.1. Fiber

3.2.1.1. Fiber type. This section summarizes the damping characteristics of composites with different types of fibers.

Fig. 2 presents a summary of loss factor and Young's modulus values collected from the literature for epoxy matrices with different UD reinforcements made from different types of plant and synthetic fibers. The presented results were collected using DMA tests at 1 Hz and ambient temperature.

As expected, the Young's modulus of the composites in the longitudinal direction is significantly higher than that of neat epoxy. The stiffening factor varies as a function of fiber type. Among the results in Fig. 2 (a), compared with the stiffening factor of pure epoxy, the value for carbon fibers is approximately 25 times greater, that of glass fibers is 8 times greater and that of flax fibers is at least 5 times greater.

It can also be observed that the fiber type has a significant effect on the damping properties (the fiber volume fraction can also be a factor, but most authors do not directly address this factor). The addition of synthetic fibers into epoxy induces a decrease in damping in the longitudinal direction. The results in Fig. 2 (b) indicate a decrease in damping of approximately 40% and 20% for carbon fibers and glass fibers, respectively, compared with that of neat epoxy. This result is attributed to stress transfer from the matrix to the fibers and to the fact that the presence of stiff fibers limits the chain mobility in the matrix, which implies that the friction of the intermolecular chain is reduced [49,108,109]. Conversely, the addition of plant fibers increases damping. Damping is approximately 70% higher with flax fibers, as shown in Fig. 2 (b). This increase is attributed to the friction at the interface but may also be due to the intrinsic damping capacity of the fibers themselves [27,68,102]. However, damping is also sometimes reported to decrease in flax/epoxy composites [50] compared with that of pure epoxy [27], but this comparison may ignore the impact of different test methods. Fig. 2 also shows that the loss factor obtained with flax fibers is higher than that obtained with sisal. More tests including a large variety of fibers in the form of continuous UD reinforcement and with the same matrix and similar volume fractions are recommended to better evaluate the influence of fiber type on the damping of composites.

It was shown by Hadiji et al. that nonwoven composites reinforced by plant fibers present higher loss factors than glass-based composites [149]. The loss factors of polypropylene composites based on nonwoven hemp, flax and kenaf reinforcements are 2 to 25 times higher than those of glass-polypropylene (PP) composites. Among the tested plant fibers, higher damping is obtained with hemp and flax.

Some authors also show that the incorporation of ramie fiber into epoxy tends to increase damping due to weak adhesion, which indicates low interfacial shear stress [28]. Another reason that may explain the diverse damping results with these plant fibers is the difference in the inherent morphology of the fiber surfaces [93].

The damping performance of hybrid PFCs has also been reported. The results show that hybrid PFCs with banana/coconut sheath or kenaf/bamboo possess higher loss factors than single fiber composites [112]. Hybrid fibers combine the advantages of their components and achieve superior performance that cannot be obtained from only one type of component; authors also claim that damping values are higher for all hybrid composites, possibly due to greater energy dissipation and restricted molecular mobility at the interface [113–115].

3.2.1.2. Fiber microstructure. Plant fibers differ from conventional fibers in terms of composition and microstructure. Indeed, plant fibers often have unique microstructures and morphologies, notably different cell wall layers and a complex cross-sectional area that varies along the fiber length [111,116–119]. In addition to this complex morphology, plant fibers have a polymer-based composition and a very hierarchical organization with different layers and sublayers made of a mixture of carbohydrates and polyphenols [120,121]. This structure imparts viscoelastic properties [122–126]. These particularities also lead to specific static and fatigue behaviors that have been widely studied in the literature, including nonlinearity [127,128], stiffening effects [129] and moisture activation of some mechanisms [130–132].

The fiber microstructure could also be the origin of specific energy dissipation mechanisms and damping behavior. Few studies have investigated the damping behavior of plant fibers [133–136], and unfortunately, the influence of the fiber microstructure on the damping of PFCs themselves has not been studied thus far.

PFCs are made of single individual fibers but also bundles of fibers. Friction at the interface between individual fibers within the fiber bundle and internal friction within the fiber wall (between the heterogeneous polymers constituting the wall and particularly between the rigid cellulose microfibrils and the amorphous polymers in which they are embedded) [27,68,102] are also potential sources of damping. Additionally, plant fibers have a finite length, in contrast to synthetic fibers. The effect of such discontinuities, even under continuous reinforcement conditions, on the damping behavior of PFCs is unclear and deserves to be investigated in the future.

3.2.1.3. Treatment methods. Several investigations on the effect of pretreating plant fibers to achieve better mechanical performance in PFCs have been reported. This section summarizes the relevant treatment methods and their effects on composite damping; the considered methods include functionalization using nanotubes and chemical treatment, which may change the interface state.

Carbon nanotubes (CNTs) have been proposed to enhance the damping properties of PFCs and SFCs [137]. Damping is further enhanced by the stick–slip action of CNTs that takes place at the CNT/-matrix interface. In addition, the penetrated CNTs interact with microfibrils in the S2 cell wall of plant fibers, leading to effective stress transfer from the matrix to the microfibrils, which contributes to energy dissipation and enhanced damping properties [45]. In contrast, some authors claim that the presence of stiff fibers limits the chain mobility in the matrix, which implies that the friction of the intermolecular chain is reduced [49,108,109].

Other studies have reported the effect of microfibers. The addition of macro/microfibers decreases the damping characteristics of PFCs and increases the storage modulus, as the added fibers act as barriers to the free movement of the macromolecular chains. In contrast, unfilled matrices have the highest damping ratio, indicating a significant degree of mobility [138].

The above results demonstrate that the improved interactions derived from chemical treatment makes PFCs and SFCs more compatible and causes them to have better adhesion than untreated fiber composites [139,140]. Moreover, some authors claim that a high-quality interface tends to lower energy dissipation, resulting in a lower damping peak value [141,142]. The effects of chemical treatments such as acid, alkali, ethanol, and silane agents have been studied. Chemical modifications cause hemicellulose removal, which increases the number of hydrogen bonds between the modified fibers and the matrix [143]. Alkali and potassium permanganate treatment of PFCs leads to higher damping than that described in earlier reports [41,144]. The authors explain that the damping characteristics of heterogeneous systems are not only based on interfacial bonding but also depend on different parameters, such as changes in interfacial thickness, fiber bending, broken fibers, matrix cracking and the formation of cavities due to fiber pullout [47].

Different chemical reaction times result in little difference in the height of the loss factor peak [32]. Some authors claim that a reduction in the amplitude of loss factor peaks means a well-combined load capacity due to good stress transfer at the interface [30,37]. Silane-treated fiber composites lead to better fiber/matrix interactions than other treatments [145,146]. Alkali- and silane-treated surfaces are rough and are formed by the elimination of lignin and hemicellulose compounds. A rough surface enhances fiber/matrix adhesion and increases both the glass transition temperature and loss factor in the glassy state [145,147]. This effect can also be explained by the combination of the shear stress concentration at the fiber end and the additional viscoelastic energy dissipated in the matrix material [146,148,149].

Yadav & Gupta found that fiber coating (polylactic acid (PLA) + chloroform) followed by chemical treatment can improve damping at ambient temperature and could also be considered a practical approach to improve the performance of composite materials for advanced applications [150].

In general, the effect of treatment on composite damping is based on changes in the fiber/matrix interface. The quality of the interface determines the change in damping, but some conflicting conclusions remain.

3.2.1.4. Fiber volume fraction. PFCs with a single type of reinforcement in the form of short fibers have been studied to investigate the influence of the fiber volume fraction on damping properties. Sathishkumar et al. showed that damping, measured using the free vibration technique, increases with fiber content (up to 50 wt%) for sisal but decreases with fiber content for banana fiber composites [93]. This result is attributed to the difference in the inherent morphology of the fiber surface [93]. Etaati et al. also investigated the influence of the fiber volume fraction on the damping behavior of short hemp fiber-reinforced polypropylene composites [42]. They reported that the composite with 30 wt% noil hemp fiber showed the highest damping capacity among all investigated composites for fiber volume fractions between 0 and 60%. Tajvidi et al. indicated that the presence of a higher fiber content can considerably reduce damping, indicating that composite materials are more elastic at higher fiber contents [151]. The interface area increases with the number of incorporated fibers, which leads to stronger interactions. Therefore, the molecular mobility of the polymer decreases, and the mechanical loss that overcomes intermolecular chain friction is reduced [152]. As previously mentioned, other reports show that the dynamic characteristics are significantly influenced by increases in fiber length and fiber loading by changes in interface but not in a geometric progression, as in the case for *S. cylindrica* fiber-reinforced polyester matrix composites [35].

Among nonwoven composites, the loss factor of flax/PP composites decreases by approximately 20% when increasing the flax weight ratio from 30 to 70%. This decrease is attributed to the superior contribution of PP to damping [110].

Increasing the fraction of synthetic fibers in hybrid fiber composites (flax and carbon fiber) reduces damping [58], but there are also reports of increased damping [153], without a clear physical explanation of this observation.

In summary, the literature often presents conflicting conclusions on the impact of fiber content on damping considering the different types of fibers used and their architecture. Therefore, dedicated experimental studies and modeling approaches need to be established in future research to explain these inconsistent conclusions.

3.2.1.5. Fiber orientation. Different fiber orientations can be used during the design of composite laminates and structures. The damping performance of PFCs with different fiber orientations has been studied in recent decades.

The loss factor of flax/GreenPoxy 56 (GP56) composites was tested from 0° to 90° fiber orientation using a modal method [154]. The

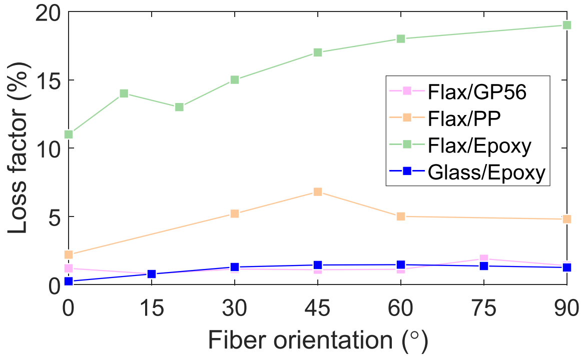

Fig. 3. Variation in the loss factor as a function of fiber orientation in UD composites in the longitudinal direction using modal tests: (a) flax/GP56 [38], (b) flax/PP [155], (c) flax/epoxy [60], and (d) glass/epoxy [156]

results show that the loss factor decreases as the frequency increases. This result is attributed to the high internal friction between cellulose and hemicellulose caused by the flax fiber microstructure, especially at low frequency [27,50,59,154]. A maximum loss factor is always found at $70^\circ - 75^\circ$ fiber orientation for different frequencies.

In other reports, the loss factor was found to first increase and then decrease with increasing fiber angle in flax fiber-reinforced PP [155]. Some authors show that the maximum loss factor is obtained at approximately 45° fiber orientation, which is similar to glass fiber composites and carbon fiber composites [156–158]. This phenomenon is attributed to the in-plane shear strain energy of fiber-reinforced composites, which is the maximum at this fiber orientation [109]. However, the global trend is that the loss factor for a fiber orientation at 90° is higher than that at 0°, as shown in Fig. 3, in which (a) and (b) are measured at approximately 500 Hz, (c) is obtained at approximately 300–400 Hz and (d) is measured at approximately 300 Hz.

Unlike UD PFCs, the loss factor varies slightly from the longitudinal direction (0°) to the cross direction (90°) in nonwoven PFCs [110]. Indeed, the anisotropy level is less pronounced in nonwoven PFCs than in UD composites.

It should be emphasized that testing UD composites at angles other than the longitudinal and tangential directions requires close attention to the experimental setup to guarantee the homogeneity of the strain and stress fields in the sample. Moreover, the identified properties correspond to coupled information between the material properties corresponding to the principal directions. For this reason, it may be preferable to focus only on the principal directions when using DMA-like tests or to use free-free vibration tests that are not affected by out-of-axis boundary conditions. Additionally, purely UD panels are rarely used in practical applications where cross-ply composites are preferred, whose properties can be identified from longitudinal and tangential data.

3.2.2. Matrix

This section summarizes some research results on the dynamic mechanical properties of conventional polymers and their PFCs.

Fig. 4 summarizes some dynamic mechanical properties of pure matrices that are widely used in industrial production. Thermoset polymers, such as epoxy, are the most widely used matrix for PFCs and SFCs due to the excellent adhesion of resin and the long lifecycle. However, thermoset polymers tend to be more brittle and less tough than thermoplastics [1]. The reason is that high loss factor values are associated with ease of movement of side chains, functional groups, segments, pendant groups, and even entire molecules in the polymer. Moreover, the loss factor is reduced by the presence of negatively charged atoms (such as oxygen and nitrogen) in the molecules, which reduces the motion of hydrogen bonding [160]. This phenomenon is also interpreted as a mechanism for damping in polymer blends provided by networks and interfaces [161]. Although thermoplastic polymers exhibit higher energy dissipation than thermosets, thermosets are often preferred due to their higher stiffness and better adhesion properties [1,162].

Results for materials with particle addition have also been reported. A mixture of agar particles restricts the mobility of the chains, which reduces the sharpness and the maximum value of the loss factor. The viscosity is substantially enhanced by fillers at a low shear rate, and in this case, the rheological behavior is utterly dependent on the composition of the polymer in the interfacial region [57]. It has also been reported that the incorporation of solid fillers into the polymer matrix could increase or decrease the damping of the polymer, depending on the quality of fiber–matrix bonding [32,76,163,164]. Additionally, the damping factor decreases with increasing biofiller content because the rigid particles restrain the mobility of the polymer molecules, raise the storage modulus, and reduce the loss factor [165].

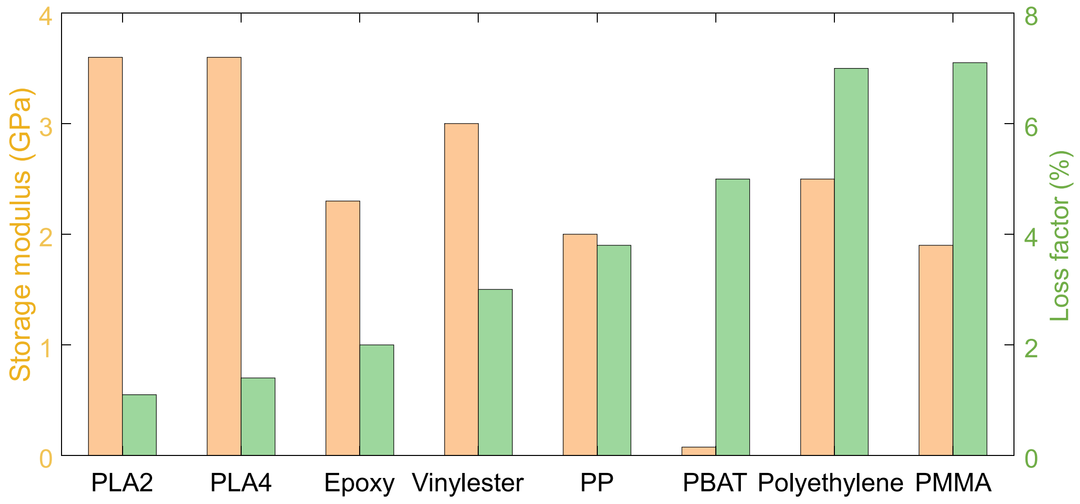

Fig. 4. Loss factor and storage modulus of different polymers at 1 Hz and ambient temperature, summarized from [27,28,36,39,61,71,159] (Polylactic acid 2, 4 (PLA 2, 4), Polypropylene (PP), Polybutylene adipate-co-terephthalate (PBAT), Polymethyl methacrylate (PMMA)).

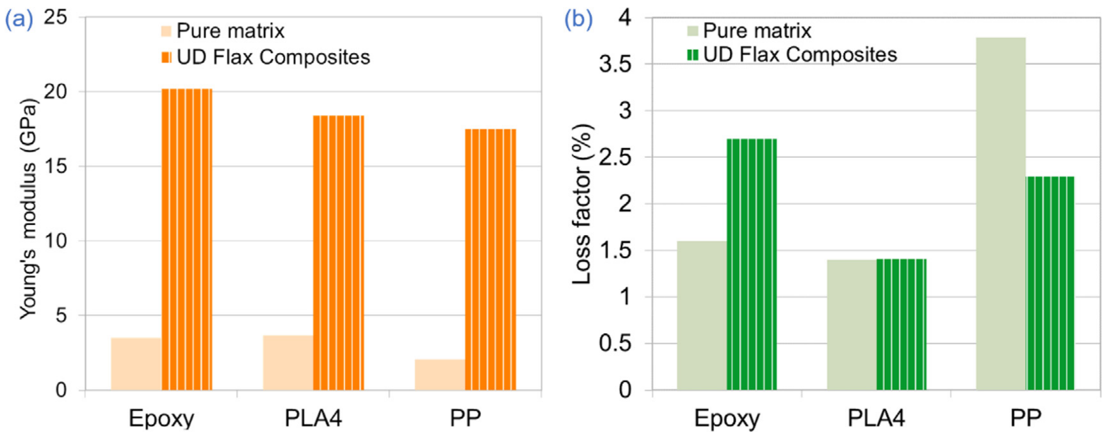

Fig. 5. Young's modulus (a) and loss factor (b) of flax composites in the longitudinal direction and of the pure matrix, measured by DMA at 1 Hz and ambient temperature (summarized from ref. [27]).

The Young's modulus and loss factor of the more widespread thermoset (epoxy), thermoplastic (polylactic acid 4 (PLA 4), and polypropylene (PP)) polymers used for flax composites are reported in Fig. 5 [27] for both pure resin and UD flax composites. Although the reinforcement is the same, their global damping is quite different. The addition of plant fiber to epoxy, PLA4, and PP results in a distinctly different trend in loss factor but a total increase in modulus. This effect occurs because of the interactions between the fiber and matrix and aspects discussed in the following section. These trends could also depend on the contribution of the internal friction in the fibers to the overall damping response [27].

3.2.3. Interface/interphase

As mentioned above, interfaces play a critical role in the damping properties of composites. The properties of interfaces depend not only on the manufacturing process but also on treatment, which was discussed in the fiber treatment section, as shown in Fig. 6. This section focuses on the original interface.

It has been reported that a composite with weak interface bonding tends to dissipate more energy than one with good interface bonding [49,166]. However, other reports show that increased damping can often be obtained by improving fiber/matrix adhesion, which may activate damping phenomena such as intracell wall friction between cellulose microfibrils and the hemicellulose/lignin matrix in each cell wall and intercell wall friction between cell walls [102].

In most cases, higher resin contents for most organic-based composites should lead to higher damping due to the viscoelastic properties of resin. However, in some cases, a reduction in the matrix fraction increases damping. This effect is due to the interface thickness and interface stiffness, which also play essential roles in damping mechanisms [12].

It was previously reported that the incorporation of stiff fibers affects the damping behavior of matrices by changing the movement of polymer chains [96,167–169]. In certain thermoset systems, the proximity of stiff fibers and the preferential adsorption and/or absorption of diffusible constituents, in particular low-molecular-weight curatives, on the fiber surface or in the fiber wall may impose a relatively high crosslink density, locally decreasing the damping behavior of the resin. This configuration may also lead to some softening of the matrix in the zone next to the interface because of the depletion of the curative [167]. This effect is particularly possible with plant fibers, which have a certain affinity and/or absorption ability with curatives. Plant fiber reinforcements are also generally composed of yarns of elementary fibers. The friction mechanisms between fibers (intra-yarn friction) and the friction between the yarns (inter-yarn friction) can increase the intrinsic damping with respect to that obtained with synthetic fibers [27].

Some studies show that the loss factor and stiffness of interleaf films play an essential role in the loss factor of interleaved laminates at test temperatures [170].

3.2.4. Porosity

Porosity is inevitable during the manufacturing of composite materials, particularly when using plant fibers. However, the influence of porosity on the damping behavior of PFCs is poorly discussed in the literature. A report on hybrid fiber composites (SFCs + PFCs) describes the effect of the existence of voids on damping characteristics. Damping is found to be not sensitive to the void content. This result might be due to the small void content in the samples and therefore small contribution [47]. Regarding nonwoven PP composites, a recent study by Hadiji et al based on modal analysis shows that the loss factor increases by 108.7% when the porosity changes from 9 to 64%

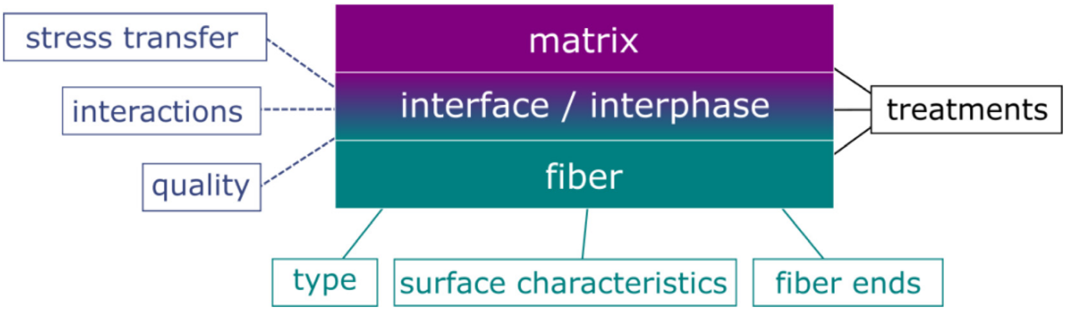

Fig. 6. Parameters related to the interface properties.

[110]. This result is attributed to poor adhesion between the fiber and matrix, leading to more energy dissipation [110,171].

Additional research on this topic regarding different types of PFCs, such as woven patterns and matrices (thermosets or thermoplastics), is necessary since not enough conclusions have been reached at this time.

3.3. Testing and surrounding conditions

3.3.1. Testing technique and frequency dependence

The testing techniques used may have an influence on the determined loss factor values [89]. Therefore, the damping results from DMA tests and modal analysis tests have been compared in some studies [60,70,89]. Regarding PFCs, Rueppel et al. describe damping measurement tests with three different strategies: DMA, LDM and vibration beam measurements (VBM) [60]. The values obtained from DMA and VBM differ significantly, which is attributed to air resistance effects, as the amplitude of vibration is larger during VBM [60,172]. LDM provides nonlinear decay for a material, and the authors recommend carefully considering the initial parts of the displacement curve during tests, especially for highly damping materials. It is thus essential to take into account the experimental techniques used when comparing the damping properties of different materials.

The damping properties may vary as the frequency changes. The loss factor of UD or twill flax fabric-reinforced epoxy composites shows a decreasing trend for low frequencies (<500 Hz) and then stabilizes at higher frequencies (500–2000 Hz) [38,59,154,173]. Assarar and Daoud explained that the vibration behavior at low frequencies results from the internal friction between cellulose and hemicellulose in plant fibers, and this kind of friction is more pronounced at low frequencies [27,38,59]. However, UD flax-reinforced polypropylene or epoxy composites exhibit a slight increasing trend at low frequencies (<1000 Hz) [50,155,174]. In addition, the damping properties of UD flax/PA11 composites were obtained over a large frequency range (2000–10000 Hz), and it was difficult to derive a trend due to the coupling of plate vibration with aerodynamic phenomena [43]. Therefore, an experimental technique that can eliminate the influence of air and show the contribution of each component (fiber, matrix and interface) to damping properties as a function of frequency should be developed in the future.

3.3.2. Environmental conditions

Researchers have also paid attention to the influence of some external factors in addition to the inherent factors of PFC components. In this section, the effects of the external environment, such as water aging or moisture content, temperature and various coupling conditions, are summarized.

3.3.2.1. Moisture.

The environment in which PFC materials are serviced is sometimes harsh, and in most cases, the environment exhibits changes in moisture content.

Plant fibers are sensitive to moisture and temperature due to the hydrophilicity of some of their wall constituents and to their hollow morphology [175–178]. Therefore, the hygroscopic properties and effects of such fibers need to be studied if PFC materials are to be used in engineering fields. Many factors affect the water absorption characteristics of PFCs. External factors such as temperature, manufacturing features such as the fiber fraction, fiber orientation, size and percentage of voids, and interface factors such as the exposed area, surface treatment, component hydrophilicity, and bonding quality of fiber–matrix interfaces have been proven to be critical influencing factors [179–181].

Generally, the absorption of water in PFCs is started by water entering the plant fiber through capillary transport. Materials with microcrack defects also accelerate the diffusion of water. Plant fibers absorb water and cause the fibers to swell, leading to microcracks in the fiber–matrix interface area [182,183]. Moreover, this diffusion is enhanced by the aging of the material itself [181], which causes the deformation and mechanical properties of PFCs to decline [184,185]. Many studies have shown that good interfacial properties between the fiber reinforcement and matrix or better moisture absorption resistance can reduce the effect of moisture absorption on plant fibers [184].

Damping generally increases with increasing relative humidity in PFCs at the expense of Young's modulus. The damping of wood fiber composites is more sensitive to relative humidity than is Young's modulus and changes by 26% to −13% under dry to humid conditions, respectively, as shown in Fig. 7 (a) [186]. Berges et al. indicated a 50% increase in damping ratio after water vapor saturation of flax-tape/epoxy composites [188]. Reports on SFCs are also available, but the effect of relative humidity on stiffness is not significant [130,131]. In addition, the matrix of a composite material usually exhibits plasticization and swelling when exposed to moisture. Damping is very sensitive to changes in the stiffness of the outer layer due to the plasticization of macromolecular networks, which exacerbates energy dissipation [189]. In addition, the moisture present in the areas at the interfaces increases friction losses [131].

Not only are PFCs more affected than SFCs by the matrix in the presence of wet environments, but the changes in fiber molecules also need to be understood. Dynamic Fourier transform infrared spectroscopy (FT-IR) can be used since traditional macromechanical tests cannot provide information about the stress transfer between the fiber and the matrix [190]. As moisture is transported from the plant fibers to the interface between the fiber and matrix, the ability to transfer stress between the fibers and the matrix is reduced [190]. The matrix

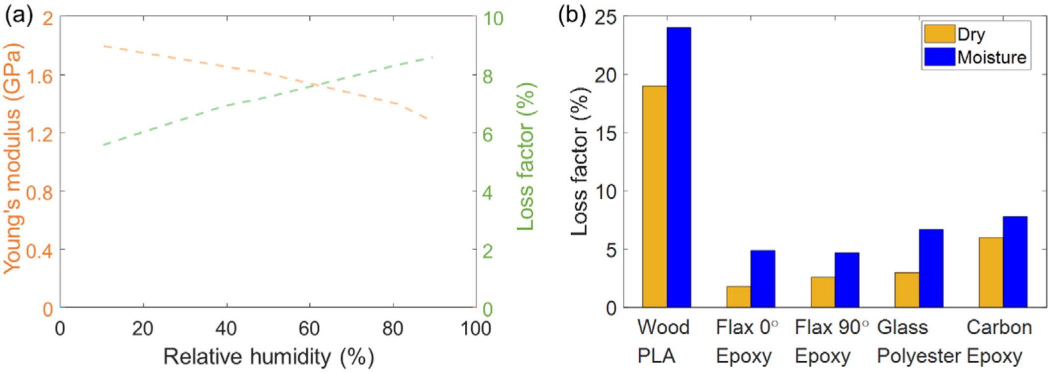

Fig. 7. Young's modulus and loss factor of (a) a wood fiber composite and (b) different kinds of composites based on DMA tests at 1 Hz and ambient temperature with respect to relative humidity and water absorption (summarized from ref. [173,186,187]).

Table 1
Main features at the mesoscale and microscale and surrounding condition parameters.

Parameters	Damping source	Reference
Mesoscale parameters		
Fiber length	Ratio of fiber length to diameter, surface contact area	[93–97]
Weave pattern	Interlace between the warp and weft directions	[27,47,98–102]
Stacking sequence	Shear effect, effective load transfer	[45,104,106,107]
Microscale parameters		
Fiber type	Stress transfer, intrinsic damping capacity of plant fibers	[49,108,109,27,68,102]
Fiber orientation	In-plane shear strain energy	[109]
Fiber volume fraction	Increased interface or restricted mobility of the matrix	[93,152]
Treatment	Stress transfer, quality of interface	[45,141,142]
Matrix	Molecular structure, interactions at interfaces	[27,160,161]
Interface	Fiber/matrix adhesion	[49,166]
Porosity	Not enough studies on porosity	–
Surrounding conditions		
Moisture effect	Friction losses caused by interface damage	[131,145,182,183]
Temperature	Internal movement of molecule chains, changes in the microstructure of the plant fibers	[95,197]

bears a greater load, and the in-phase contribution of the matrix increases relative to that of cellulose [190]. The energy dissipation is related to the strain energy of the fiber, and the friction between the different components increases with water absorption [132].

The effect of fiber orientation changes has also been studied in UD composites. The sensitivity of damping in different fiber orientations to moisture decreases gradually from 0° and 90° to 45° [173]. PFC laminates with 90° outer layers are profoundly affected by moisture, resulting in a more sensitive effect on damping [131]. Therefore, this situation should be avoided in the design of composite materials if the materials are intended to be used in high-humidity environments. However, another reason explaining the effect of stacking sequences is that different fiber orientations undergo a different amount of water absorption before the specimen reaches saturation, which is not taken into account when discussing the effect on damping. Similar research has also been reported for SFCs [131]. In the referenced work, a dehydrated flax composite specimen after water absorption is compared with the original specimen. Although a 15% decrease in the bending modulus is observed, the author claims that the damping performance is reversible because the damping in PFCs is mainly driven by the water content in the fiber and by fiber friction. The effects of cracks and interface failures are found to be negligible [173]. Several authors claim that this behavior appears to be unrecoverable in glass fiber-reinforced polymer composites because the damping of SFCs is mainly determined by the damping of the matrix and the interface [12,187].

The damping performance in seawater or strong acids has been studied in addition to the performance in freshwater or pure water environments [62]. Research shows that plant fibers are more susceptible than synthetic fibers to acids [191]. In addition, a silane agent has been proven to decrease water absorption, which is caused by reducing the chance of hydrogen bonding between free –OH groups in cellulose and water molecules [145]. V. Fiore et al. also claim that $NaHCO_3$ treatment shows a beneficial effect on the damping properties of flax composites but not jute composites during exposure to salt-fog environments, which is strictly related to the fiber's chemical composition [192].

In general, many reports on the effects of moisture on SFC behavior are available, while research related to PFCs has focused more on monotonic mechanical behavior. The effect of water-heat coupling on damping using different types of PFCs needs more research.

3.3.2.2. Temperature. The dynamic mechanical properties of organic-based composites are also strongly sensitive to temperature. Temperature is the first factor that affects damping properties in various external environments [193].

Below the glass transition temperature, the loss factor increases with temperature, which is attributed to matrix softening [95]. The free volume and space of internal molecular movement increase when the temperature rises, which causes the storage modulus and loss modulus to decrease. An ideal damping material should have a wider transition region and higher loss factor peaks. However, the stiffness of the matrix of composite materials decreases significantly in the transition zone, which requires engineers to find a suitable compromise between stiffness and damping.

Damping performance is strongly related to the glass transition temperature (T_g). The incorporation of plant fibers into the matrix generally induces a shift in T_g toward higher temperatures and a reduction in the loss factor peak due to the restriction of matrix chain movements. This relationship suggests an increase in the stiffness of the fiber–matrix interfacial zone; however, contradictory effects have sometimes been observed [32,36,37,194–196]. The effect strongly depends on the matrix type, the affinity of the matrix with the plant fiber and the resulting stiffness properties at the interface between fiber and matrix.

Some results have reported the damping properties of flax/epoxy composites during thermal shock cycling conditions from -40 ℃ to 28 ℃ [197]. The maximum observed decrease in the loss factor is 8%. In addition, the storage modulus is reduced by approximately 50%, and the dynamic mechanical properties reach an equilibrium state due to microdamage saturation after 100 thermal shock cycles. The glass transition temperature (T_g) is not affected by the thermal shock cycling conditions.

However, most of the results available to date represent a combined effect of increased temperature and specimen drying since it is difficult to use traditional experimental methods (such as DMA testing) to maintain a constant moisture content within PFC samples while changing the temperature. Hence, more research is suggested to decorrelate the effects of temperature and moisture content.

In this section, the effects of mesoscale parameters (reinforcement type and stacking sequence), microscale parameters (fiber, matrix, interface and porosity) and surrounding conditions are discussed. The main features of damping sources are summarized in Table 1.

4. Limitations of existing PFC damping studies

(1) **Porosity** – The influence of porosity level has been recently investigated for PFCs made of nonwoven fabrics and thermoplastic polymers [110]. However, the results in the literature remain poor, particularly for short fiber composites and woven fabric-based composites. Additional research on this topic regarding different types of PFCs with different matrices (thermoset or thermoplastic) is necessary since not enough conclusions have been reached at this time. In addition to the porosity level, the influence of the size and distribution of porosity should be investigated.

(2) **Environmental conditions** – The effect of hygrothermal coupling on damping using different types of PFCs needs more research. At present, the influence of environmental conditions is generally investigated using DMA tests involving moisture content variations while sweeping temperature. The use of vibration tests is also recommended in the future to obtain direct measurements in a mid-frequency range.
(3) **Characterization at the microscale and multiscale** – For the characterization of damping, a large number of reports focus on the macro- and mesoscales, while studies at the microscale are currently rarely seen. However, microscale measurements are required to map the damping in different constituents (the plant fiber wall, the surrounding matrix and the interface) to better understand the influence of microscale parameters on damping at the macroscale. Particular attention must be paid to the time scales related to each dissipation phenomenon occurring at various spatial scales.
(4) **Wideband frequency and experimental technique effects** – Evolution with frequency – Most of the results obtained for nonwoven composites as well as noncrimp and woven composites show that the loss factor varies slightly with frequency [43,110]. However, it is sometimes difficult to derive a trend on the basis of such results. Combining data collected using different experimental techniques for the same PFCs is suggested to observe the trend of the loss factor over a wide range of frequencies.

Comparison of experimental techniques – The comparison of different test methods for specific PFCs under the same conditions to determine their influence would also constitute valuable analysis for future research since many other influential parameters vary from one study to another.

Use of additional techniques – In parallel to the classical DMA and vibration techniques, other methods, such as ultrasonic testing, nanoindentation, and scanning microdeformation microscopy, have been investigated for the damping characterization of polymers [118]. These techniques could also be used for PFCs. Although the techniques are also limited by frequency and temperature, they can complement the limitations of other experiments on multiple scales [70,89]. Wavenumber-based approaches can be an optional method to address high-frequency-range issues.

(5) **Fiber length and microstructure** – Even if the influence of fiber length on the damping properties has already been investigated for short-fiber composites, more in-depth study is necessary to better comprehend the influence of fiber length, fiber ends and discontinuities on the damping behavior, particularly in noncrimp fabric composites. For such composites, the influence of fiber type and fiber microstructural features should also be studied.
(6) **Stress level effect** – Since most PFCs exhibit nonlinear static behavior as a function of stress level, it would also be interesting to verify the linearity of the damping behavior as a function of the stress level.
(7) **Other factors** – Composite materials face fatigue issues during long-term service. Some effects of fatigue on damping performance have already been reported. The loss factor is shown to decrease substantially in the first cycles, then· slightly decrease, and then stabilize before the final failure [129]. This trend deserves to be explained since one may expect an increase in the damping capacity with damage creation and propagation.

The effect of various coupling conditions, such as fatigue, moisture, and temperature, on the damping properties of PFCs should be studied in the future.

Different parameter configurations during the composite manufacturing process also have an impact on the damping performance. One study found that higher pressures appear to reduce the damping ratio due to alterations in the fiber–matrix bond [46]. The influence of parameters in the manufacturing process can be considered in the future.

5. Conclusions

This article critically reviews many factors that affect the damping properties of PFCs in terms of mesoscale parameters, microscale parameters, surrounding conditions, etc. based on recent research reports. The literature shows that PFCs have loss factor values between 0.7% and 14%, while the values are between 0.24% and 2.5% for SFCs. Therefore, the damping capacity of PFCs is generally much higher than that of SFCs. The damping range is also more widespread. These damping properties are linked to the wide variety of fibers and their hierarchical organization and complex composition. This review also points out some contradictory results. These contradictions are attributed to the wide variety of PFCs studied, involving various types of plant fibers organized in different reinforcement architectures embedded in a very broad set of polymer matrices. This variety sometimes prevents reaching a consensus and establishing generic conclusions. The review also shows some knowledge gaps to be bridged in the future.

The main conclusions are the following:

(a) The damping characteristics of PFCs are unique because of their microstructural and morphological properties, which are linked to their polymeric nature, moisture sensitivity, complex interface, and finite length, in contrast to SFCs. Quantitative analysis of the influence of microstructure on damping performance is rarely seen, although there have been many studies on static mechanical properties.
(b) The diameter-length ratio of plant fibers has a significant effect on the damping of PFCs, and different reinforcement types have different trends. The outer layer in the stacking sequence has a considerable effect on damping.
(c) Interface properties between fibers and matrices have a significant effect on damping performance, with sometimes contradictory interpretations. Additional studies and knowledge are necessary to shield light on this complex issue.
(d) The special damping mechanisms of PFCs are mainly due to intracellular and intercellular wall friction, intrayarn and interyarn friction, and fiber/matrix sliding. The effect of treatment methods on composite damping is caused by changes in interfacial properties between the fiber and matrix.
(e) PFCs are more sensitive than SFCs to moisture content because of the mismatch of the moisture expansion coefficients between the matrix and the fiber, which would induce a modification of the interfacial properties.
(f) Future work can expand on these issues regarding the effect on damping properties, such as comparisons of multiscale experimental methods, different reinforcement types, surrounding conditions, and parameters in the manufacturing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors express their gratitude for the funding received from the Bio Based Industries Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No. 744349-SSUCHY project and the funding received from the Region Bourgogne-Franche-Comté under grant agreement No. 2016Y-06124-D-BCOMP project. Financial support from the EUR EIPHI Graduate school (contract “ANR-17-EURE-0002”) is also gratefully acknowledged.

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