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Single fibre damping, insight, advances and challenges

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Abstract. This review paper provides insights into damping characterisation at the fibre scale. With the growing demand for composite materials, understanding damping behaviour within these materials is becoming increasingly crucial. However, research on damping characterisation at this scale remains limited, highlighting a notable gap in the field. This paper presents a detailed analysis of methodologies used to assess fibre-scale damping and examines the influence of environmental factors such as temperature, humidity, and pressure, as well as the impact of the identification method. While most studies have focused on ceramic and metallic fibres, some efforts have also been made to investigate natural fibres. However, these studies remain relatively scarce, and the characterisation of natural fibre damping is still in its early stages. Reported damping values vary significantly across studies, reflecting both the influence of fibre type and methodological differences. For instance, damping values for cotton fibres range from 13.7% to 21.7%, carbon fibres from 0.09% to 0.9%, and flax fibres from 3.9% to 11.5%. Moreover, a noticeable contrast can be observed between organic and inorganic fibres. One of the main findings of this review is the significant variation in damping values obtained for the same fibre type, depending on the characterisation method used. This highlights the need for standardisation and further refinement of experimental techniques to improve the reliability and comparability of damping measurements.

Keywords. Elementary fibre, Damping, Influencing parameters.

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1. Introduction

In numerous engineering applications, the focus is placed on vibration control. This control is crucial for ensuring user safety and enhancing personal comfort, resulting in designs that are structurally stable and inherently resilient. Specifically, when addressing vibration control, the more precise term would be “damping” control, which characterizes a structure’s ability to dissipate energy, directly influencing its safety. This concept is observed across various structures and

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various scales, from the world's tallest tower integrating mass-tuned dampers to the microsensors inside every smartphone, passing by the muted closing noise of car doors. Effective vibration control requires a deep understanding of the physical phenomena contributing to energy dissipation. Among the available strategies, passive damping control can be identified. By tailoring the material properties or structural design to naturally absorb vibrational energy, passive approaches offer a feasible solution. Within this context, optimizing the damping characteristics becomes one of the strategies for managing vibrations efficiently. As a direct consequence, developing new materials, concepts, and technologies that ensure safer and more comfortable structures, while addressing environmental concerns, remains a complex yet essential challenge. In the last 30 years, metallic structures in the fields of aeronautics, aerospace, land transportation, and maritime transport have been increasingly replaced by composite materials made of carbon or glass fibres [1]. However, problems remain with the production of those synthetic composites. Indeed, materials typically reinforced with fibres such as glass or carbon require significant energy for production and release large amounts of greehouse gases. An alternative has recently emerged that takes into consideration environmental problems [2]: composites with plant fibre reinforcement are shown as a potential alternative to synthetic fibres. In addition, plant fibres present good mechanical properties such as rigidity, tensile and shear properties [3–8]. The increasing adoption of plant fibre-reinforced composites has brought new opportunities. Remarkably, these composites have shown, in certain instances, higher damping properties compared to conventional synthetic fibre-reinforced composites [3,5,9–11]. However, Duc et al. [11] highlighted the insufficient understanding of damping within these composites. While a rule of mixture fairly accurately describes the rigidity of a composite, establishing a similar law for damping proves to be challenging. Notably, while the rigidity (storage modulus) increases in the fibre direction with the addition of fibres as reinforcement inside the composite (see Fig.1.a), the damping behaviour follows a different pattern. As a matter of fact (Fig.1.b), the addition of fibres to the matrix can either enhance, reduce, or leave the composite's damping unaffected. It underscores the need to understand composite damping.

Existing literature suggests that damping sources within the composite may be influenced by four primary factors: the matrix, porosity, interfaces (both between fibres and between fibre and matrix), and the fibre itself. The matrix is an important contributor due to its viscoelastic nature. Under dynamic loading, internal friction within the polymer chains leads to energy dissipation, a phenomenon that is further amplified by environmental factors such as temperature and humidity. Porosity also plays a non-negligible role. Microvoids zones can facilitate localised deformation and micro-slipping, contributing to energy loss, particularly under repeated loading. Interfaces, whether between fibre and matrix, or between fibres themselves in bundles, have been studied [11–13]. The interphase region, which possesses properties distinct from both the fibre and the bulk matrix, is critical in this regard. Depending on its strength and adhesion quality, it may enable frictional sliding or delamination under stress, significantly increasing damping. Damage-related mechanisms such as matrix cracking or fibre–matrix debonding can further enhance this effect. Lastly, the fibre itself is considered a source of damping within the composite. By "fibre itself," this refers not only to macroscopic factors such as volume fraction, dispersion, and orientation [3,9], but also to intrinsic properties at the level of the elementary fibre. These include the fibre's viscoelastic nature, chemical composition, surface morphology, and internal porosity[12]. However, these aspects remain understudied in the literature and therefore constitute the focus of the present work.

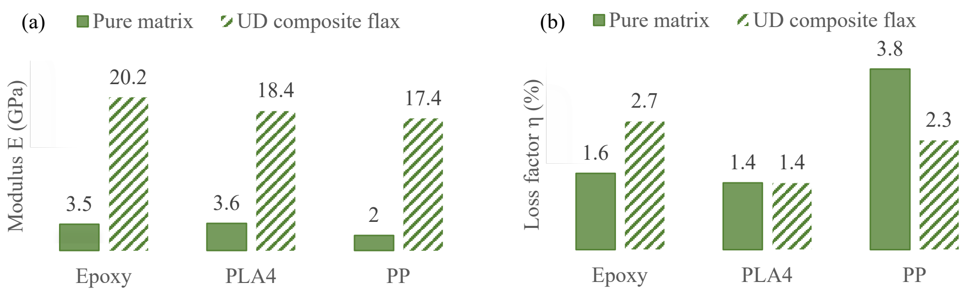

Figure 1. (a) storage modulus and (b) loss factor of unidirectional (UD) flax composites in the longitudinal direction and of the pure matrix, measured in bending by Dynamical Mechanical Analysis (DMA) in flexion at 1 Hz. Inspired by the work of Liu et al. [14] (PP stands for polypropylene and PLA4 for polyamide 4).

Despite this, it is important to highlight that damping properties at the scale of elementary fibres have been very rarely investigated, mainly due to the experimental challenges associated with handling and characterizing such small and fragile structures. As a result, typical orders of magnitude for fibre-scale damping remain poorly defined. Furthermore, input data required for multiscale modelling of composite materials are often unavailable or difficult to access, particularly at the fibre level. To date, no comprehensive review has focused specifically on this topic, and researchers frequently encounter difficulties when seeking consistent mechanical and viscoelastic parameters for their models. The present study seeks to address this gap by gathering the existing data and practical insights tailored to the needs of modellers, thereby facilitating the integration of fibre-scale properties into multiscale simulation approaches.

2. Definitions and terminologies

To establish a common understanding, the fibre classification system described by R. Mather et al. [15] is adopted in this work. According to this system, fibres are divided into two main categories (Fig.2). The first category includes:

- man-made fibres composed of regenerated fibres (derived from natural sources and undergo chemical processing to extract the fibre-forming polymers) such as viscose, rubber...;
- inorganic fibres (glass, carbon, metal...) presented as synthesized from non-biological or mineral compounds;
- synthetic fibres (polyamide, polyester, polypropylene...).

The second category gathers the natural fibres that contain cellulosic fibres (bast fibres, leaf fibres, seed fibres), proteinic fibres (wool, hair, silk...), and mineral fibres.

In addition, as the damping is the central point of interest, it is important to remember all the nomenclature used to design this quantity. Indeed, some of the commonly used terms in different fields of physics are related to each other. First, from the perspective of a mechanical resonator (mass, spring, damper...):

- the quality factor Q which represents the ratio between the maximum amplitude at resonance in the harmonic regime and the amplitude for a static response;
- the specific damping capacity ψ which is a measure of the ability of a material or structure to dissipate energy per unit mass during vibration;

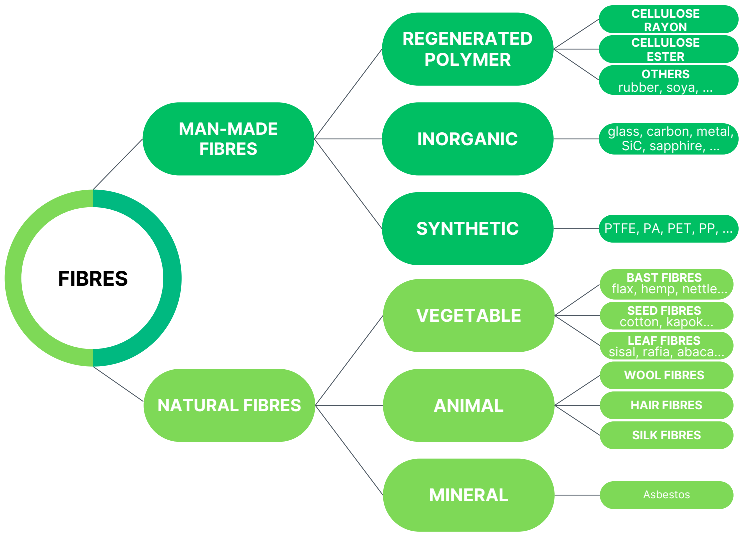

Figure 2. fibre's classification based on the work of Mather et al. [15]

- the damping ratio ζ which is a fundamental parameter in the analysis of second-order mechanical systems, which typically consist of a mass, a spring, and a viscous damper. It quantifies the level of damping present in the system and is defined as the ratio between the actual damping coefficient and the critical damping coefficient, its definition is extended to ζ_n, the modal damping ratio of a given mode n of a structure, whose dynamic behaviours represented by modal mass and modal stiffness;
- the viscous damping coefficient α which relates the velocity to the viscous damping force acting on the system in response to its motion.

From a material point of view:

- the loss factor η or $\tan\delta$: is a material quantity that quantifies the ability of a material to dissipate energy when subjected to deformation.

When the mechanical system (the fibre in this article) can be described as a resonant system on a single mode (eg. the first bending mode of the fibre), the damping parameters are linked by the following expressions:

$$\eta = \frac{\psi}{2\pi} = 2\zeta = \frac{\alpha}{\omega_0} = \frac{1}{Q} = \tan\delta. \quad (1)$$

They provide different perspectives on the damping properties of the system and are used in different fields of physics. In this work, the formalism used to describe damping is the loss factor η expressed in percent (Eq. 1). By utilizing the loss factor, it aims to give a consistent and unified approach to discuss the damping properties of the fibres under investigation.

3. Fibre scale damping: characterisation methods

Damping characterization is commonly used for macro-scale structures or materials. However, it is important to note that many of the techniques commonly used in structural dynamics at the macro scale cannot be directly applied to elementary fibre damping characterization. At the macro scale, measurements are most of the time conducted with accelerometers glued to the structure or laser vibrometry, both of which can be challenging to perform on fibre samples. Moreover, excitation is usually achieved with a shaker or by impacting with a hammer equipped with a force sensor, neither of which is feasible for a fibre. These limitations highlight the need for specialized methodologies specifically tailored for fibre characterization. Although ropes and wires have been extensively studied, the literature on this specific topic (damping characterization at the fibre scale) remains sparse. Fig.3 illustrates the historical progression of paper contributions to damping knowledge and characterization at fibre scale until now. It emphasizes the limited research performed at this scale. To the best of the authors' knowledge, only around 15 papers have addressed fibre-scale damping properties from 1954 to 2024.

In this paper, various methodologies are employed to investigate the dynamic properties of fibres. These methodologies can be classified into three categories based on the nature of the mechanical response: quasi-static methods, modal analysis techniques, and wave propagation techniques. Quasi-static methods assume that the fibre behaves as a simple mass-spring-damper system, with no internal dynamic effects. Techniques such as Dynamic Mechanical Analysis (DMA), torsion pendulum, nanoindentation, guided tension, and tilting bench fall into this category. These methods primarily probe the viscoelastic behaviour and overall mechanical properties of fibres, neglecting density-related effects. Modal analysis techniques focus on the study of resonant behaviours, where vibrational modes emerge with wavelengths ranging from a few fibre lengths (first elastic mode) to fractions of the fibre length. Methods such as cantilever

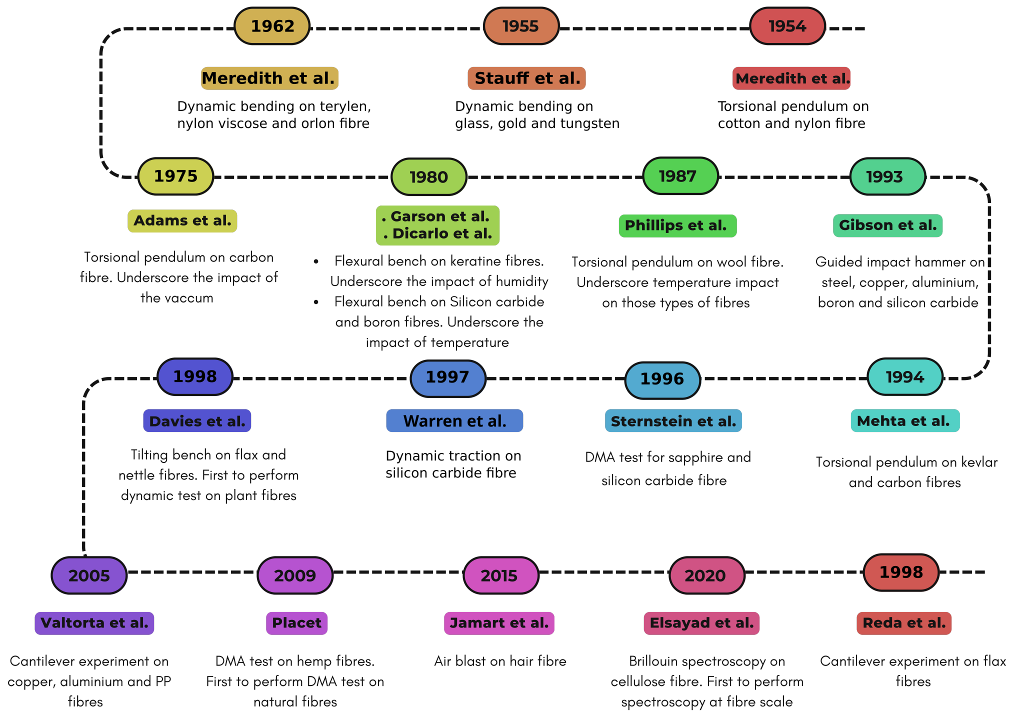

Figure 3. history of dynamical tests at fibre scale [16–31]

beam excitation, air-blast excitation, and electric flexural bench enable the characterization of structural damping and the dynamic response of fibres. Wave propagation techniques explore the regime where the fibre behaves as a continuous medium, with wavelengths much smaller than its characteristic dimensions. In this case, density effects become significant, and the fibre is treated as an elastic waveguide. Techniques such as Brillouin spectroscopy and ultrasonic methods provide insights into wave dispersion and local dynamic interactions at the microscale.

All these methods use vibrations to excite the structure and this work discusses two types of excitations: free and forced responses. In the case of free response, the structure oscillates or responds without any external force acting on it, with movement driven solely by elastic, inertial, and loss forces within the fibre or a passive device, such as an inertial mass. The system's behaviour is determined by its intrinsic properties, including mass, stiffness, and damping, which limit access to only the first eigenfrequency and mode. On the other hand, in forced

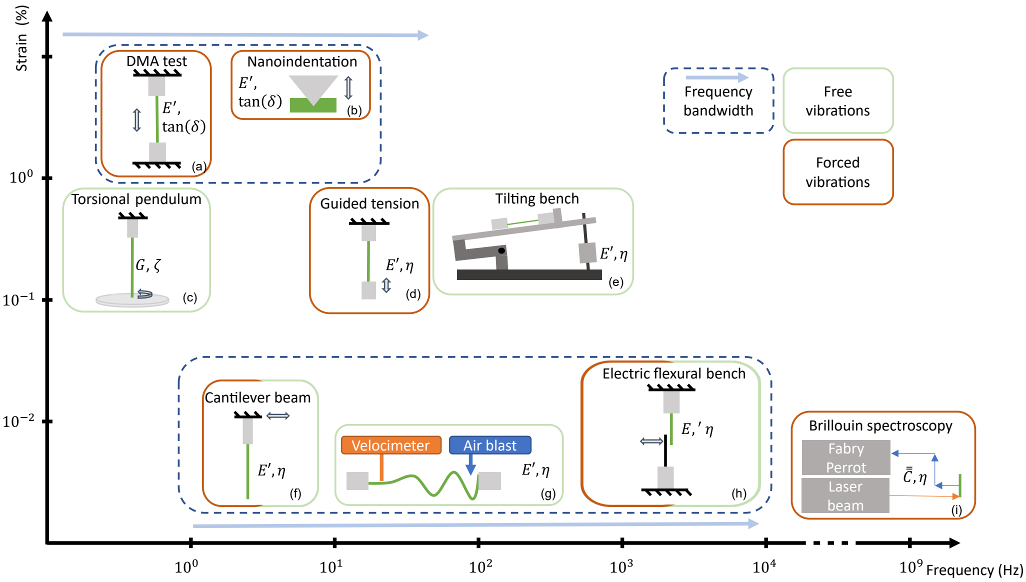

Figure 4. dynamic test methods for the dynamical characterization at the fibre scale, considering their strain level and frequency bandwidth [18–32]

response, the system is subjected to an external force or input. This external force acts as a driving function, causing the system to respond in a particular manner. The system's response is influenced by the characteristics of the external force and the properties of the system itself. This response allows access to several eigenfrequencies, thus several modes. The overall methods employed in this work are illustrated in Fig.4. They are categorized based on the applied strain rate to the sample and the frequency bandwidth they can operate within. Forced and free excitation are depicted in orange and green, respectively. It is worth emphasizing that the following of the section is dedicated to methodological discussions, and as such, does not include numerical data. Subsequent sections will develop the quantitative analysis, providing numerical values and further elucidating literature findings.

3.1. *Quasi-static techniques for damping identification*

3.1.1. *Torsion method*

In the literature, the torsion pendulum method (see Fig.4.c) stands out as an interesting and unique technique for torsional modulus and torsional damping phenomena across diverse materials [33]. Inspired by the original Coulomb pendulum design, this method employs a wire (usually the sample of interest) supporting an inertial mass [33–36]. The suspended mass is twisted and then released, creating oscillatory motion driven by a torque proportional to the angular displacement oscillating, the fibre playing the role of a linear torsion spring. The damping (torsional damping) is typically determined thanks to the logarithmic decrement method with the oscillations made by the mass. The torsional pendulum method proves efficient in characterizing multiple materials' damping properties [34]. Its sensitivity enables the detection of low damping levels, providing good insights into material performance [36]. Despite its efficiency, challenges persist. Sensitivity to external factors like temperature, humidity, and aerodynamical effects needs strict environmental control for accurate data. However, ongoing efforts by Adams et al. [19] on carbon fibre, Philips et al. [22] on wool fibre and Yu et al. [36] on carbon, copper, silver and tungsten fibre, aim to overcome these challenges, pushing the boundaries of the torsion pendulum method, enhancing its accuracy.

3.1.2. *Tension method*

Among the identified work on damping characterization, another solicitation method is tension. Tension occurs when a fibre bears weight, parallel to its longitudinal axis, on one end, while undergoing dynamic solicitations. For the quasi-static methods, the main method for damping characterization is the well-known DMA (Fig.4.a). This method subjects the material to dynamic mechanical forces or displacement while measuring its response. This method evaluates properties such as storage modulus, loss modulus, and damping across diverse environmental conditions, offering insights into the material's viscoelastic behaviour. This method gives the loss factor that corresponds to the phase shift between the strain and stress curve. While DMA is commonly used for larger-scale structural and material applications, damping characterization at the fibre scale presents challenges: clamping conditions are not well optimized for small fibre diameters, risking damage to the fibre microstructure and possible slippage between the jaws. However, studies on ceramic fibre (sapphire and silicon carbide) by Sternstein et al. [25] and Warren et al. [37] and on hemp fibre by Placet [28] have explored fibre-scale damping showcasing the feasibility of such kind of studies.

Beyond DMA, other quasi-static tension methods have been explored for fibre damping characterization. For instance, the work of Gibson et al. [23] on steel, copper, aluminium, boron, and silicon carbide (SiC) introduces an apparatus for quasi-static fibre evaluation. This setup suspends a mass from the fibre specimen, inducing extensional vibrations and utilizing an impulse frequency response technique for experimentation at less than 25 Hz. The method involves longitudinal excitation using an electromagnetic hammer equipped with a force transducer, ensuring impulses for precise measurements (Fig.4.d). This comprehensive apparatus allows the testing of elementary fibre on forced vibrations with an impulse, ensuring the characterization of their dynamic properties across diverse temperatures conditions. The modulus as well as the damping are then identified. The loss factor is identified with the bandwidth at the half-power point method from the frequency response function (FRF). However, despite its design, the apparatus faces limitations. It can reach temperatures up to 1400°, but expansion of stainless-steel bolts in clamping fixtures poses a risk of specimen slippage. Another study by Davies et al. [26] introduced an alternative approach in the case of nettle and flax fibre. A tilting bench (Fig.4.e) was used to apply tension to the fibre under investigation, with tilting controlled by a motor.This incremental motor mechanism induced vibrations (between 10 and 300 Hz) at each tilting step, enabling the determination of damping values for nettle and flax fibre with free response induced by the increments of the motor. The damping was identified using the logarithmic decrement method.

3.1.3. *Nanoindentation*

Although typically applied at the composite scale, nanoindentation provides valuable insights into fibre damping, hence its relevance in this discussion. In this method (Fig.4.b), a sharp indenter is pressed into a material's surface with controlled force, creating a small indentation. By measuring the resulting force-displacement curve, key properties such as hardness, elastic modulus, and material deformation behaviour can be determined. This study has been used to determine the damping and the rigidity of fibres inside the composite between 1 to 5 Hz by Liu et al. [14]. In this study focusing on the fibre scale, two distinct methods, continuous stiffness measurement (CSM) and constant amplitude method (CAM), are employed to unravel the dynamic properties of the flax-reinforced composite. These methods offer diverse perspectives on inelastic behaviour assessment. CSM, by considering energy dissipation during both loading and unloading phases, accounts for irreversible mechanisms, while CAM emphasizes determining damping capacity and viscoelastic parameters after the initial loading and unloading. However, it is important to note that fibres are embedded within the resin during these experiments, resulting in a possible infusion of resin inside the fibres. Additionally, the exact boundary conditions are uncertain (because fibres are placed inside the matrix), and the deformation rate associated with nanoindentation is among the highest compared to previously presented methods. Consequently, a significant challenge lies in ensuring that the measurements primarily capture the behaviour of a fibre, rather than contributions from the overall system.

In conclusion, quasi-static methods, torsion pendulum [19,36], with tension method [22,25,28,37] and nanoindentation [14], represent tools for characterizing damping properties across varying material. These methodologies offer insights into material behaviour, even if they present challenges when applied at the fibre scale.

3.2. *Modal range techniques for damping identification*

For the characterization of fibre damping using modal range techniques, in the litterature, only flexion is studied. In applied mechanics, flexure (or bending) describes how a slender structure deforms under a load perpendicular to its length. For example, the studies conducted by Garson et al. [20] on hair using a method that consists of exciting embedded fibres using an electric field with the fibre's resonant frequencies (Fig.4.h). These fibres are stimulated by an electric potential, inducing charges on their surface. This periodic electrostatic action generates detectable vibrations, and by adjusting the frequency of the electric field, the resonant frequencies of the fibre and the corresponding damping ratio can be identified with the FRF and the half-power point method.

The other bending method identified in the existing literature consists of cantilevered fibre subjected to flexural forced or free vibrations (Fig.4.f). In this method, the fibre is clamped at one end and excited at its base, causing it to oscillate like a cantilever beam. The experimental setup consists of mounting the fibre on an electrodynamic shaker through a support system. This differs from the method used by Garson et al. [20], where excitation occurs at the free end. By systematically scanning through a range of frequencies, the resonance of the fibre can be identified. The technique relies on simple beam theory based on the zones of resonance detected during the frequency scan. Jamart et al. [29] also used this type of measurement system on hair, using compressed air cycles and precise laser measurements to induce impacts on the hair sample without direct contact (Fig.4.g). By measuring the deflection at the impact point and monitoring wave propagation using lasers, the system allows for analysing the fibre's dynamic behaviour under varying moisture conditions. Valtorta et al. [27] in their research on copper, aluminium, and polypropylene (PP), also developed a flexural damping measurement technique using this type of resonance approach. Disturbances in a light beam, caused by the fibre's motion, are detected generating peaks corresponding to instances when the fibre intercepts the light beam. Utilizing phase information between the excitation signal and the fibre's motion provides valuable insights into the damping characteristics. This method eliminates the need for continuous measurement of fibre displacement by focusing on periodic disturbances in the light beam, enabling the process of characterizing flexural damping in thin fibres.

Other studies should be mentioned because they also use modalr range method but limit it to rigidity characterization. Indeed, Perrin et al. [38] and Chupin et al. [39] used the cantilever method to assess Young's modulus of glass and miscanthus fibres.

3.3. *Wave propagation method for damping identification*

The main method used in high frequency for damping characterization at fibre scale is the Brillouin Light Spectroscopy (BLS). BLS primarily used in optical applications and notably in optical fibre, can also serve as a sophisticated technique for characterizing damping in multiple materials [40–42]. This method revolves around the interaction of light and elastic waves within a material. Micro-Brillouin light spectroscopy is a non-invasive and non-contact technique based on the inelastic scattering of light from acoustic phonons inherent in the probed material (Fig.4.i). By measuring the frequency shift of the Brillouin scattering peaks relative to the probing laser, BLS determines the velocity of elastic waves, which is directly related to the elastic storage modulus and the damping at the corresponding frequency. This approach offers insights into the mechanical behaviour of fibres in different directions (longitudinal and transverse to the fibre axis) [32,41,42].

Today, there is only one paper (to the best of the authors' knowledge) in this field that treats single fibre damping behaviour using Brillouin spectroscopy. Indeed, Elsayad et al. [30] used this technique on cellulosic fibre to determine their modulus and damping. It is worth mentioning that Koski et al. [32] worked at the scale of silk fibre but kept it to the modulus. The limitation of this technique is the requirement for sophisticated data analysis that pose challenges in obtaining accurate and reliable results. For example one of the main difficultiy lies in the challenge of accurately determining the material's refractive index, which is essential for reliable measurements. Moreover, due to the very high frequencies involved, it is often unclear which component of the system is actually responding, whether it is the material itself or another constituent. Despite this constraint, Brillouin Light Scattering (BLS) remains a powerful technique for investigating material mechanics, particularly due to its ability to perform localised measurements and spatial mapping.

Each method, as depicted in Fig.4, brings insights into the dynamic properties of fibres, offering a piece of understanding of their mechanical dynamical responses. However, these methods present challenges, from intricacies in setup and calibration to limitations in frequency ranges and susceptibility to surrounding factors. Therefore, the damping characterization should be approached with care, considering the potential limitations of each method.

4. Influencing parameters on fibre's damping

This section examines the impact of temperature, humidity, boundary conditions and frequency on the dynamic behaviour of the fibre, based on the litterature results obtained using the previously presented methods. It is important to note that the damping levels reported in this section are taken from the published data, without trying to quantify the precision/uncertainties associated with the values.

4.1. *Temperature*

Limited studies have investigated the effect of temperature on fibre damping. This section summarizes the significant changes observed in damping and rigidity properties due to temperature fluctuations. The literature primarily focuses on inorganic fibre, including silicon carbide, sapphire, carbon, and various metal fibres, predominantly utilized in aerospace applications.

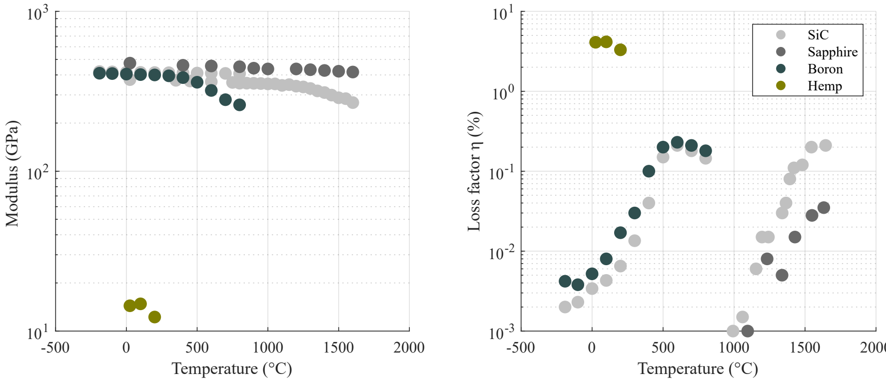

Figure 5. (a) longitudinal moduli and (b) loss factor of different types of fibre as a function of temperature [21,25,28].

The study of Dicarlo et al. [21] examined the impact of temperature variations (ranging from -190 °C to 800 °C) on SiC and boron fibres (Fig.5, respectively light grey and dark blue) with an electrical flexural bench (Fig.4.h) in the range of 15 to 20 kHz. The findings suggested, in terms of rigidity, a slight decrease from -190 °C to 800 °C as presented in Fig.5.a. In terms of damping, a significant increase of both fibre types by approximately two orders of magnitude within this temperature range (from 0.002% to 0.21% for the SiC and 0.004% to 0.23% for boron fibre). Notably, a significant rise in damping began around 0 °C, reaching a maximum at 600 °C before declining. Another study by Sternstein et al. [25] and Warren et al. [37] on SiC and sapphire fibres observed an increase in damping for both types (from 0.001% to 0.035% for sapphire and 0.001% to 0.2% for SiC) presented in Fig.5.b (respectively in dark grey and light grey) in the frequency range of 0.1 to 1000 Hz between 1000 to 1800 °C. Moreover, at higher temperatures, SiC demonstrated a more pronounced increase compared to the slower increase observed for sapphire. Additionally, the modulus decreased with rising temperatures for both fibre types.

A study by Placet [28] also investigated the temperature's impact on hemp fibre mechanical properties using a DMA test (see Fig.5, represented in golden brown). A increase in normalized modulus of 0.6 GPa between room temperature and 100 °C, followed by a decrease is observed. Regarding damping, an increase from 4.1% to 4.2% between room temperature and 100 °C, followed by a decrease from 4.1% to 3.3% between 100 °C and 200 °C is observed.

At macro scale also, temperature is demonstrated to present a significant impact. Observations on inorganic (boron, SiC, and sapphire) fibres suggest a substantial increase in damping capacity with elevated temperatures, followed by a subsequent decline in some cases. These temperature-induced alterations in damping properties, coupled with changes in rigidity for certain fibre types, underscore the intricate dynamics within fibre materials. Another consideration is the drying process of vegetal fibres with temperature increase, further highlighting the challenges associated with these materials. It is worth noting that for inorganic fibres, increasing the temperature to thousands of degrees is manageable without damaging the microstructure of the fibre, unlike natural fibres, which are much more thermally sensitive.

Moreover, these comprehensive investigations into temperature effects emphasize the need for further research to understand the nuanced relationships between temperature fluctuations and fibre damping characteristics, particularly in the context of natural fibres.

4.2. *Humidity*

This section presents a summary of existing research on the influence of humidity on elementary fibre properties.

Firstly, one can consider the study conducted by Davies et al. [26] using a tilting bench. This research primarily investigated the effects of relative humidity (RH) on the dynamic modulus of flax and nettle fibres (Fig.6, in green) from 0.1 to 600 Hz. It can be observed that as RH increased within the range of 30-70%, the dynamic modulus of flax fibre exhibited an increase of 0.7% per percentage change in RH (starting at 60 GPa), whereas nettle fibre increased by 0.2% in their modulus (starting at 45 GPa). Regarding the loss factor, measurements were conducted exclusively under ambient relative humidity conditions, yielding values of 3.6% for flax fibres and 3.9% for nettle fibres.

Another significant study, by Philips et al. [22], focused on wool fibre's response to humidity fluctuations (Fig.6, diamond marker in light orange) with the use of a torsional pendulum in the range of 0.01 to 0.1 Hz. The first conclusion that can be made is that the modulus tends to decrease as humidity increases from 65% to 95% RH from 0.9 GPa to 0.25 GPa torsional modulus). In addition, wool fibre damping increases with humidity (from 16.9% to 32.8%). Finally, the work

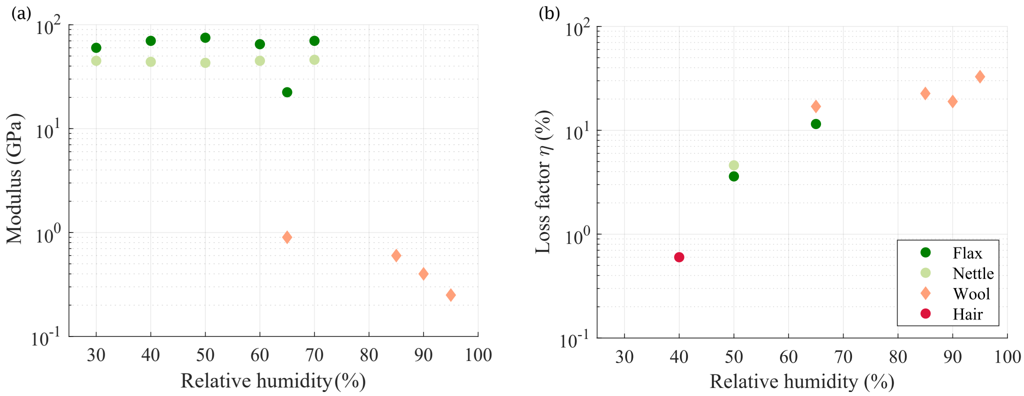

Figure 6. (a) moduli and (b) loss factor of different types of fibre as a function of relative humidity (diamond-shaped markers represent torsional moduli/loss factor, while circular markers represent longitudinal moduli/loss factor). [22,26,29,31].

of Garson et al. [29] investigated hair damping using flexural vibrations technique and reported a loss factor of 0.5% (this study focused solely on damping, and no modulus values were provided).

Comparative studies on the impact of humidity on fibre-damping characteristics remain relatively scarce, primarily focusing on the responses of natural fibres to humidity fluctuations. The study focuses on the impact of RH on flax, nettle, and wool, uncovering diverse behaviours. Moreover, the unique microstructure of plant fibres, characterized by distinct cell wall layers and complex cross-sectional areas that vary along the fibre length, may undergo potential changes with fluctuations in humidity, contributing to variations in damping properties. In contrast, wool fibres exhibit a unique pattern, demonstrating an increase in damping with humidity, coupled with a decrease in rigidity.

4.3. *Aerodynamical effect*

Depending on the method used, vacuum pressure can affect the characterisation of the damping behaviour of elementary fibres, particularly due to the aerodynamic effects that occur in its absence. This section deals with this specific aspect, which occurs mainly in the case of bending vibrations of a fibre. At the fibre scale, understanding damping is not straightforward, as it raises questions about whether the measured damping solely reflects the characteristics of the fibre or if it is influenced by a combination of fibre and air friction damping. The earliest study by Adams et al. [19] investigated the influence of pressure on carbon fibres using a torsional pendulum. This setup required accounting for the added mass, which introduced significant inertia and therefore needed to be minimized or removed. It can be observed that at extremely low pressure (above 6×10^{-5} Pa), the impact of air damping becomes negligible and the carbon presents a loss factor of 0.09% (see Fig.7.b in purple diamond). Another study, conducted by Valtorta et al. [27] using vibrations test, focused on copper, aluminium, and PP fibre (respectively light blue, blue, and brown in Fig.7.a.b). Furthermore, under a pressure of 5 Pa to minimise air damping effects, it is observed that the measured damping is primarily governed by the fibre's internal viscoelastic properties, with a residual contribution from viscous air damping. Vacuum experiments effectively mitigated the influence of air damping. Subsequently, it was observed that the loss factor for copper, aluminium, and PP initially measured 0.64%, 1.4%, and 6.4%, respectively, under atmospheric pressure; under vacuum conditions, these values decreased to 0.23%, 0.72%, and 5.8%, respectively (see Fig.7.b). Similarly, Stauff et al. [17] investigated the damping behaviour of glass fibres using vibrations under vacuum conditions and observed a marked pressure dependence: the loss factor decreased from 14.8% at ambient conditions to approximately 0.8% at a pressure of 0.09 Pa.

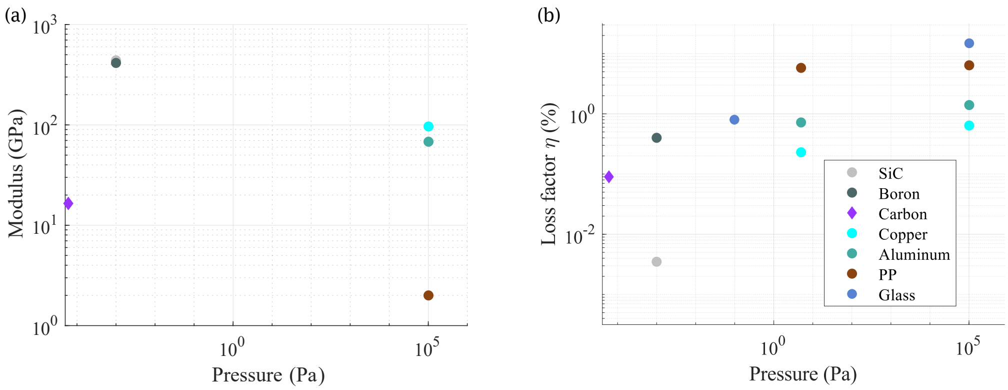

Figure 7. (a) moduli and (b) loss factor of different types of fibres as a function of surrounding pressure [19,21,27] (diamond-shaped markers represent torsional moduli/loss factor, while circular markers represent longitudinal moduli/loss factor)

This investigation into the impact of pressure on fibre damping highlights the importance of distinguishing between intrinsic fibre-related damping and the influence of external factors such as air friction, which depends on the experimental method used. Nouira et al. [43,44] conducted a study identifying six sources of energy loss in the case of a cantilever beam vibrating in free gases. Among these, they emphasized airflow damping, described using the Navier–Stokes equations and modeled through the Hosaka approach [45], which links damping behaviour to pressure variations. Similarly, Sumali et al.[46] examined various analytical models[47–50] to characterize the evolution of damping with pressure on small cantilever beams. These studies consistently show that vacuum pressure significantly influences structural damping. Perrin et al. [38] analysed the role of air friction, highlighting its effect on broadening resonance peaks. These presented models suggest that the frequency shift due to air damping is minimal (about 0.5%), indicating that its impact on the observed resonance frequency is negligible. It is therefore essential to note that this effect is method-dependent: if a fibre is vibrating in free air, it can be subject to aerodynamic friction, which must be accounted for when interpreting damping measurements. A notable research gap exists regarding natural or plant-based fibres: no dedicated studies have explored how pressure variations affect the measurement of their damping properties. Unlike inorganic materials, plant fibres may present specific challenges due to their organic nature. While air friction can influence damping measurements, it is important to clarify that pressure does not alter the intrinsic damping of the fibre itself, but rather affects how it is measured. Furthermore, exposing plant fibres to vacuum conditions could cause dehydration, potentially altering their microstructure, which must be considered when designing experiments.

In summary, studying how temperature, humidity, and boundary conditions influence fibre damping helps reveal the complex behaviour of fibre materials. Humidity emerges as a critical influence, significantly altering natural fibre properties. The effect of pressure on damping, particularly due to air friction, shows how difficult it is to separate fibre-specific damping from external influences. While each parameter brings its unique impact, their coupled influence on fibre behaviour remains an ongoing subject of interest. Understanding and distinguishing the individual contributions of these parameters to fibre damping presents critical challenges and opportunities for further exploration.

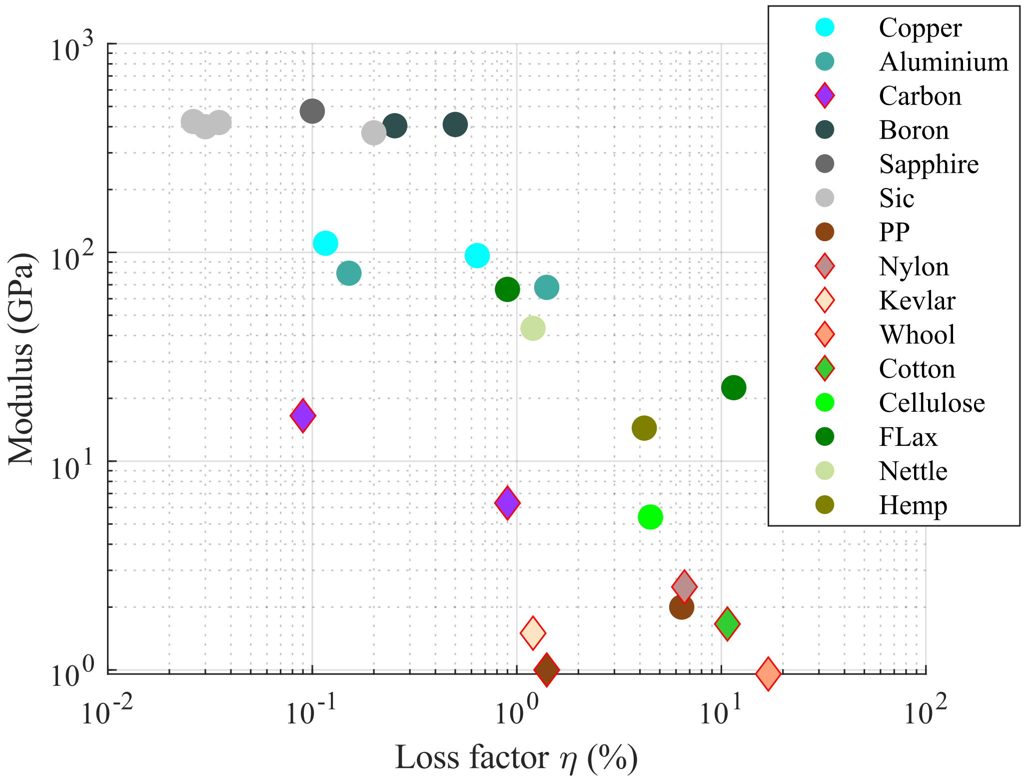

Figure 8. modulus as a function of the damping loss factor for different types of fibres [18–31] (diamond-shaped markers represent torsional moduli and loss factors, while circular markers correspond to longitudinal moduli and loss factors. Circled markers indicate values obtained from vacuum studies).

4.4. *Fibre damping across methods and frequencies*

The previous section provided an in-depth review of methodologies used to characterize fibre damping properties, with a focus on environmental influences. While each technique presents unique advantages and limitations, the following discussion synthesizes key findings from the literature, offering a comparative perspective on the performance of different fibre classes.

Figure 8 illustrates the relationship between modulus and damping loss factor across various fibre types. Synthetic and metallic fibres exhibit high modulus but low damping. In contrast, polymeric fibres display low modulus but high damping. Finally, bio-based fibres (in green in the plot) tend to balance intermediate values of both properties. This comparison underscores the distinct mechanical behaviours inherent to each fibre type under standard conditions.

The difference in damping identification depending on the method used is discussed with reference to Fig.9, where damping values from the literature are converted into loss factors. The following part of the section focuses on comparing the influence of frequency on the reported damping values.

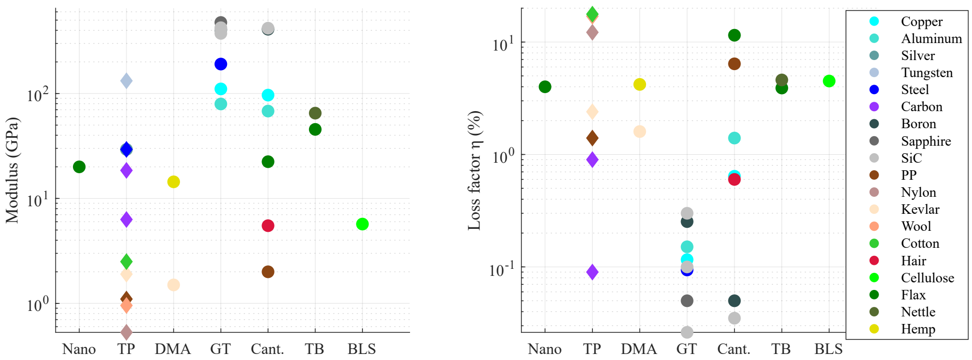

Figure 9. (a) moduli and (b) loss factor of different fibres concerning their damping characterization methods [18–31] (diamond-shaped markers represent torsional moduli/loss factor, while circular markers represent longitudinal moduli/loss factor)

From 0.1 to 10 Hz In this frequency range, three methodologies have been used: nanoindentation, the torsional pendulum, and DMA. Various types of fibres, including natural, inorganic, and synthetic variants have been studied. Considering the torsional pendulum, there are significant discrepancies in modulus and damping values between torsional pendulum studies. For example, for the same fibre same method, the torsional modulus and damping of carbon has been reported and is respectively as 6.3 GPa and 0.9% [24] but also 18.5 GPa and 0.08% [19]. In terms of damping, using torsional pendulum, cotton exhibits the highest loss factors [18], followed by wool [22], nylon [18] and flax [31]. Cotton demonstrates a loss factor of 17.7%, while wool and nylon display loss factors of 16.9% and 12.3%, respectively. DMA and nanoindentation have been applied to a limited selection of fibres, primarily flax and hemp. For flax, a loss factor of 4% and a modulus of 20 GPa have been reported. Similarly hemps exhibits a loss factor of 4.2% for a modulus of 14.4 GPa.

From 10 to 100 Hz In the open literature, three main methods of identification are prominent: guided tension (GT), cantilever (Cant), and tilting bench (TB). Various materials such as SiC, steel, aluminium, copper, and boron fibre have been tested using the guided tension method. PP and copper have been studied using the cantilever beam method, while flax and nettle fibres have been analysed with the tilting bench method. Notable findings include a modulus of 66.5 GPa and a damping factor of 3.9% for flax, as measured using the tilting bench method [26], which is comparable to that of nettle fibre, exhibiting a modulus of 70 GPa and a damping factor of 4.6% [26]. Copper's modulus and damping measured using the guided tension method at 45 Hz (110.58 GPa and 0.12% [23]) are consistent with those obtained via the cantilever method at around 25 Hz (96.5 GPa and 0.64% [27]).

From 100 to 1000 Hz and above The primary method utilized in this frequency bandwidth is the cantilever beam method, with a particular focus on samples such as SiC, boron, and flax. For boron fibre, a modulus and loss factor of respectively 410 GPa and 0.05% are reported [24]. In the case of flax fibre, Reda et al. [31] reported a modulus of 22.41 GPa and a loss factor of 11.5%.

This comparison shows the influence of frequency on the loss factor of the fibre. Unfortunately, however, it also shows the significant impact of the measurement method.

In conclusion, understanding damping at the elementary fibre scale remains a challenging and still emerging field. The literature reveals a limited number of dedicated studies, with noticeable disparities in both methodologies and reported results. For instance, flax fibre shows a wide variation in reported damping values, ranging from 3.9% to 11.5%, while carbon fibre spans from 0.09% to 0.9%. Similarly, SiC values range between 0.026% and 1.5%, and aluminium between 0.15% and 1.4%. Such variability highlights the absence of even a consistent order of magnitude across studies.

This underlines the need for careful selection of characterization methods, ensuring alignment between each method's frequency range, strain amplitude, and the specific characteristics of the fibres studied. Controlling experimental conditions, such as boundary constraints, environmental parameters, and handling procedures, is essential to obtain reliable and comparable data.

To overcome the inherent limitations and uncertainties associated with individual techniques, combining multiple methods on the same fibre samples is recommended. Such an approach provides a broader perspective, helping to identify consistent trends while mitigating the weaknesses of single-method analyses. Furthermore, the complex coupling between damping and rigidity highlights the necessity of developing dedicated models. Modelling efforts are crucial to complement experimental data, fill existing knowledge gaps, and provide a deeper, more consistent understanding of fibre-scale damping phenomena across different fibre types and applications.

5. Recommendation on damping characterisation at fibre scale

Currently, the comparison of data is challenging due to the disparate information obtained from various experimental techniques. However, this review underscores several critical limitations inherent in current approaches to characterizing damping at the fibre scale. To address these challenges and advance the field, several key recommendations are provided.

- Ensure rigorous control of boundary conditions and sample handling. Clamping methods, pre-stress effects, and fibre preparation procedures critically influence damping measurements. Standardising these steps is necessary to improve reproducibility and reduce artefacts, yet detailed procedural descriptions are often missing from the literature.

- Expand characterisation beyond single-mode and single-direction studies.Most existing works focus on one solicitation mode and one material direction, which may suffice for isotropic fibres but fails to capture the anisotropy and complex geometries of natural fibres. Advanced experimental methods and post-processing techniques must be developed to address this gap.

- Clarify damping terminology and units. A consistent definition of damping indicators, with appropriate units and uncertainty intervals, should be systematically provided to enable reliable comparison across studies.

- Validate methods and account for experimental artefacts. Variations between different experimental protocols highlight the need for method validation campaigns, particularly regarding acquisition chain contributions and the influence of added mass or pre-stress on measured damping.

- Broaden the range of studied fibre types and explore alternative measurement methods. While glass and carbon fibres are well documented at the composite scale, their fibre-scale damping characterisation remains limited. Plant-based fibres are also underexplored in terms of their damping properties. Methods such as ultrasound could complement existing approaches by extending frequency ranges.

- Systematically assess environmental effects. Temperature, humidity, and pressure can all influence measured damping, particularly for organic fibres where dehydration under vacuum may impact microstructure. Controlled environment setups should become a standard practice.

In conclusion, a deeper understanding of fibre-scale damping remains essential for advancing applications in both high-performance and bio-based composite materials. Addressing the identified methodological gaps, diversifying the range of studied fibres, and exploring multi-physical effects will enable more accurate, transferable knowledge in this field.

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Conflicts of interest

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

Dedication

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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