



Review

Biocomposites for Marine Applications: A Review of Friction, Wear, and Environmental Degradation

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Abstract

This review explores the latest developments in the study of friction, wear, and degradation mechanisms in the case of biocomposites, including either natural fibers or bio-based matrices or both, intended for marine applications. Biocomposites are increasingly favored, especially for their environmental benefits and sustainability potential. However, they often exhibit inferior mechanical properties compared to traditional composites, especially under demanding conditions. In marine environments, their performance is further challenged by factors such as high humidity, saltwater exposure, fluctuating temperatures, and biofouling. All of the above significantly impact their durability and functionality. This paper examines the performance and degradation characteristics of biocomposites subjected to seawater exposure, especially considering aspects such as friction, wear, and degradation. Additionally, it discusses the recent advancements in surface treatments and material formulations aimed at enhancing the resistance of biocomposites under marine conditions. The review also highlights the critical role of testing methodologies in simulating real-life conditions to better predict the material behavior. By providing a detailed analysis of current research and emerging trends, this paper aims to guide future studies and technological innovations in the field of marine biocomposites.

Keywords: marine biocomposites; natural fibers; bio-based matrices; friction; wear; degradation; seawater; moisture



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1. Introduction

When proposing the use of biocomposites—which are here intended as materials containing biomass in some form, therefore prone to interaction with biological organisms—the characteristics of the environment where the service takes place need to be elucidated and described to the maximum possible extent [1]. This is particularly true in the case of marine applications, where the combined presence of water, salt content (variable over different regions and climates), and a large variety of biological life considerably accelerates and diversifies the modes of material degradation [2]. In the specific case of polymer composites, concern can normally be expressed on the wearing out of the material surface,

which generates the need for protection treatments, e.g., on fiberglass for pipelines [3]. A long duration of service, as for structural composites, increases the moisture effect, which eventually causes the water to penetrate the matrix and its interface with the fibers; this can be prevented with the insertion of barrier materials, such as nanoclay [4].

A broader point of view would consider that the use of lignocellulosic fibers in the marine environment, particularly some specific ones, such as flax canvases from waxed threads in sails [5] and hemp in ropes [6], has a very long history. However, though the suitability for use was of course ensured, until the introduction of biocomposites, the investigation of the aging process was only scantily pursued [7]. The recent availability of large amounts of biomass, in some cases as a by-product, if not waste, of other processes, considerably increased the production of lignocellulosic fiber composites, which can in a wider sense be referred to as “biomass composites” [8].

“Marine degradation” for ship hulls involves different and superposing issues, namely fouling from biological interaction [9] and wear due to loss of material and degradation of properties, which might in turn be enhanced by the biofouling progress [10]. A factor for the acceleration of wear is the presence of friction phenomena arising from the contact with harder surfaces above or below the water surface, especially in the harbor context [11].

The works selected for reference in this review are all those that can explain the potential and difficulties of the introduction of lignocellulosic fibers, or generically “biomass”, into materials aimed for application in marine composites. This might of course also concern the effect of treatment and hybridization with other fillers, e.g., ceramics, on their performance and durability, always bearing in mind the seawater environment.

The core of the review is structured into four parts: Section 2 explores the effect of the marine environment on composites, including the multiple degradation phenomena induced by seawater exposure, such as moisture absorption, ion penetration, thermal and hygrothermal effects, and biofouling. Section 3 will concentrate on the growing role of biocomposites in marine environments, with particular reference to how their structure, composition, and degradation mechanisms influence friction and wear performance. Section 4 outlines the current strategies for enhancing the durability and wear resistance of biocomposites in marine conditions, highlighting integrated design approaches, protective coatings, and anti-biofouling solutions. The positive or negative effects of the combination of material, environment, and protection procedures will be finally discussed in Section 5, where also the limits of investigations and knowledge on the subject so far will be presented.

2. Effect of Marine Environment on Composites

2.1. The Marine Environment: Relevance and Engineering Challenges

Around 71% of the Earth’s surface is covered by the seas, which are crucial and essential regions for human production and biodiversity. The efficient and sustainable use of marine resources is fundamental for the survival of humanity and the progress of society [12]. Industrial sectors involving operations in the oceanic context include, among others, navigation, fishing, resource exploitation, and offshore wind operations [13]. The marine environment poses greater challenges for materials than those normally experienced, including higher exposure to physical, chemical, and biological strain [14]. Under marine conditions, all materials are prone to corrosion and degradation caused by splashing, flooding, and the pressured infiltration of seawater solutions [15]. In particular, the high salinity and humidity in the maritime environment increase this process, reducing the longevity and safety of marine structures [16]. Studies on fiberglass elucidated that initially a Fickian behavior is observed, so that the diffusion coefficient decreases with an increase in salinity, and the highest salt concentration offers a lower water uptake, yet with

matrix degradation, the situation reverses [17]. These concerns can only be addressed by developing advanced functional materials capable of resisting the drastic conditions of the maritime environment. In this scenario, the interaction between biocomposites, including lignocellulosic fibers, and the marine environment introduces specific tribological issues, such as friction, wear, and corrosion, which are often exacerbated by the presence of salt-water and suspended particles [18]. Understanding how materials behave at sea under combined mechanical and environmental stresses due to their respective contacts is the object of marine tribology.

2.2. Background on Marine Tribology

Friction and wear are not intrinsic properties but depend on experimental parameters and the conditions of use [19]. Water transport, an easily feasible way to move or trade heavy goods and bulk products, involves the use of naval machinery and different equipment; hence, the study of friction and wear under seawater conditions appears as an essential requirement to ensure prolonged service [20]. In particular, pumps, open hydraulic drive systems, and ships' blades are exposed to seawater during the running of the machine [21]. In this case, the effect of liquid lubricants over wearing protection is limited due to oil leakage and the highly corrosive nature of seawater. As a consequence, the mechanical parts are required to have great tribological and excellent corrosion-resistant properties in seawater, which is corrosive and highly reactive, to extend the service life while reducing maintenance costs [22]. Recent developments in this area involve the use of new materials with anti-corrosive and anti-wear properties under seawater conditions, among which some polymers have outstanding positions. For example, Yuan et al. [23] explored the tribological behavior of polyphenylene sulfide (PPS)-based composites under cyclic seawater loading, emphasizing their enhanced wear stability. Obviously, other solutions do exist: the application of titanium-based ceramics by pressure vapor deposition resulted in lower friction coefficients in artificial seawater than in other media [24]. In particular, Liang et al. [25] demonstrated that bioinspired surface textures can significantly reduce friction and improve the wear resistance of tribological pairs in seawater. With this perspective, with the continuous increase in market demand, biocomposites could represent valid candidates for specific design in marine applications when promoting the use of sustainable and available materials.

Understanding the origins and principles of tribology assists in defining and delimiting the current efforts to optimize biocomposites for marine applications. Additionally, Chamley et al. [26] highlighted the challenges posed by deep-sea environments, where the (bio)degradation of biopolymers, more specifically poly(butyl succinate) (PBS) and poly(hydroxy butirate-co-valerate) (PHBV), and biocomposites becomes particularly critical. This represents a challenge, because many studies have been carried out in a coastal or harbor context; however, they are not very representative for their use in real navigation.

Tribology, as a field of engineering, could be deemed to have started with the pre-historic materials, which happened to be fretted against a harder tool [27]. Beyond the intentional contact between the two surfaces for working purposes, other relations exist during service, such as in the braking effect, which equally leads to energy consumption and dispersion of particles, sometimes with pollution consequences [28]. The use of composites, which is normally recommended due to their higher strength-over-weight ratio with respect to metals, does indeed present some challenges in practical use, in particular their sometimes-limited resistance to the application of localized forces and contact, resulting in wear by attrition with harder surfaces, which has been recently assessed on a variety of materials [29]. In the case of friction, which involves relative motion with loss

of material, lubrication is normally used to reduce metals' wear, yet this is normally not applicable to composites, where other types of surface treatments may be involved [30].

Aiming for the application of more sustainable composites, such as biomass-including materials, or the treatments to improve their tribological behavior are important aspects nowadays. In [31], concern has been expressed over the fact that more sustainable materials may have a reduced friction resistance, which has pointed out the need to carry out specific investigations, hence developing a research field defined as "green tribology" [32]. This is one of the reasons why, for example, the use of natural fiber composites in brake pads has reduced, which proved effective up to a given fiber/matrix ratio for a number of fibers, among the hardest ones, such as kenaf, coir, oil palm jute, etc. [33]. Beyond enabling the use of some by-products of large economical systems, such as bagasse from sugarcane, this approach helps to avoid problems linked to the harmful effects of asbestos and copper disposal, which, through powder dispersion on road surfaces, would end up in the aquatic environment [34]. Some properties need to be considered so as to evaluate whether the substitution with bio-based materials does work in practice: The first set of properties is based on the realization and mechanical soundness of the composites, such as interfacial adhesion and bonding strength between fiber and matrix [35]. Following this, other characteristics are related to the operation of the material under friction conditions: these are the coefficient of friction (COF) and the measurement of wear by weight loss, volume loss, or linear dimension change [36]. Furthermore, in general, these tribological characteristics in biomass composites are influenced by the applied load, sliding distance, sliding velocity, and fiber orientation [37]. One of the most complex studies on tribological performance has been conducted on the jute, flax, and hemp composites with epoxy resin and their binary and ternary hybrids [38]. The highest performance has been obtained on jute/hemp hybrids, with the lowest wear rate plateauing down at a load of 30 N and for a sliding velocity of 1, 3, and 5 m/s. The beneficial effect of jute suggested that it is applicable also to a seawater situation, depending on the composite layup. However, a minor wear rate would not correspond to a lower flexural strength and modulus decrease after 30 days of seawater aging, as demonstrated in a study on glass/bamboo/jute laminates [39]. Despite these promising advances, the application of jute, perceived as a "less developed" fiber, is still limited, among other sectors, including the nautical one, though some examples of its use exist [40,41].

2.3. Importance of Friction and Wear in Marine Applications

The use of composites in an environment exposed to saltwater does present some severe challenges, not only connected to the presence of high stresses and impact forces due to wind, waves, and tidal energy but also to specific issues, such as salt corrosion and biofouling [42]. This is not exclusively intended for their application in ship components but also in specific structures, such as turbine blades [43]. In the most frequent cases, fiberglass for marine structures has been produced using thermoset matrices, though the situation is gradually changing due to the environmental impact and the complex and ineffective end-of-life of these materials [44]. The potential entry of natural fiber composites in the marine sector has been driven by their lower weight connected to a higher presence of bio-based content. On the other hand, it introduces much more critical variability in the final properties and makes material processing considerably more difficult, often further limited by poor fiber–matrix compatibility [45]. Once again, it is essential to consider that the amount of fiber in the composites is of paramount importance for the assessment of their behavior with regard to the friction properties, even though it is the matrix that is physically exposed to the contact [46]. It also needs to be considered that seawater does provide an alternative way of lubrication, which was extensively investigated too [47].

2.4. Salinity and Ionic Interactions with Polymer Matrices

The marine environment is characterized by high salinity and a rich ionic composition (Na^+ , Cl^- , Mg^{2+} , SO_4^{2-} , etc.), which deeply influences the chemical and physical behavior of polymer matrices in biocomposites. These ionic interactions can alter interfacial adhesion, mechanical stability, and water permeability and even trigger cross-linking or degradation processes.

Among the main mechanisms, it is possible to recognize the following:

1. Ion exchange and release of functional components: in polymer systems containing quaternary salts or antifouling materials, salinity accelerates the ion exchange between the matrix and seawater, facilitating the release of components such as biocides or functional additives. In this sense, a low salinity can be considered a safety requirement against the development of biofouling [48]. This phenomenon has been observed in PMMA matrices containing saline polymers, where the release of active cations significantly increased in saline solutions (up to 2 M NaCl) [49].
2. Ion-activated cross-linking: Some composites are designed to trigger ionic cross-linking in the presence of salt water. In an innovative system with inorganic fillers, ion diffusion activated bonds with matrix functional groups, improving structural strength and paving the way for self-healing materials in saline environments [50].
3. Effects of single ions on enzymatic degradation: Different cations and anions influence the enzymatic degradation of anti-biofouling matrices. Chaotropic ions (e.g., I^-) reduce the enzymatic activity by “salting-in”, while kosmotropic ones (e.g., SO_4^{2-}) increase it by “salting-out”, thus modulating the stability and longevity of polymeric materials in the sea [51].

2.5. Moisture Absorption, Swelling, and Fiber–Matrix Debonding

Moisture absorption is one of the main damage mechanisms in marine biocomposites, with significant impacts on both the mechanical properties and tribological behavior (wear, friction, surface fatigue). It occurs through three intertwined mechanisms:

1. Moisture absorption and diffusion: moisture enters the polymer matrix mainly through diffusion according to Fick’s law, driven by the polarity of the material and the ambient temperature. Natural fibers, being hygroscopic, accelerate absorption, leading to matrix plasticization, reduction of T_g (glass transition temperature) and maximum service temperature, and loss of structural stiffness [52].
2. Swelling and microfractures: once absorbed, moisture causes uneven swelling of the fibers, exerting pressure on the matrix that can trigger internal cracks, interlaminar stresses, and cyclic hydrolysis fatigue. Some longtime aging studies exist that confirm this evidence; for example, in flax/poly(lactic acid) (PLA) biocomposites exposed to marine immersion for 2 years, a mechanical decline directly proportional to water absorption (~12%) and a progressive loss of cohesion between fibers and matrix are observed [53]. The selection of PLA in the specific investigation is justified by the widespread use of this polymer as the matrix for biocomposites in different sectors [54]. This suggested a potential penetration also into the marine field, which has remained more limited than previously expected, despite the considerable interest in additively manufactured parts made with PLA [55].
3. Fiber–matrix debonding by tribological effects, due to the combined effect of swelling of the fibers and hydration of the matrix, impedes the interfacial adhesion. This phenomenon has been largely documented: in composites reinforced with glass microspheres, the water absorption increases with volume fraction, inducing a 9–13% drop in tensile strength and over 20% in flexural strength [56]; in z-direction stitched glass–epoxy laminates, a 55% loss in fracture toughness was observed af-

ter 35 days in seawater, with debonding visible under SEM microscopy [57]. In three-dimensional woven (3D6D) materials, interstitial swelling and water transport along the microchannels led to up to a 47% decrease in compressive strength, confirming that moisture delamination is the main driver of mechanical degradation [58]. Even though all cases are related to the synthetic composites, there is no reason to assume that the phenomenon would be absent in biocomposites, where wettability issues are inherently severe and need specific studies every time a less-used lignocellulosic fiber is introduced in the composites [59].

Due to its general relevance, a large number of papers investigated the effect of moisture absorption on biocomposites, especially in the case of natural fiber composites (NFCs). For example, the negative effect of water absorption on the mechanical properties of hemp-reinforced composites was analyzed by Dhakal et al. [60], showing that exposure to high temperatures significantly accelerates the overall degradation introduced by water absorption. In a study of injection-molded thermoplastics containing short sisal fibers [61], moisture uptake enhanced impact resistance, possibly due to the limited dimensions of interfacial contact, at the expense of tensile modulus and strength, due to the modification of the fiber-to-matrix interface. Finally, Le Duigou et al. [62] evaluated, following from their previous study in [53], the hygrothermal degradation of flax–poly(lactic acid) (PLA) composites in seawater, finding reduced strength and stiffness after exposure at 40 °C.

2.6. Thermal Cycling and Hygrothermal Aging

In marine biocomposites, hygrothermal aging and thermal cycling are among the most insidious long-term degradation mechanisms. They combine the action of humidity (typically seawater) with temperature variations—for example, those that occur during day/night alternation, seasons, or variable sea depths. These processes influence not only mechanical resistance but also tribological behavior.

Among the main mechanisms, it is possible to identify the following:

1. Hygrothermal absorption and microstructural damage: A study on ultrahigh molecular weight poly(ethylene) (UHMWPE) biocomposites loaded with different weight fractions of mollusk shell powder shows that hygrothermal aging accelerated by exposure at 80 °C in a Ringer's physiological solution reduces wear resistance and modifies tribological behavior. This results in the generation of microcracks and localized swelling that favor delamination [63]. On biocomposites, an issue that is of significant importance is the need to have adequate fire-resistant behavior through the addition of adapted additives, such as 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO) or aluminum diethyl phosphinate (AlPi). An analysis carried out in [64] on flax/epoxy composites demonstrated that though DOPO approximately doubled the amount of water absorbed, the fire-retardant effect was maintained, except for the highest level of humidity at 70 °C temperature.
2. Plasticization and loss of mechanical properties: In glass fiber (GF)–thermoplastic composites immersed at 35 °C and 70 °C, mechanical loss reaches up to 50%, especially for flexural and compressive properties. Matrix cracking and fiber–matrix debonding are observed as the main failure mechanisms [65]. Early studies involving bio resins, such as poly (butyl succinate) (PBS), with silk and henequen fibers at 60 °C and 85% relative humidity (RH) indicated a decrease in storage modulus in the region of 20 and 505, respectively [66].
3. Changes in glass transition (T_g): Contrary to expectations, some studies on fiberglass show that hygrothermal aging can also increase T_g due to secondary cross-linking reactions, affecting stiffness and tribological response under repeated loading, which extends the temperature range of glassy polymer [67]. However, the presence of

lignocellulosic fibers, such as in the case of hemp, indicates a reduction in T_g , both using a partially bio-based epoxy and a poly(methyl methacrylate) (PMMA) matrix, though slightly more severe for immersion at 60 °C than is the case at 21 °C [68].

Despite the only partially and qualitatively elucidated character of the above phenomena, predictive damage modeling could eventually come into the picture. A recent model shows how moisture absorption and temperature increase directly influence Young's and shear modulus, with losses growing exponentially near the T_g of the material due to the progressive propensity to extension of the polymer chains [69]. Even if developed for epoxy reinforced by high-strength carbon fibers (T700), its general outcomes can be presumably extended to biocomposites.

2.7. Biofouling and Microbiological Impacts on Material Surfaces

In marine environments, biofouling—the colonization of surfaces by microorganisms, algae, and higher marine organisms—is one of the main causes of surface degradation and deterioration of tribological performance in biocomposites. Different levels of biofouling at the microscopic level (microfouling) are qualitatively reported in Figure 1. Biofouling proceeds through different steps, starting from the accumulation of microorganisms on the material surface—like microalgae, bacteria, and diatoms—leading to the formation of a biofilm having a low thickness: this can be referred to as microfouling or soft fouling. The accumulation of biological material can be even more pronounced with time, especially when larger organisms and plants like weeds, diatoms, mussels, and barnacles adhere to the surface of ship hulls; as a result, a thicker calcareous layer of biological material is formed, usually referred to as macrofouling or hard fouling [70,71]. Preventing biofouling is very important, since it can increase the ship's drag, inducing up to 18% of penalty in shaft power, with negative consequences for both the economic and the environmental aspects of the shipping industry as a result of larger fuel consumption and larger greenhouse gas emissions [72]. A specific study was also carried out to study the application of flax into PLA or PBAT composites to obtain artificial reefs: the formation of biofilm as the first stage of fouling was assessed using specific marine microorganisms, such as *Pseudoalteromonas* sp. 3J6 and *Cylindrotheca closterium* [73]. This allowed establishing the presence of flax fiber leachates and plastic monomers, which did not find large differences between the two matrices.



Figure 1. Qualitative levels of micro biofouling (original image by the authors).

In addition to the increase in hydrodynamic resistance and surface mass, biological growth accelerates micro-degradation, delamination, and surface aging, especially in natural or bio-derived materials.

The main mechanisms are the following:

1. Microbial colonization and release of degrading metabolites: Immersed composite surfaces are attacked by bacterial communities that produce organic acids, biosurfactants, and hydrolytic enzymes. These compounds degrade polymer bonds, promoting interlaminar detachment and surface embrittlement. Studies on graphite/epoxy composites have shown that biofouling accelerates the decline in tensile strength and induces microfracture signals detectable by acoustic emission [74]. Other long-term studies based on jute and sawdust epoxy composites exposed to drain water showed a significant loss due to the microbial damage, in particular a reduction in the tensile strength of 57% for the jute composite and of 40% for the sawdust composite, after their exposure to drain water for 1 year. Regarding the flexural strength, a decrease in the flexural strength of 43% and 34% for the jute and the sawdust composite, respectively, during the same period was observed. In this case, the biological action of some microorganisms producing enzymes like lipases and proteases led to the deterioration of the composite matrix, worsening the structural and mechanical properties of the composite material [75].
2. Biofilm–matrix interaction and tribology: Biofilm acts as a viscoelastic intermediate layer between the material and the surrounding medium, altering friction, adhesion, and wear rate. In biodegradable polyurethane composites modified with clay and the biocide dichloro octylisothiazolinone (DCOIT), colonization by bacteria and diatoms was significantly reduced, confirming the role of chemical design in biofouling management [76]. As a whole, it can be suggested that biocides commonly used in biocomposites, such as tannic acid, might have an effect in considerably delaying the formation of biofilm [77]. In a more general way, tannins form a multifunctional category of chemicals widely used in the development of bioplastics and biocomposites, according to a recent review [78].
3. Role of plasticizers in the formation of fouling biofilms: The chemical formulation of the matrix influences the selection and density of microbial communities. It is no surprise that the use of bioplasticizers for the formulation of plastics might promote biological action in them [79]. This will likely lead to a larger and faster formation of biofilms, since also on conventional plastics, such as poly(vinyl chloride) (PVC), bioplasticizers are well known to promote some biodegradation [80]. Conversely, in polystyrene (PS), microplastics from plastics and resins produced using bisphenol A (BPA) or diethylhexyl phthalate (DEHP) showed greater biofilm-induced biodegradation than those in the absence of plasticizers. This occurred in a specific context that aimed at reproducing the Australian coral reef environment [81].
4. Accelerated degradation in the presence of natural fillers: In polyhydroxybutyrate co-valerate (PHBV)-based biocomposites with olive pomace flours, microbiological degradation is more marked, with crack formation and erosion visible already after 6 months at 40 °C in seawater, confirming that the biocompatibility of the matrix accelerates environmental decomposition [82]. Natural fillers—like rice husk, peanut and groundnut shell powder, and wood sawdust—are, in fact, hydrophilic species and consequently favor water absorption in the composite matrix [83]. In marine environments, water absorption in the polymeric matrix favors its biodegradability and the colonization of microorganisms with consequent biofouling. A review by Brebu [84] reports the effect of natural fillers blending on different polymeric matrices: Polyethylene (PE) and polypropylene (PP) composites do not show great biodegradability, while polyhydroxyalkanoate (PHA)-based composites showed better biodegradability performances; wood plastic composites (WPC) were shown to be subjected to attack by fungi in case of warm temperature and high moisture environments, thus not making them useful for outdoor applications; poly lactic acid (PLA),

a hydrophobic polymer obtained from natural sources, can be modified to be more hydrophilic if blended with chitosan, favoring microbial colonization. This, together with an increase in the crystallinity of the polymer in the composite material, leads to an enhancement of the biodegradability of the material. The biodegradability of poly butylene succinate (PBS) was also reported to increase when used with hemp fillers up to 70%.

5. Correlations with surface energy and hardness: Polymers with high surface energy (e.g., GFRP) are more susceptible to biofouling than flexible ones (e.g., silicone), since they provide an easier gripping surface. The surface free energy is defined as the energy needed to create a new surface from a bulk solid. The relationship between surface energy and bacterial adhesion, due to critical surface tension depending on contact angle, can be described by the Baier curve (Figure 2), which reaches its minimum around 22–24 mN/m. This experimental data allows the design for fouling release and anti-fouling materials and coatings [85]. Hydrophobic materials having low surface energy avoid initial fouling and facilitate the detachment of already present organisms on the ship hulls [86]. Furthermore, tribological properties worsen in proportion to biological accumulation, with a loss of mechanical resistance up to 7.5% in poly(ethylene terephthalate) (PET) and polyurethane (PU) [87].

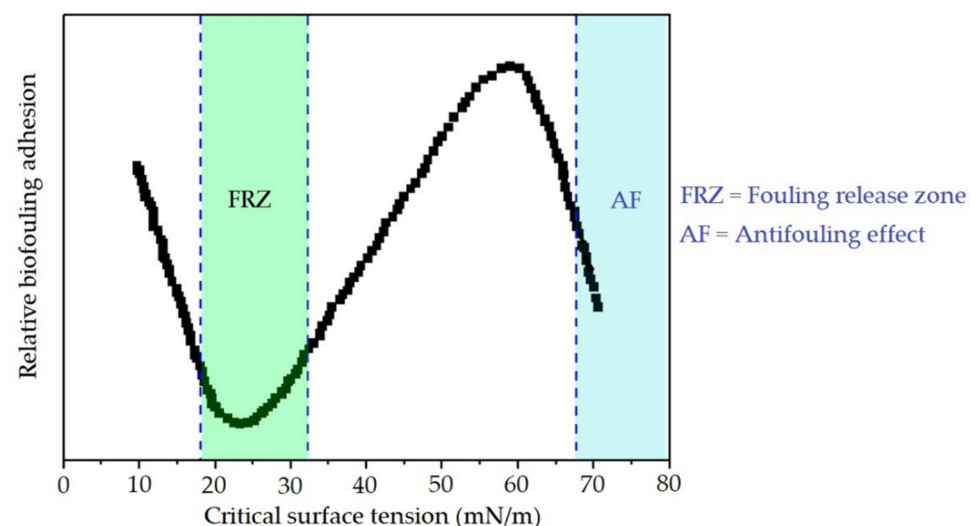


Figure 2. Example of a typical Baier curve (original figure by the authors).

3. Biocomposites in Marine Applications

3.1. Natural Fibers: Types, Properties, and Marine Performance

Natural fibers, sourced from renewable plant or animal materials, are increasingly being considered in the development of biocomposites due to attributes such as low cost, low density, and environmental sustainability. In marine applications, however, their performance is affected by environmental factors, including water absorption, swelling, biodegradation, and reduced mechanical strength. Among plant-based options, bast (e.g., flax, hemp, jute), leaves (e.g., sisal, abaca, pineapple), fruit hair (e.g., coir), and seed hair (e.g., cotton) fibers are the most commonly utilized, though other derivations also exist, such as from bark or grass. In Figure 3, a (non-exhaustive) number of categories and subcategories of fibers are reported, each of which is supported by evidence from existing studies and applications; it is also worth noticing that for some specific categories, comprehensive reviews have recently been provided [88].

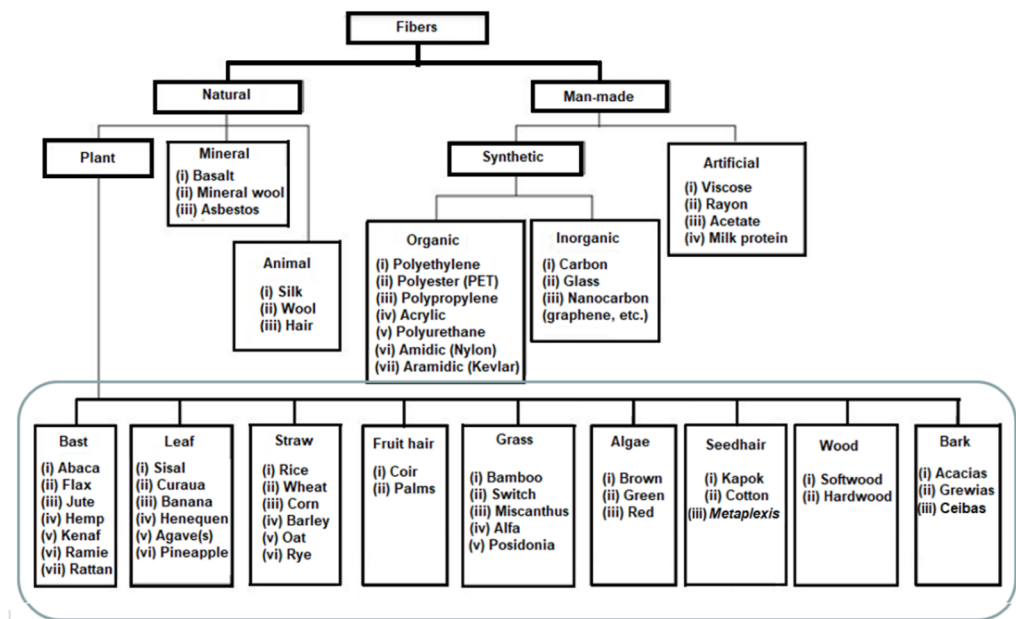


Figure 3. Fiber classification by categories (origin) and subcategories (species/group of species) (original image by the authors).

Concentrating on lignocellulosic (not wood) fibers—as defined in the scope of this review, containing more than 50% cellulose and hemicellulose, some amount of lignin, and in some cases pectin and waxes—some of these have attracted significant interest for enhancing the composite strength over the last decades, which hints at their prospective possible application in the marine sector. Among these are some bast fibers that have become classical for their diffusion and mechanical strength and moisture resistance, and are widely investigated for their use in composites, such as flax [89], hemp [90], and jute [91]. In other cases, such as for coir, the higher lignin content guarantees a more effective protection against microbial attack—a characteristic exploited and improved by their use in geotextiles; however, they are not comparable with the previously mentioned ones as far as stiffness is concerned [92].

Despite their many advantages—which support their application in composites as the replacement for fibers such as glass ones [93]—lignocellulosic fibers have a serious drawback when used in moisture-filled or seawater environments. These issues are compounded by their low resistance to abrasion, which calls for cautious approaches, such as using hybrid composites (e.g., bamboo/jute/glass), including some inorganic fibers [94]. The biodegradable character of these fibers presents the advantage of preventing their accumulation in the water drainage system, unlike what happens with polymers [95].

On the other hand, addressing biodegradation represents a challenge, which is even greater for marine applications, as the materials are constantly in contact with salt water, high humidity, temperature changes, and UV radiation. In this environment, natural fiber composites absorb water through capillarity and suffer mechanical embrittlement [96]. During immersion, absorbed moisture will migrate through the polymer matrix and into the fiber, where swelling will produce microcracks and result in debonding at the fiber–matrix interface, leading to the ineffective transfer of the load [97]. Some indications of the incorrect working of the composites in that case are reported in Figure 4. In a saline environment, this phenomenon is accelerated by osmotic effects and possibly microorganism colonization, which will gradually pave the way for biofouling, protection from which will be specifically dealt with in Section 4.4. For this reason, plant fibers have generally poor durability in marine exposure, more often hindering their direct application in long-lasting

structural marine components, since their hierarchical cellular structure unduly favors water penetration [98].

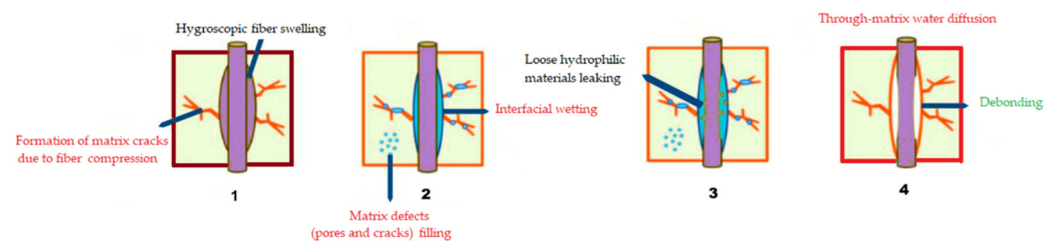


Figure 4. Ineffective working of fiber–matrix interface in case of water penetration (original image from the authors).

To overcome these issues, a great deal of studies are available on chemical and physical treatments for increasing the marine performance of natural fibers by regularizing their surface [99]. Alkali treatment, most frequently performed using sodium hydroxide (NaOH) with different concentrations, times, and temperatures, is frequently employed to remove surface impurities and for hemicellulose cleaning [100]. This treatment has a proven effectiveness in increasing surface roughness, which is beneficial for matrix adhesion; extensive studies have been carried out, e.g., on bamboo fibers [101]. Other well-known surface modifications that have been indicated to reduce the moisture uptake and are therefore specifically of interest for marine applications include the coating of fibers through silane coupling agents [102]. Another treatment that has earned particular interest is acetylation, derived from the tradition of cellulose modification [103]. Acetylation can also, not differently from silanization, follow alkali treatment on fibers, providing substantial mechanical improvements, as reported on banana unidirectional mats in [104]. When applying polyolefin thermoplastic matrices, maleic anhydride grafting is normally used to enhance the lignocellulosic fiber–matrix relationship by reacting with the hydroxyl groups present in the former, which also results in an improved water resistance [105].

Among the many plant-based fibers that have been proposed for marine applications, attention has been given recently to the fibers derived from the plants growing in marine environments. One of those promising organisms is *Posidonia oceanica*, a Mediterranean endemic marine plant. These fibers are in direct contact with seawater during their life cycle and have a marine resistance that does not exist in terrestrial fibers. Recent studies have shown that *Posidonia oceanica* fibers display lower water absorption and greater dimensional stability when immersed in seawater [106]. Using epoxy as the matrix, which is an inherent limitation, yet on the other hand allows an easier comparison of the performance of natural fibers among them, *Posidonia oceanica* fibers exhibit enhanced mechanical properties, preserving and reducing interfacial deterioration, and may contribute to an increase in the service life of the composites in marine environments [107]. Other studies with more ambitious objectives suggested the use of polyhydroxyalkanoates (PHB) with bacterial origin as the matrix for *Posidonia* fibers in composites explicitly aimed at the marine environment [108].

So far, in the marine industry, natural fiber composites are being used to a quite limited extent as non-structural or semi-structural elements, such as boat interiors, paneling, insulation, and some small deck elements [109]. Their use is also being investigated for biodegradable fishing gear, aquaculture apparatus, and underwater ecological facilities [110]. In such use, a partial loss of mechanical strength might still be acceptable or even environmentally desirable. When it comes to real structural use, natural fibers have some limitations, such as an inevitable inherent variability in properties, as they are also influenced by the pre-production characteristics, which involve, among other factors, growth conditions, harvesting, and processing/extraction methods [111]. In order to enhance

performance and maintain sustainability, the formulation of marine class standards and durability test protocols will be necessary to ensure their use [112]. In conclusion, despite the environmental and economic advantages, successful utilization of natural fibers in marine applications requires a sensible selection of materials, treatment of fibers, and composites. Indications of the potential offered by different fiber treatments are qualitatively summarized in Figure 5.

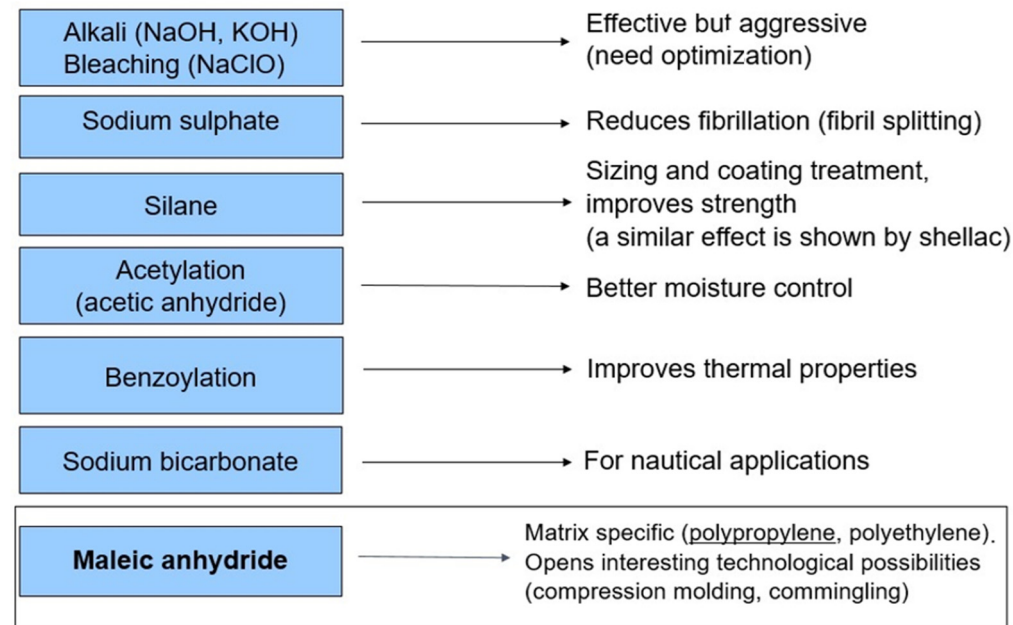


Figure 5. Some types of fiber treatments and their qualitative importance (original image by the authors).

A large amount of literature exists in terms of the influence of chemical treatments—non-exhaustively reported in Figure 5—on water absorption resulting in the geometrical modification of the fibers. As suggested above, most of the studies concern mercerization, the traditional alkali treatment performed using sodium hydroxide and, more rarely, potassium hydroxide, especially on less standardized fibers [113]. Therefore, it is possible to consider the aforementioned treatment as the “standard” mode for modifying the surface of lignocellulosic fibers and removing loose material so as to make their section closer to a quasi-circular shape. In terms of water absorption, a number of reviews are available on the effects of alkali treatment on lignocellulosic fibers. In particular, Chandrasekar et al. (2017) reported an increase in tensile strength for the treated fibers, ascribed especially to the change in failure mode and more limited proneness to fibrillation and, hence, pull-out in the composite. This was reported with reference to jute fibers immersed in 5% NaOH solution for a minimum of 4 h [114]. The benefits of using alkali-treated fibers—in mechanical and tribological terms—for the production of biocomposites have also been recognized in [115]. However, more concentrated solutions (of up to 15%) for much longer immersion times (up to 72 h) have been experimented with, providing different levels of efficacy on the improvement of tensile strength and stiffness, yet tending to separate fibers, such as abaca. This also poses the question of how drying should be performed, naturally or accelerated at higher temperatures [116]. Another possibility arises from the mixing of sodium hydroxide solution with other agents, such as hydrogen peroxide, acetic acid, and carbamide, on luffa sponge fibers, with sodium hydroxide primarily contributing to the reduction in moisture regain [117].

A similar treatment, bleaching with sodium hypochlorite, proved effective on Yucca fibers, resulting in an increase in the thermal degradation temperature (in that case of up to

40 °C), and can be intended as a thorough oxidative washing [118]. Other washings did not give comparable results, such as sodium lauryl sulfate (SLS) on ramie fibers, where crystallinity and thermal resistance were only slightly improved [119].

Less popular treatments have also been proposed with some degree of success. Sodium sulphate has been used, based on the experience with cellulosic fiber processing in textile industries to produce viscose, making fibrillation less likely and, therefore, obtaining a sounder interface and making water penetration more difficult; this has been applied, e.g., on alfa fibers [120]. Together with sodium carbonate, the action of sodium sulfate solutions on cellulose fibers results in a controlled swelling, which is less destructive for fibers, though it is of lesser interest for those that present a higher lignin content [121]. However, one important limitation is the relative scarcity of comparative studies among different treatments on the same fiber: an example is the one performed on *Bauhinia variegata*, comparing the effects of benzylation, alkalization, and bleaching [122]. Sodium bicarbonate treatment has been demonstrated to be specifically effective in the case of water absorption (immersion time has been optimized in the case of *Washingtonia filifera* palm waste, based on a 3% treatment concentration) [123]. Specific studies were carried out using this treatment on flax [124] and sisal fibers [125], both intended for use in epoxy composites.

The integration of marine-adapted fibers, such as *Posidonia oceanica*, together with the progress in hybrid composites and bio-based resin systems, appears as an interesting path for more resistant and sustainable marine materials, which would ideally replace the characteristic fiber structures for GFRPs. These can take different forms, such as woven and unidirectional, and are normally arranged in the composite to be completely filled with resin, to the extent that the term “matrix layers” is sometimes used in this case [126]. The basic applications of the most well-known lignocellulosic fibers in the marine environment are listed in Table 1.

Table 1. Principal applications in marine environments of some natural fibers (original table by the authors).

Natural Fiber	Sea-Related Properties	Some Applications
Coir [127]	High resistance to saltwater and microbial attack	Ropes, mats, and fenders
Jute [128]	Moderate resistance to water; non-Fickian behavior	Non-structural components, paneling, and linings
Flax [129]	Low water absorption when treated	Composites for boat hulls, decks, and other structural components
Hemp [130]	Resistant to UV light, durable, and strong; Fickian behavior	Ropes and sails, composites for boat hulls
Sisal [131]	Resistant to salt water yet not to microbial degradation (risk of fungal growth) [132]	Ropes and twines
Bamboo [133]	High strength-to-weight ratio, high anisotropy owing to variable porosity structure [134]	Materials for flooring, decking, and structural components in boat hulls
Kenaf [135]	High tensile strength, light yet stiff, biodegradable	Interior panels and in structural applications after treatment
Pineapple leaf (PALF) [136]	Abundant waste, good torque properties for thinner filaments	Ropes (as the competitor with sisal)
Banana fronds (flower pistils) [137]	Quasi-constant flexural properties at all orientations, not very resistant to saltwater	Ship components above water

3.2. Matrix Systems: Bio-Based vs. Synthetic Resins

In marine biocomposites, as in composites in general, the matrix system is crucial to transfer loads, protect the fibers, and ensure mechanical and environmental stability. Matrices are mainly divided into synthetic resins (e.g., epoxy, polyester, vinyl ester) and bio-based resins derived from renewable sources (such as PLA, PHA, and bio-epoxides). Synthetic resins are usually appreciated for their high mechanical strength (tensile strength up to 80–100 MPa); thermal stability ($>100\text{ }^{\circ}\text{C}$), though this might be affected by trespassing the glass transition temperature (see below); and excellent resistance to moisture and chemicals, characteristics that make them ideal for naval structures. However, they are derived from non-renewable resources and are not biodegradable as such, although end-of-life strategies based on enzymes are currently being developed, aimed at their mineralization for disposal. Apart from the well-known case of polystyrene, which is consumed by black (*Tenebrio obscurus*) and white mealworms (*Tenebrio molitor*) [138], other strategies are gradually being developed for the recycling of epoxy [139]. This obviously will displace the problem of eventual biodegradation, provided the adapted environment for enzymatic action will be set when preparing for material disposal.

About reducing the resource depletion during polymer production, the question is different: bio-based resins, such as PLA, PHA, and bio-epoxides, where bisphenols are synthesized from a raw material partially derived from vegetable oils, offer a reduced environmental footprint. However, they tend to present lower water resistance, mechanical brittleness, and limited thermal stability (e.g., PLA: glass transition $\sim 60\text{ }^{\circ}\text{C}$). In a recent study, epoxy resins with 28% bio-based content combined with flax or hemp fibers showed water absorption up to 9.8% and a drop in mechanical properties (tension/flexure) between 26% and 74% after immersion in seawater [140]). In a direct comparison, partial bio-based epoxy resins (with biomass content) showed good performance when combined with synthetic fibers (glass, carbon), suggesting an effective trade-off between sustainability and strength [141]. The limited, though present, water absorption by bio-epoxy resins (in the order of 1–1.5%) did not limit, so far, their applications in other challenging systems, such as aerospace [142] and automotive [143]. However, the commercial availability of such resins is still limited. To improve the performance of bio-based resins in marine environments, approaches such as chemical modification of resins, the use of nanofillers (e.g., graphene, nanocellulose), and hybrid systems (bio resin + synthetic additives) are being explored [144]). The cost of bio resins also remains higher than the conventional ones, even if rapidly decreasing, thanks to new production technologies (e.g., biotechnologies from sugars or agricultural residues). Furthermore, the low density of biofiber allows for the possibility of using higher fiber content in composites, which can also further reduce the non-renewable petroleum-based polymer content in products. This weight reduction can help in reducing the fuel consumption and lead to lower carbon emissions, which is a crucial point for the naval sector, even for high-technology applications, such as racing boats [145]. Concerning life cycle assessment (LCA) and energy consumption, it was reported that the LCA of biobased composites (from biobased epoxy resin and natural fibers) was more advantageous than traditional petro-based composites (from epoxy and glass fibers) in terms of energy use and environmental impact, as observed from the LCA comparison of fiberglass and flax fiber composites in ships' hulls [146]. These are some of the main reasons that make biofiber-based biocomposites an attractive alternative to synthetic fiber-based composites for many industrial sectors, including naval constructions.

Recently, particular attention has been paid to the development of furan-based bio resins derived from renewable sources, such as furfural and 2,5-furandicarboxylic acid (FDCA). These resins, including poly(methylene furanoate) (PMF) and furan epoxides, offer an attractive combination of good chemical resistance, thermal stability (T_g up to

120 °C), and low water absorption, making them promising for marine applications [147]. Furan-based bio resins improve the thermal resistance and marine durability compared to traditional PLA or PHA. In particular, FDCA-based bio resins stand out for their high stiffness and resistance to saline environments—thanks to the furan aromatic backbone, which confers greater protection against hydrolysis compared to traditional polyester bio resins—and potential self-healing at low loads [148]. Furan-epoxy can also offer potential for composites starting from biomass, such as it is the case for eugenol from cloves [149]. Some outcomes are reported in Table 2.

Table 2. A rapid overview of synthetic vs. bio-based resins concerning marine applications (original table by the authors) (some indicative data from literature are offered).

Property	Synthetic Resins	Bio-Based Resins
Origin	Petrochemical	Renewable sources (biomass, vegetable oils)
Typical Examples	Epoxy, Unsaturated polyesters, Vinyl esters	PLA, PHA, Bio-epoxies, Furano-epoxies
Tensile Strength	Normally around 80–100 MPa Over 60 MPa for epoxy [150]; 63 MPa for vinyl esters cured at 40 °C [151]; A value of 114 MPa was measured in [152].	50–70 MPa for PLA (up to 58 MPa was measured in [153] for different raster angles); 70–90 MPa for furans (over 65 MPa was measured in [154])
Young's Modulus	Over 3 GPa for epoxy [150], less for other resins	1–2.5 GPa, yet often much lower for PHA (even limited to 300–400 MPa) [155]
Water Absorption	Very low and rapidly desorbed (may produce critical effects only at temperatures such as 90 °C) [156]	High-moderate (depending on the type of bio resin)
Chemical Resistance	Very good (problems with acids, improving with polyamine concentration in epoxy) [157]	Good, but lower in saline environments for PLA/PHA
Thermal Stability	High (>100 °C)	Limited (~60–80 °C for PLA; >100 °C for furan-based resins)
Glass Transition Temperature (T_g)	90–130 °C (~100 °C for unsaturated polyester) [158]	60–120 °C (depending on the bio resin type)
UV Resistance	Variable (may require additives, such as UV stabilizers) (organic polymer coatings) [159]	Generally low, requires surface treatments
Biodegradability	None in non-prepared environment	High (especially for PLA, PHA)
Durability in Marine Environments	Excellent (with protective coatings)	Variable, can be improved with surface treatments
Environmental Compatibility	Low (end-of-life issues)	Higher (possible compostability)
Commercial Availability	Wide	Limited but growing
Raw Material Cost	Medium (relatively inexpensive)	Variable (currently higher than synthetic resins)

Other studies on the use of different biocomposites for marine applications have been carried out by various authors. For example, pineapple leaf fiber (PALF) holds potential for industrial use, particularly in reinforcing materials. A study carried out by Rahman and Ariffin [160] focused on utilizing PALF as reinforcement with epoxy for marine applications. Their research explores the impact of layering, orientation, and material volume on flexural strength and water absorption. The samples, composed of three layers with 70% epoxy and 30% PALF, underwent a 3-point bending flexural test, evaluating maximum force, stroke, stress, strain, and Young's modulus; however, the results appeared incoherent and hardly applicable.

A study on bamboo-epoxy composites for structural applications was conducted by Biswas [161], in which physical and mechanical properties were studied. Composites were fabricated using short bamboo fibers at four different fiber loadings (0, 15, 30, and 45 wt.%); it was observed that the void fraction increases significantly with respect to fiber loading, and, in particular, this property increased from 1.71% to 5.69%. In order to reduce the void fraction and to improve the hardness and other mechanical properties, silicon carbide (SiC) filler was added to bamboo fiber-reinforced epoxy composites at four different weight

percentages (0, 5, 10, and 15 wt.%) at the highest fiber content (45 wt.%). The significant improvement in Vickers hardness (from 46 to 57 HV) at 15 wt.% SiC, tensile strength (from 10.48 to 13.44 MPa) at 10 wt.% SiC, flexural strength (from 19.93 to 29.53 MPa) at 5 wt.% SiC, and reduction of void fraction (from 5.69 to 3.91%) at 5 wt.% SiC were observed. The results of this study indicate that using particulate-filled bamboo fiber-reinforced epoxy composites could successfully allow developing a composite material offering high strength and rigidity for lightweight applications.

Fitriadi et al. [162] investigated the physical characteristics and thermal conductivity of composite materials from a mixture of cocopeat and polyurethane for the fishermen's fish box insulation, which, though being a simple structure, is deemed to be in continuous contact with saline atmosphere, if not with saltwater at all. The obtained results show that cocopeat can be used in a cocopeat–polyurethane mixture for this application, although the heat conductivity results are still lower than those obtained with the 100% polyurethane material (0.026 m.K). However, the test results are still within the recommended insulation material limits of 0.023–0.04 W/m.K. The material composition chosen for the fish box insulation on fishing boats is a 1-to-1 composition; in this regard, there is a conductivity value of 0.037 W/m.K with a yield stress of 0.05 MPa and a maximum stress of 0.7 MPa; therefore, this material can save polyurethane usage by 50%.

Dhanenderan et al. [163] formulated sustainable material by utilizing banana flower pistil waste, a byproduct of banana flower consumption, as a reinforcement agent. A composite with 25 wt.% banana flower pistils demonstrated the highest mechanical performance, achieving 64 MPa in tensile strength, 185 MPa in flexural strength, 7.64 kJm^{-2} in impact strength, and 89 Shore D hardness. However, the composite with 30 wt.% banana flower pistil also showed the utmost water absorption, much higher than usual values, of 21% over 10 days. These findings indicate that the 25 wt.% composite optimally balances mechanical strength and water resistance. The resulting composite could be used in the shipbuilding industry, especially where moderate load-bearing capacity and sustainability are prioritized.

Another important cellulose fiber is kenaf, and its application in marine environments remains relatively scarce. However, cellulose fibers are extensively used in marine-related fields, including boat construction, marine sports equipment, coastal engineering, offshore engineering, and environmental protection. The application of kenaf fiber-based composites in marine environments remains in the primary stage, with relatively few cases reported, according to the very recent review by Huang et al. [164]. However, interesting studies on kenaf-based composites are also the ones based on the incorporation of nanoparticles. Taj et al. successfully reduced the porosity and seawater absorption of kenaf/epoxy composites by optimizing the ratio of alumina to graphene nanoparticles [165]. Raj et al. incorporated 0, 2, 4, 6, and 8% graphene nanofiller in kenaf/epoxy and discovered that the composite with the maximum graphene content demonstrated the lowest water content (5.1%), which represents a 51.4% decrease relative to the graphene-free composite [166]. A similar result was observed by Palmiyanto et al., who added 4%, 8%, and 12% microcrystalline cellulose (MCC) nanoparticles to glass and kenaf fiber-reinforced phenolic resin composites and found that 12% MCC nanoparticles exhibited the lowest seawater absorption [167]. It can be concluded that integrating nanoparticles to a certain proportion in fiber-reinforced composites can significantly decrease water uptake, though it involves increased costs and might not always be sustainable if the nanoparticles have to be synthesized.

Concerning the bamboo-based composites, there is currently a great deal of interest in developing a new generation of these composites for use in fishing vessels; indeed, bamboo is suitable as a material for construction because it is sufficiently hard, strong, and dimensionally stable. Manik et al. [168] investigated laminated bamboo composites (LBCs)

and fiberglass mats to obtain certain mechanical characteristics. The LBC with $45^\circ / -45^\circ$ cross-fiber directions combined with chopped strand mat fiberglass was developed under different layers and mass fractions with the same composite thickness. The influence of different numbers of laminated bamboo layers (3–7 layers) on several mechanical properties was investigated. The result showed that an improvement in the strength properties of LBCs could be achieved by using a thinner bamboo lamina with a higher number of bamboo layers. It was found that bamboo composites with seven layers, hence with a higher epoxy mass matrix, had superior mechanical properties to those with three and five layers at the same thickness. Another finding revealed that adding fiberglass mat to current LBCs improved the mechanical properties compared to previous research; specifically, the bending strength increased between 4 and 7.5% and the tensile strength between 12.4 and 17.7%.

Corradi et al. [169] analyzed the overall mechanical characteristics of bamboo fiber-reinforced composites and sandwiches for general marine applications. For this study, bamboo laminates were made from bamboo strips milled out from bamboo wall cores. An accurate analysis of the processing possibilities and chemical–physical characterization was conducted, evaluating the relationship between composites' performances, processing characteristics, and environmental aging. As applications, a hull panel and a spinnaker pole were used and tested for impact and for axial compression load, respectively; subsequently, a complete 6 m boat hull was realized in order to analyze critical lamination points and the effectiveness of vacuum bagging. The tests of accelerated aging and water absorption highlighted the resistance of the adopted material to the aggressiveness of the marine atmosphere; in the realization of the real prototypes, however, the utilization of waterproofing treatments on the exposed parts is expected to improve the mechanical properties of the composite. Adhesion tests offered an optimal interlaminar shear strength (ILSS) value, over 3.5 MPa, for the utilization of such material in sandwich skins, even without any application of fiber treatment.

3.3. Filler and Coupling Agents: Role in Durability and Wear

In the context of marine biocomposites, the integration of fillers and coupling agents represents a key strategy to improve durability, wear resistance, and mechanical performance over time. Fillers, which can be natural (e.g., fruit shells, seaweed) or minerals (e.g., hydroxyapatite, alumina), help increase stiffness, reduce thermal shrinkage, and modulate environmental degradation properties. However, the addition of fillers can introduce discontinuities at the interface with the matrix, generating weak points unless a compatible coupling agent is used. Coupling agents—such as grafted maleic anhydride (e.g., PE-g-MA, SEBS-g-MA) or titanates—chemically bond the polymer matrix to the filler surface, improving interfacial adhesion and reducing delamination and water absorption. A study on HDPE biocomposites reinforced with green algae showed that the use of PE-g-MA reduced water absorption by up to 0.94% and increased stiffness to 1.63 GPa [170]. In the applications exposed to marine humidity, the use of marine bio-fillers, such as brown algae or mollusk shells, has been shown to improve moisture resistance and mechanical stability. In addition to traditional natural and mineral fillers, seashell-derived powders have been investigated as sustainable reinforcements capable of enhancing mechanical stability and moisture resistance in saline environments [171]. In epoxy, a combination of marine shell powder with jute fabric composites proved particularly effective [172]. In thermoplastic polyolefin matrices, the final result does not only depend on the filler loading and grain size but also on the presence of the coupling agent, i.e., normally maleic anhydride (MA). In the absence of the latter, fillers can generate internal voids and lead to increased wear by friction or mechanical fatigue over time [173]. Studies with argan shell fillers in polymer

matrix have highlighted that the use of SEBS-g-MA significantly improves tensile strength and reduces water absorption, promoting better distribution and dispersion of the filler in the matrix [174].

3.4. Fabrication Techniques and Effects on Tribological Behavior

The manufacturing technique strongly influences their behavior with respect to friction, wear, and mechanical contact resistance of biocomposites [175]. This is critical in marine contexts, where materials are simultaneously exposed to cyclic loading, particle abrasion, biofouling, and saline environments; more details are offered in Table 3. The most common techniques in this context include

- **Compression Molding:** This generates compact and homogeneous structures with low porosity, contributing to better wear resistance. However, it is less suitable for complex geometries.
- **Injection Molding:** This allows high productivity and complex shapes but can introduce internal defects such as microvoids, which increase susceptibility to fatigue wear.
- **Resin Transfer Molding (RTM):** This is used for structural components; it offers a good compromise between dimensional control and quality of the fiber–matrix interface.
- **Electrospinning and 3D Printing:** This allows customizable microstructures and potential friction reduction, thanks to controlled surface geometries, but is still limited by industrial scalability [176].

Although no specific study seems to directly correlate the manufacturing techniques of marine biocomposites with their tribological properties in saline environments, parallels can be drawn from the following:

- Studies on food biocomposites for aquaculture show that technique and formulation influence stability in water, a parameter useful as an indirect indicator of tribological resistance [177].
- FEM analyses on marine biocomposite panels reveal that manufacturing defects influence flexural behavior and delamination resistance, aspects that can be correlated to contact wear [178].
- Work on metallic nanoporous structures highlights how microstructural modifications in manufacturing influence friction and surface adhesive strength, principles applicable to composite matrices [179].

Table 3. Overview of marine biocomposite fabrication techniques (original table by the authors).

Technique	Advantages	Disadvantages	Marine Suitability
Compression (or vacuum) molding	High fiber content, low porosity, good mechanical strength	Limited shape complexity, longer cycle times	Excellent for panels and structural parts with water resistance. Applied for flax–epoxy in [180].
Injection molding	Suitable for complex geometries, high production rate	Possible void formation, lower mechanical integrity in moist environments	Moderate; careful design needed to minimize water ingress. Potential offered as far as tensile performance is involved is explored in [181], as opposed to vacuum infusion (Figure 6).
Resin Transfer Molding (RTM)	Good control over fiber orientation, uniform resin distribution	Higher cost, complex tooling, limited to low-medium volume	High; ideal for load-bearing marine components. Flax–cork sandwich panels were proposed in [182].

Table 3. Cont.

Technique	Advantages	Disadvantages	Marine Suitability
Extrusion	Continuous process, scalable, good for thermoplastics	Poor control over fiber distribution, limited to simple shapes	Moderate; applicable with proper material selection, interesting when constant-thickness components are needed [183].
Electrospinning	Nanostructured fibers, tunable properties, high surface area	Scalability issues, high cost, slow throughput	Experimental; potential for coatings or specialty layers with antibacterial properties—an application concept adapted from biomedical industry [184]
3D printing	Custom geometries, minimal waste, rapid prototyping	Material limitations, anisotropy, mechanical weakness in some directions	Low to moderate; promising for non-structural components, yet resistant to seawater, depending on the matrix material [185].

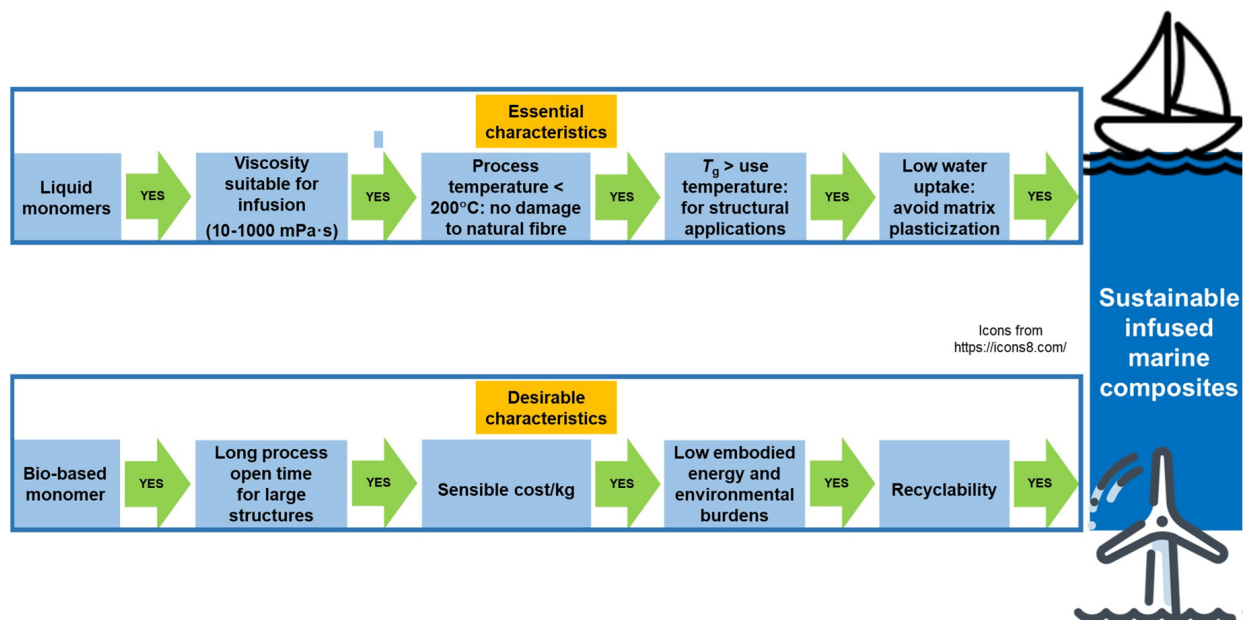


Figure 6. Conditions for infusibility of sustainable marine composites, in view of the application of lignocellulosic fibers as their reinforcement [181].

Overall, there is a need for dedicated research that combines tribological parameters (e.g., friction coefficient, wear mass loss) with the choice of manufacturing processes in the marine environment, also considering the role of biofillers, surface hydrophilicity, and biofouling. Some examples are given in Table 3; it is noticeable that the practical examples of attempted applications are mainly based on the use of flax fibers so far.

4. Advances in Seawater Protection of Biocomposites

4.1. Interfacial Engineering for Moisture and Wear Resistance

There are several techniques that can be used to improve the adhesion between fiber and matrix and reduce the delamination and friction phenomena in humid or brackish conditions. Among these, the use of chemical coupling agents, such as silanes or copolymers grafted with maleic anhydride (e.g., PE-g-MA, SEBS-g-MA), represents a consolidated approach to promote the chemical interaction between natural fibers and thermoplastic or thermosetting matrices [186]. Another promising strategy is surface activation through plasma or corona discharge treatments, which increase the surface energy of the plant

fibers, improving wettability and interface–fiber cohesion [187]. More advanced techniques include the molecular functionalization of fibrillar surfaces with amino, epoxy, or catechol groups (inspired by marine biology), which allow for increased adhesion even in the presence of water. For example, copolymers containing cationic–aromatic sequences have demonstrated strong adhesive properties in seawater, thanks to the cation– π interaction that counteracts the shielding effect of salt ions and preserves electrostatic adhesion [188]. Finally, mechanical approaches, such as z-stitching or interlaminar nano-reinforcement, can also prospectively offer protection against progressive delamination under load cycles in humid environments, increasing the overall integrity of the composite [189].

4.2. Surface Treatments and Barrier Coatings

To improve wear resistance in marine environments, bio-based surface treatments and barrier coatings represent an effective and sustainable approach. These solutions aim to prevent the ingress of moisture and salt ions, preventing delamination and chemical degradation of the matrix in biocomposites. Recent research has demonstrated the effectiveness of bio-based coatings with high barrier properties, such as those made with PLA and PHBV copolymers combined with functionalized talc, which offer excellent resistance to corrosion and water absorption even after prolonged immersion in saline solutions [190]. Another innovative approach involves the use of bio-inspired interfaces and self-healing capsules loaded with vegetable oils (e.g., tung oil) in epoxy matrices, capable of regenerating the integrity of the coating after damage and maintaining adhesion in highly aggressive marine environments [191]. Finally, the integration of graphene or nanofillers in coatings demonstrated a synergistic effect in reducing water absorption by 50% and friction coefficient by 19% in composites exposed to salt water for over six months [192].

4.3. Functional Fillers for Enhanced Tribological Stability

The use of fillers and nanofillers, natural and otherwise, is frequently reported for their ability to increase surface hardness, reduce friction, and improve erosion resistance. For instance, Hudda et al., 2022 [193] demonstrated that nanofillers have shown the ability to “seal” the micro-porosities of the matrix, improving the resistance to the entry of ions and limiting delamination or accelerated degradation phenomena in saltwater. Parallel studies have shown that nanofillers, such as nanoclay, graphene, or titanium dioxide, can reduce the friction coefficient by up to 19% in long-term saline environments, as well as significantly reduce the water absorption and improve the internal cohesion of the matrix [194]. In the case of bio-based matrix biocomposites, the use of natural fillers, such as lignocellulosic flours or functionalized biochars, also allows for maintaining the biodegradability of the system while offering similar tribological benefits, thanks to a greater controlled roughness and load distribution on the surface; an example is groundnut biochar in sisal fiber composites [195]. Finally, some recent formulations have adopted hybrid systems, where mineral fillers (e.g., talc or expanded glass) are combined with nanoparticles, obtaining a synergistic resistance against abrasion, humidity, and contact stress, ideal for prolonged marine applications [196].

4.4. Anti-Biofouling Strategies and Their Impact on Friction

Biofouling is one of the main threats to the durability of biocomposites in marine environments, as it promotes the formation of microbial biofilms and encrusting organisms (algae, diatoms, molluscs), which modify the surface roughness, increase friction resistance, and accelerate surface degradation phenomena.

Anti-biofouling strategies can be divided into passive and active approaches. Among passive approaches, eco-friendly low surface energy copolymers, such as oleamide combined with PDMS (polydimethylsiloxane), have demonstrated efficacy in inhibiting biolog-

ical adhesion, thanks to their smooth and hydrophobic surface. Such materials also show the ability to reduce hydrodynamic drag and friction coefficient in salt water [197].

On the active functional coatings front, recent developments include hybrid materials capable of generating friction energy (triboelectrification) that disturbs the adhesion of microorganisms and reduces biofilm formation. These coatings protect the surface mechanically and chemically, offering a biological coverage of less than 10% even after prolonged immersion [198].

Other, more sustainability-oriented strategies include the use of bioactive copolymers, natural additives (e.g., essential oils, DCOIT), or self-healing materials inspired by natural systems, such as the adhesive secretion of mussels [199]. Such approaches not only reduce the environmental impact but also limit the onset of critical tribological phenomena, such as localized abrasion and cyclic bioadhesion fatigue degradation.

Finally, it has been observed that an effective anti-biofouling strategy can reduce friction up to 20% compared to untreated surfaces, prolonging the composite lifetime and improving efficiency in dynamic and offshore applications [200].

4.5. Integrated Material Designs for Marine Tribological Durability

The integration of multiple functionalities within a single biocomposite represents an advanced strategy to address the complex tribological conditions in the marine environment. These systems combine mechanical stability, moisture resistance, and anti-biofouling barriers in a synergistic way, improving the long-term durability of the material even under dynamic and multi-agent conditions (salt water, pressure, friction, biological colonization). For example, bio-inorganic hybrid composites—combining bio-based polymers with ceramic or mineral fillers, such as zirconium dioxide (ZrO_2) or marine shell powders—have demonstrated increased wear resistance and a significant reduction in the friction coefficient in sliding tests, thanks to the formation of protective surface layers [201]. Furthermore, recent review studies highlight how the rational combination of biofibers, compatibilized matrices, and nanofillers can ensure high performance even in offshore applications, reducing the wear rate and extending the useful life of the material [202]. Other works have proposed design models where tribological functionality, controlled ecotoxicity, and hygrothermal stability are integrated, highlighting that the best performances are obtained through a hierarchical customization of the material properties (from the microstructure to the surface) [203].

5. Discussion

5.1. Summary of the Main Degradation Mechanisms

The literature analysis confirmed that the main degradation mechanisms of biocomposites in marine environments derive from the synergic interaction of mechanical, chemical, and biological factors. Santulli & Fiore [204] provided an extensive overview of these degradation processes, emphasizing the complex interplay between mechanical loading and seawater exposure. In a more general sense, in the case of biocomposites, a complex relation exists between the aging history of the material—which can be narrated and dealt with through a series of tests, including thermo-oxidative aging, accelerated or natural weathering, fatigue, and creep—and water/moisture absorption. Among these, the latter is possibly the most critical phenomenon because of its unpredictability in biocomposites: water penetrates the polymer matrix and natural fibers, causing matrix plasticization, fiber swelling, and debonding at the fiber–matrix interface. These effects result in a progressive loss of mechanical strength, reduction of the elastic modulus, and increased susceptibility to fatigue, which is correlated to the progressively decreasing contact angle counterbalancing the reinforcement effect of lignocellulosic fiber addition [205].

The more the cellulose content in a composite, the larger are the effects of salinity added to these phenomena. The ionic interaction accelerates the chemical degradation, modifying interlaminar cohesion and promoting the processes of hydrolysis and localized corrosion. In particular, the presence of Cl^- and Mg^{2+} ions can catalyze degradation reactions in both synthetic and bio-based matrices, although with different intensity depending on the resin chemistry. On the other hand, investigations on biocomposites do allow the tailoring of material degradation under seawater action, which has found applications in developing nets for aquaculture that are soluble over time [206].

A further critical element is represented by biofouling, i.e., the accumulation of microorganisms and higher organisms on the surface of the material. In addition to increasing the surface roughness and, therefore, the resistance to hydrodynamic friction, the microbial biofilm can produce degradative metabolites—such as organic acids and biosurfactants—that favor the breaking of chemical bonds in the polymer matrix and accelerate the aging process [207].

Finally, the combination of thermo-hygrometric cycles (temperature and humidity variations) contributes significantly to the onset of microcracks, internal delaminations, and lowering of the glass transition temperature (T_g), drastically reducing the useful life of the material. This effect is particularly pronounced in PLA-based biocomposites, while it is partially mitigated in systems based on furan or bio-epoxy resins [208].

Overall, marine exposure induces a progressive and multifactorial deterioration in biocomposites, where the coupling of chemical, mechanical, and biological degradation makes it difficult to isolate a single dominant parameter, underlining the need for integrated design and testing approaches.

5.2. Effects of Structure and Materials on Tribological Phenomena

The internal structure and the choice of materials are crucial in modulating the tribological behavior of biocomposites in marine environments. In particular, the type of fiber used significantly influences the friction and wear properties. Natural fibers with a high lignin content, such as coconut or kenaf, tend to offer greater resistance to water absorption and, consequently, greater dimensional and mechanical stability than more cellulosic fibers, such as hemp or flax. An outstanding performance of coir with respect to other fillers has been reported, e.g., in [209]. However, ligneous fibers can introduce local inhomogeneities that facilitate the nucleation of microcracks under cyclic stress.

The polymer matrix plays a crucial role in protecting the fibers and distributing tribological loads. Synthetic matrices, such as epoxy resins, generally guarantee superior mechanical properties and lower moisture absorption, but at the expense of environmental sustainability. In contrast, bio-based matrices—such as PLA or PHA—show higher ecological compatibility but also a higher vulnerability to plasticization, hydrolysis, and enzymatic–biological degradation processes. A particularly significant influence of surface roughness on the formation of biofilms during the environmental exposure of PHA has been demonstrated in [210]. The adoption of furan or bio-epoxy resins with high aromatic content represents a promising solution, offering a compromise between durability and sustainability.

Fillers and coupling agents employed in the formulation of biocomposites are essential to modulate tribological responses. The integration of natural fillers (e.g., shell powders) [211] or mineralogical fillers (e.g., nanoclay) [212] combined with the use of compatibilizing agents (e.g., PE-g-MA) improves interfacial adhesion, reduces microcrack propagation, and lowers the friction coefficient during dynamic contact in salt water.

Finally, the microstructure obtained from the manufacturing process directly influences the behavior under friction. Techniques such as compression molding generate denser

and more wear-resistant structures, while injection molding can introduce microvoids and anisotropies that facilitate the initiation of surface damage. Homogeneity of fiber distribution, low porosity, and effective adhesion at the interface are therefore key parameters to optimize tribological resistance.

Overall, the tribological properties of marine biocomposites result from a delicate balance between chemical composition, microstructure, and interfacial quality, which must be carefully designed according to the specific operating conditions. On the other hand, some fiber–matrix combinations are definitely closer to potential application in a marine context with a wear-resistant structure. This is the case for flax/epoxy composite, on which a specific study on wear rate was carried out in [213] by comparing different configurations, which demonstrated that the best results were obtained for 45 wt.% of silane-treated continuous fibers with an applied load of 10 N, a sliding velocity of 1 m/s, and a sliding distance of 600 m. Silane treatment did not, unlike alkali or alkali–silane ones, improve the crystallinity, yet it was able to protect the fibers more effectively against wear. However, other wear studies on flax–epoxy with short fibers involve either the manufacturing of a 1:1 flax–ramie hybrid (best results at 40 wt.% total fibers) [214] or the substantial addition of metal (alumina or iron filing) fillers with only 6 wt.% flax fibers [215]. Another limitation for the characterization of biocomposites to wear is the absence of tribological standards, which would be suitable for use in the specific and extreme environmental conditions represented by seawater and possible biological contamination. Tests such as the pin/ball on disk (ASTM G99) or block-on-ring (ASTM G77) imply that the sample has a relatively smooth surface and has not been subjected to water absorption/desorption.

5.3. Comparison of Mitigation Strategies: Benefits and Limitations

Mitigation strategies aimed at improving the tribological durability of marine biocomposites can be grouped into four main categories: fiber–matrix interface modification, surface treatments and barrier coatings, use of functionalized fillers, and anti-biofouling strategies. Each of these has distinct advantages but also intrinsic limitations that need to be considered in the design phase.

Interface modification, through coupling agents, such as silanes, or grafting of functional groups (e.g., PE-g-MA), has proven to be very effective in improving fiber–matrix adhesion, reducing the risk of delamination in humid environments. However, resistance to ionic or biological degradation strongly depends on the chemical stability of the introduced bonds, which can be compromised after prolonged exposure to salt or biofouling metabolites.

Surface treatments and protective barriers, such as plasma treatment or coatings based on functionalized biopolymers (e.g., PLA/PHBV with talc), show a significant reduction in moisture absorption and an increased resistance to ionic corrosion. The main limitation of these approaches lies in the mechanical fragility of coatings under dynamic conditions: cracks or scratches can quickly compromise the protection, making self-healing or multifunctional solutions necessary.

The use of functional fillers, both natural (e.g., biochar) and inorganic (e.g., nanoclay, graphene), offers the dual advantage of increasing surface hardness and limiting water diffusion into the matrix. However, high filler loadings (>20–30%) can cause dispersion problems, introducing microstructural defects that favor crack nucleation under hydrothermal stress.

Anti-biofouling strategies, based on low surface energy materials or controlled release of bioactive agents, represent a promising approach to preserve tribological properties in the long term. Marine-inspired systems (e.g., cationic–aromatic copolymers) offer remarkable

results in terms of preventing biological adhesion. However, the protection duration and ecotoxicological balance remain critical areas that require further full-scale validation.

In summary, although each strategy leads to specific improvements, no single solution is sufficient to ensure the total protection of marine biocomposites. The best results emerge from the integration of different technologies—for example, combining interfacial modifications, barrier coatings, and functional fillers—within a holistic and hierarchical design approach.

5.4. Gaps in the Literature and Research Perspectives

Despite the large number of experimental studies and reviews on biocomposites in marine environments, several knowledge gaps emerge that limit the full understanding of tribological degradation phenomena and the optimal design of more resistant materials.

One of the main limitations lies in the poor integration between tribological tests and realistic environmental simulations. Most of the works analyze properties such as friction coefficient or mass loss in controlled laboratory conditions but without simultaneously reproducing complex marine variables, such as salinity, cyclic loading, active biofouling, and thermal variations. This makes it difficult to predict the long-term behavior of materials in real offshore or underwater applications.

A second gap concerns the limited duration of accelerated aging tests. While many investigations focus on exposures of a few weeks or months, marine operating conditions would require multi-year scale evaluations to correctly simulate cumulative degradation mechanisms, such as progressive delamination and tribological alterations due to environmental fatigue.

From a materials perspective, there is little systematic exploration of new advanced bio resins (e.g., furan- or FDCA-based) and their synergistic effects in combination with natural fibers or hybrid fillers. Similarly, the most innovative manufacturing processes—such as electrospinning or industrial-scale 3D printing—are still understudied for marine applications, despite their potential for microstructural customization.

Finally, the ecotoxicological impact of bioactive- or nanoparticle-based anti-biofouling strategies has not yet been adequately characterized in complex marine environments. The long-term sustainability of biocomposites should take into account not only biodegradability but also the ecological neutrality of the materials under controlled release or degradation conditions. To overcome these limitations, future research lines should focus on

- The development of multi-agent testing protocols (combining mechanical, chemical, and biological stress).
- Full-scale validation through exposure to controlled or natural marine environments.
- Multiscale optimization of materials, integrating molecular modifications, microstructural reinforcements, and surface functionalizations.
- Eco-friendly design, considering the complete life cycle of the material and its interaction with marine ecosystems.

5.5. Practical Implications for the Design of Marine Biocomposites

The results emerging from the literature indicate that the design of biocomposites intended for marine applications requires a multifactorial approach that integrates accurate choices at the level of materials, microstructure, and surface treatments.

First, the combined selection of natural fibers with low hydrophilicity (such as ligneous or marine fibers) and bio-based matrices with high hydrolytic resistance (such as furan or bio-epoxy) appears essential to reduce the risk of early degradation by moisture absorption or ion exchange. The most satisfactory performance is obtained where it is possible to

ensure a robust interface between fiber and matrix, mediated by appropriate coupling agents or chemical–physical treatments.

Secondly, microstructural design should aim to minimize internal porosity and manufacturing defects, adopting consolidated processes such as compression molding or resin transfer molding (RTM), possibly combined with interlaminar reinforcement techniques (e.g., z-stitching, nanoparticles) to increase the tolerance to thermo-hygrometric cycles and reduce susceptibility to delamination.

On the surface protection front, the integration of multifunctional bio-based coatings represents a promising strategy to combine moisture barrier, wear resistance, and anti-biofouling capacity. However, these coatings must be designed to resist localized mechanical damage, possibly integrating self-healing properties or controlled release of protective agents.

Finally, the design should always consider the specific operating conditions (e.g., depth, temperature, presence of biofouling) and adopt accelerated qualification tests that include combined exposure to salinity, cyclic stress, and hydrodynamic loads to realistically predict the useful life of the material. Some real exposure tests for 1000 h have been performed trying to elucidate the effect of biofouling on the flexural performance of carbon fiber/vinyl ester composites, showing that UV rays impact the composite strength more than saltwater [216]. Limitations of this knowledge, even on traditional petrochemical polymers used offshore, are recognized, although it is generally suggested that the wear degradation rate would substantially decrease with increasing water depth [217]. This does create a particular concern regarding the use of biopolymers in small boats that operate close to the water surface. Also, the influence of variation in temperature appears limited, provided, as is usually the case, the polymer is used at temperatures sufficiently distant from its glass transition temperature (T_g). It also needs to be considered that the previously discussed addition of fillers would also result in a further increase in T_g and, as a consequence, also the potential service temperature.

Ideally, for biocomposites, the enlargement of the service temperature interval would need to be combined with the progressive decrease in mechanical properties with increasing temperature and biological contaminations. However, such complex and multidisciplinary studies, though strongly needed, are not available so far. Only through a systemic and eco-friendly approach, which combines innovation of materials with a careful evaluation of environmental sustainability, will it be possible to develop biocomposites truly suitable for the marine sector, both in the structural and functional fields.

5.6. Final Considerations

This review has shown that biocomposites, although representing a valid sustainable alternative for marine applications, are subject to complex degradation phenomena in saline environments. In particular, moisture absorption by natural fibers and the consequent delamination of the fiber matrix are the main deterioration mechanisms, accompanied by tribological effects, such as increased friction and accelerated surface wear. The presence of salinity and biofouling further aggravates these phenomena, reducing the useful life of the materials; therefore, suitable protection is needed more often than not, which also results in an environmental benefit [218].

The identified improvement strategies include the use of natural and mineral fillers (e.g., seashell powders, functionalized biochar, nanoclay) to increase the resistance to water absorption and improve mechanical stability. Chemical (silanization, grafting of functional groups such as PE-g-MA) and physical (plasma, corona discharge) surface treatments have proven effective in increasing the fiber–matrix interface adhesion and reducing vulnerability to moisture. Furthermore, bio-based barrier coatings (such as

PLA/PHBV with functionalized talc) and plant-based self-healing systems have shown good prospects in protecting surfaces from ion ingress and biological colonization.

Promising results, although premature, also come from the use of specific marine fibers, such as *Posidonia oceanica*, and bio-fillers from marine biomass, capable of improving the environmental integration of composites without significantly compromising mechanical resistance. However, the effectiveness of such solutions strongly depends on the quality of the interfacial bond and on the control of the microstructures introduced during the manufacturing processes (compression molding, RTM, injection molding). Setting the parameters of the manufacturing process is of paramount importance; however, sometimes this encounters problems. For example, compression molding does not normally allow the introduction of a sufficient amount of fiber to control the interface, hence optimizing stress together with controlling wear. In [219], optimal parameters for the wear resistance of flax/hemp hybrid epoxy composites were recorded as only 20% of reinforcement, 150 °C molding temperature, 1 MPa molding pressure, and 20 min of curing time.

Finally, it should be noted that most of the analyzed studies focus on single degradation parameters (e.g., mass loss or friction coefficient variation), while investigations that systematically correlate manufacturing technologies, tribological parameters, and real marine operating conditions are still limited. This represents a substantial hindrance to the use of biocomposites for structural nautical applications: the characterization studies are limited, and the existing ones are seldom based on statistical/optimization approaches that could improve targeting multidisciplinary matters. It is also fair to say, though, that some biocomposites are closer (or less far away) to this target, such as flax/epoxy or hemp/epoxy.

In this sense, it is hoped that future research will adopt integrated approaches of multi-scale design and accelerated testing in simulated environments to guide the industrialization of truly performing and durable biocomposites in the marine sector. This could also exploit the economic benefits of using materials that are in themselves economically valuable, such as the by-products of other sectors (e.g., textile, construction) [220] or secondary raw matter from agri-food production [221], and hence deserve upcycling to an important sector, such as the nautical industry. Moreover, they will improve the end-of-life scenarios of specific niche sectors, such as yachting, at least increasing the amount of renewable matter used in it.

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Abbreviations

AlPi	Aluminum diethyl phosphinate
BPA	Bisphenol A
COF	Coefficient of friction
DCOIT	Dichloro octylisothiazolinone
DEHP	Diethylhexyl phthalate

DOPO	9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide
FDCA	2,5-furandicarboxylic acid
GF	Glass fibers
LBCs	Laminated bamboo composites
MA	Maleic anhydride
PALF	Pineapple leaf fibers
PBS	Poly(butyl succinate)
PE-g-MA	Maleic anhydride-grafted-polyethylene
PHA	Poly(hydroxyalkanoate)
PHBV	Poly(hydroxybutyrate-co-valerate)
PLA	Poly(lactic acid)
PMMA	Poly(methyl methacrylate)
PPS	Polyphenylene sulfide
PU	Polyurethane
PVC	Polyvinylchloride
RTM	Resin transfer molding
SEBS-g-MA	Styrene–ethylene–butylene–styrene block copolymer maleic anhydride grafted
UHMWPE	Ultra-high molecular weight poly(ethylene)

References

- John, M.J. Environmental degradation in biocomposites. In *Biocomposites for High-Performance Applications*; Ray, D., Ed.; Woodhead Publishing: Cambridge, UK, 2017; pp. 181–194. [\[CrossRef\]](#)
- Hao, Z.; Zhang, Z.; Zhou, W.; Zhang, S.; Ma, T.; Wei, H.; Wang, G.; Wang, Q.; Wang, L.; Li, R. Progress of material degradation: Metals and polymers in deep-sea environments. *Corros. Rev.* **2024**, online first. [\[CrossRef\]](#)
- Sen, R. Durability of advanced composites in a marine environment. *Int. J. Mater. Prod. Technol.* **2003**, *19*, 118–129. [\[CrossRef\]](#)
- Merah, N.; Ashraf, F.; Shaukat, M.M. Mechanical and moisture barrier properties of epoxy–nanoclay and hybrid epoxy–nanoclay glass fibre composites: A review. *Polymers* **2022**, *14*, 1620. [\[CrossRef\]](#)
- Bengtsson, S. The sails of the Wasa: Unfolding, identification and preservation. *Int. J. Naut. Archaeol.* **1975**, *4*, 27–41. [\[CrossRef\]](#)
- Dickinson, H.W. A condensed history of rope-making. *Trans. Newcom. Soc.* **1942**, *23*, 71–91. [\[CrossRef\]](#)
- Nan, J.; Zhi, C.; Meng, J.; Miao, M.; Yu, L. Seawater aging effect on fiber-reinforced polymer composites: Mechanical properties, aging mechanism, and life prediction. *Text. Res. J.* **2023**, *93*, 3393–3413. [\[CrossRef\]](#)
- Zhu, Z.; Xiao, P.; Kang, A.; Kou, C.; Chen, J. Preparation of biomass composites with high performance and carbon sequestration from waste wood fibers. *Constr. Build. Mater.* **2023**, *404*, 133295. [\[CrossRef\]](#)
- Edyvean, R. Consequences of fouling on shipping. In *Biofouling*; Dürr, S., Thomason, J.C., Eds.; Wiley and Sons: Hoboken, NJ, USA, 2010; pp. 217–225. [\[CrossRef\]](#)
- Wood, R.J. Marine wear and tribocorrosion. *Wear* **2017**, *376*, 893–910. [\[CrossRef\]](#)
- Brailo, M.; Buketov, A.; Yakushchenko, S.; Sapronov, O.; Vynar, V.; Kobelnik, O. The investigation of tribological properties of epoxy-polyether composite materials for using in the friction units of means of sea transport. *Mater. Perform. Character.* **2018**, *7*, 275–299. [\[CrossRef\]](#)
- Herbert-Read, J.E.; Thornton, A.; Amon, D.J.; Birchenough, S.N.R.; Côté, I.M.; Dias, M.P.; Godley, B.J.; Keith, S.A.; McKinley, E.; Peck, L.S.; et al. A global horizon scan of issues impacting marine and coastal biodiversity conservation. *Nat. Ecol. Evol.* **2022**, *6*, 1262–1270. [\[CrossRef\]](#)
- Elliott, M.; Borja, Á.; Cormier, R. Managing marine resources sustainably—ecological, societal and governance connectivity, coherence and equivalence in complex marine transboundary regions. *Ocean Coast. Manag.* **2023**, *245*, 106875. [\[CrossRef\]](#)
- Huang, Y.; Sultan, M.T.H.; Shahar, F.S.; Grzejda, R.; Łukaszewicz, A. Hybrid fiber-reinforced biocomposites for marine applications: A review. *J. Compos. Sci.* **2024**, *8*, 430. [\[CrossRef\]](#)
- Li, C.; Feng, C.; Zhang, L.; Shan, J.; Shi, M. A review of the effect of hydrothermal aging on the mechanical properties of 2D fiber-reinforced resin matrix composites. *Polym. Adv. Technol.* **2024**, *35*, e6239. [\[CrossRef\]](#)
- Shifler, D.A.; Aylor, D.M. Factors Affecting Corrosion Performance and Testing of Materials and Components in Sea Water. In *NACE CORROSION*; NACE: Houston, TX, USA, 2005; p. NACE-05224.
- Beura, S.; Chakraverty, A.P.; Pati, S.N.; Pradhan, D.D.; Thatoi, D.N.; Mohanty, U.K. Effect of salinity and strain rate on sea water aged GFRP composite for marine applications. *Mater. Today Commun.* **2023**, *34*, 105056. [\[CrossRef\]](#)
- Ansell, M.P. Natural fibre composites in a marine environment. In *Natural Fibre Composites*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 365–374. [\[CrossRef\]](#)

19. Gupta, B.R. Friction and wear mechanism of polymers, their composites and nanocomposites. In *Tribology of Polymers, Polymer Composites, and Polymer Nanocomposites*; Elsevier: Amsterdam, The Netherlands, 2023; pp. 51–117. [\[CrossRef\]](#)
20. Zhang, Z.; Ouyang, W.; Liang, X.; Yan, X.; Yuan, C.; Zhou, X.; Guo, Z.; Dong, C.; Liu, Z.; Jin, Y.; et al. Review of the evolution and prevention of friction, wear, and noise for water-lubricated bearings used in ships. *Friction* **2024**, *12*, 1–38. [\[CrossRef\]](#)
21. Wang, D.; Li, Z.; Zhu, Y. Lubrication and tribology in seawater hydraulic piston pump. *J. Mar. Sci. Appl.* **2003**, *2*, 35–40. [\[CrossRef\]](#)
22. Haq, M.I.U.; Raina, A.; Vohra, K.; Kumar, R.; Anand, A. An assessment of tribological characteristics of different materials under sea water environment. *Mater. Today Proc.* **2018**, *5*, 3602–3609. [\[CrossRef\]](#)
23. Yuan, W.; Yao, X.; Guo, Q.; Li, C.; Chi, B.; Yu, J. Tribological Behavior of Shaft-Surface Pairs with PPS and Its Composites in Seawater Media Under Cyclic Loadings. *Tribol. Lett.* **2024**, preprint. [\[CrossRef\]](#)
24. Shan, L.; Wang, Y.; Li, J.; Li, H.; Wu, X.; Chen, J. Tribological behaviours of PVD TiN and TiCN coatings in artificial seawater. *Surf. Coat. Technol.* **2013**, *226*, 40–50. [\[CrossRef\]](#)
25. Liang, Y.; Zhang, F.; Xing, H.; Wang, C.; Chen, N.; Wang, W.; Zhang, Z. Lubrication and wear characteristics of bionic composite texture on friction pair under seawater condition. *Surf. Topogr. Metrol. Prop.* **2025**, *13*, 015023. [\[CrossRef\]](#)
26. Chamley, A.; Baley, C.; Gayet, N.; Sarrazin, J.; Fuchs, S.; Freyermouth, F.; Davies, P. (Bio)degradation of biopolymer and biocomposite in deep-sea environments. *Mar. Pollut. Bull.* **2024**, *209*, 117230. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Monikandan, V.V.; Pratheesh, K.; Santulli, C.; Digra, S.; Prasanth, P.V.; Dhas, E.R. History of tribology: Assessing the prehistoric impacts, progress on industrial and scientific revolution eras, and contemporary interdisciplinary research trends. *Tribologia* **2024**, *41*, 4–15. [\[CrossRef\]](#)
28. Prabhakar, K.; Debnath, S.; Ganesan, R.; Palanikumar, K. A review of mechanical and tribological behaviour of polymer composite materials. In *IOP Conference Series: Materials Science and Engineering, Proceedings of the 3rd International Conference on Science, Technology, and Interdisciplinary Research (IC-STAR), 18–20 September 2017, Bandar Lampung, Indonesia*; IOP Publishing: Bristol, UK, 2018; Volume 344, p. 012015. [\[CrossRef\]](#)
29. Ravi, S.; Mohanavel, V.; Ayyar, M.; Kathiresan, S.; Kannan, S.; Munimathan, A.; Kaliappan, S. Effect of continuous fiber reinforcement on mechanical and tribological characteristics of cellulose and human hair fiber polymer composites. *Results Eng.* **2025**, *25*, 104480.S.
30. Sultan, M.; Jamir, M.; Majid, M.; Azmi, A.; Saba, N. (Eds.) *Tribological Applications of Composite Materials*; Springer: Singapore, 2021. [\[CrossRef\]](#)
31. Milosevic, M.; Valášek, P.; Ruggiero, A. Tribology of natural fibers composite materials: An overview. *Lubricants* **2020**, *8*, 42. [\[CrossRef\]](#)
32. Tran, L.Q.N.; Yuan, X.W.; Bhattacharyya, D.; Fuentes, C.; Van Vuure, A.W.; Verpoest, I. Fiber-matrix interfacial adhesion in natural fiber composites. *Int. J. Mod. Phys. B* **2015**, *29*, 1540018. [\[CrossRef\]](#)
33. Bakry, M.; Mousa, M.O.; Ali, W.Y. Friction and wear of friction composites reinforced by natural fibres. *Mater. Werkst.* **2013**, *44*, 21–28. [\[CrossRef\]](#)
34. Muthu Samy, M.; Lenin Singaravelu, D. Green friction: Exploring the evolution and potential of natural fibers and other brake pad ingredients in sustainable automotive engineering—A review. *Polym. Compos.* **2025**, *46*, 5882–5909. [\[CrossRef\]](#)
35. Ammar, Z.; Ibrahim, H.; Adly, M.; Sarris, I.; Mehanny, S. Influence of natural fiber content on the frictional material of brake pads—A review. *J. Compos. Sci.* **2023**, *7*, 72. [\[CrossRef\]](#)
36. Saindane, U.V.; Soni, S.; Menghani, J.V. Recent research status on synthesis and characterization of natural fibers reinforced polymer composites and modern friction materials—An overview. *Mater. Today Proc.* **2020**, *26*, 1616–1620. [\[CrossRef\]](#)
37. Shuhimi, F.F.; Abdollah, M.F.B.; Kalam, M.A.; Masjuki, H.H.; Mustafa, A.E.; Mat Kamal, S.E.; Amiruddin, H. Effect of operating parameters and chemical treatment on the tribological performance of natural fiber composites: A review. *Part. Sci. Technol.* **2017**, *35*, 512–524. [\[CrossRef\]](#)
38. Chaudhary, V.; Bajpai, P.K.; Maheshwari, S. An investigation on wear and dynamic mechanical behavior of jute/hemp/flax reinforced composites and its hybrids for tribological applications. *Fibers Polym.* **2018**, *19*, 403–415. [\[CrossRef\]](#)
39. Pani, P.R.; Nayak, R.K.; Routara, B.C.; Sekhar, P.C. Flexural and specific wear rate of seawater aged bamboo, jute and glass fiber reinforced polymer hybrid composites. *Mater. Today Proc.* **2019**, *18*, 3409–3414. [\[CrossRef\]](#)
40. Velasco-Parra, J.A.; Valencia, F.R.; Lopez-Arraiza, A.; Ramón-Valencia, B.; Castillo-López, G. Jute fibre reinforced biocomposite: Seawater immersion effects on tensile properties and its application in a ship hull design by finite-element analysis. *Ocean Eng.* **2023**, *290*, 116301. [\[CrossRef\]](#)
41. Castegnaro, S.; Gomiero, C.; Battisti, C.; Poli, M.; Basile, M.; Barucco, P.; Pizzarello, U.; Quaresimin, M.; Lazzaretto, A. A bio-composite racing sailboat: Materials selection, design, manufacturing and sailing. *Ocean Eng.* **2017**, *133*, 142–150. [\[CrossRef\]](#)
42. Sarkar, P.K.; Kandasubramanian, B. Metals to polymer composites for submerged hull: A paradigm shift. *Polym. Plast. Technol. Mater.* **2021**, *60*, 1785–1819. [\[CrossRef\]](#)

43. Rubino, F.; Nisticò, A.; Tucci, F.; Carlone, P. Marine application of fiber reinforced composites: A review. *J. Mar. Sci. Eng.* **2020**, *8*, 26. [\[CrossRef\]](#)
44. Santulli, C. Evolution and recent advancements of composite materials in marine applications. In *Applications of Composite Materials in Engineering*; Puttegowda, M., Yashas Gowda, T.G., Binoj, J.S., Rangappa, S.M., Siengchin, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2025; pp. 195–218. [\[CrossRef\]](#)
45. El Hawary, O.; Boccarusso, L.; Ansell, M.P.; Durante, M.; Pinto, F. An overview of natural fiber composites for marine applications. *J. Mar. Sci. Eng.* **2023**, *11*, 1076. [\[CrossRef\]](#)
46. Chengpeng, W.; Shenghui, W.; Haizeng, W.; Guoling, R.; Yexiang, X.; Jiang, Z.; Xiupeng, L.I. Research status and prospects of tribological behaviors of key friction pairs of materials in marine equipment. *Mater. Sci.* **2021**, *27*, 148–154. [\[CrossRef\]](#)
47. Wang, Z.; Gao, D. Comparative investigation on the tribological behavior of reinforced plastic composite under natural seawater lubrication. *Mater. Des.* **2013**, *51*, 983–988. [\[CrossRef\]](#)
48. de Castro, M.C.T.; Vance, T.; Yunnice, A.L.; Fileman, T.W.; Hall-Spencer, J.M. Low salinity as a biosecurity tool for minimizing biofouling on ship sea chests. *Ocean Sci.* **2018**, *14*, 661–667. [\[CrossRef\]](#)
49. Bekiari, V.; Nikolaou, K.; Koromilas, N.; Lainioti, G.C.; Avramidis, P.; Hotos, G.N.; Kallitsis, J.K.; Bokias, G. Release of Polymeric Biocides from Synthetic Matrices for Marine Biofouling Applications. *Agric. Agric. Sci. Procedia* **2015**, *4*, 445–450. [\[CrossRef\]](#)
50. Mosby, B.M.; Shah, S.; Braun, P.V. Salt Water-Triggered Ionic Cross-Linking of Polymer Composites by Controlled Release of Functional Ions. *ACS Omega* **2018**, *3*, 16127–16133. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Zhu, J.; Pan, J.; Ma, C.; Zhang, G.; Liu, G. Specific Ion Effects on the Enzymatic Degradation of Polymeric Marine Antibiofouling Materials. *Langmuir* **2019**, *35*, 11157–11166. [\[CrossRef\]](#)
52. Sathyanarayanan, S. Investigation of the Moisture Diffusion Process in Fibre-Reinforced Composites by Studying the Diffusivities in Hot-wet Temperature Resin-matrix. *SSRG Int. J. Mech. Eng.* **2014**, *1*, 7–12. [\[CrossRef\]](#)
53. Le Duigou, A.; Bourmaud, A.; Davies, P.; Baley, C. Long Term Immersion in Natural Seawater of Flax/PLA Biocomposite. *Ocean Eng.* **2014**, *90*, 140–148. [\[CrossRef\]](#)
54. Giammaria, V.; Capretti, M.; Del Bianco, G.; Boria, S.; Santulli, C. Application of poly(lactic acid) composites in the automotive sector: A critical review. *Polymers* **2024**, *16*, 3059. [\[CrossRef\]](#)
55. Menezes, O.; Roberts, T.; Motta, G.; Patrenos, M.H.; McCurdy, W.; Alotaibi, A.; Vanderpool, M.; Vaseghi, M.; Beheshti, A.; Davami, K. Performance of additively manufactured polylactic acid (PLA) in prolonged marine environments. *Polym. Degrad. Stabil.* **2022**, *199*, 109903. [\[CrossRef\]](#)
56. Anandakumar, P.; Kanny, K.; Mohan, T.P.; Velmurugan, R. Mechanical Behavior of Glass Fiber-Reinforced Hollow Glass Particles Filled Epoxy Composites under Moisture Environment. *Polym. Compos.* **2024**, *45*, 8613–8630. [\[CrossRef\]](#)
57. Hassan, A.; Khan, R.; Khan, N.; Aamir, M.; Pimenov, D.Y.; Giasin, K. Effect of Seawater Ageing on Fracture Toughness of Stitched Glass Fiber/Epoxy Laminates for Marine Applications. *J. Mar. Sci. Eng.* **2021**, *9*, 196. [\[CrossRef\]](#)
58. Wang, X.; Liu, X.; Liu, D.; Wang, Z.; Zhu, Y.; Qian, K.; Zhang, D. Influence of Moisture Absorption on Mechanical Properties and Damage Mechanisms of Three-Dimensional Six-Directional Braided Composites under Hydrostatic Pressure. *Polym. Test.* **2022**, *114*, 107693. [\[CrossRef\]](#)
59. Khaldi, M.; Vivet, A.; Bourmaud, A.; Sereir, Z.; Kada, B. Damage analysis of composites reinforced with Alfa fibers: Viscoelastic behavior and debonding at the fiber/matrix interface. *J. Appl. Polym. Sci.* **2016**, *133*, 43760. [\[CrossRef\]](#)
60. Dhakal, H.N.; Zhang, Z.Y.; Richardson, M.O.W. Effect of water absorption on the mechanical properties of hemp fibre reinforced unsaturated polyester composites. *Compos. Sci. Technol.* **2007**, *67*, 1674–1683. [\[CrossRef\]](#)
61. Chow, C.P.L.; Xing, X.S.; Li, R.K.Y. Moisture absorption studies of sisal fibre reinforced polypropylene composites. *Compos. Sci. Technol.* **2007**, *67*, 306–313. [\[CrossRef\]](#)
62. Le Duigou, A.; Davies, P.; Baley, C. Seawater ageing of flax/poly(lactic acid) biocomposites. *Polym. Degrad. Stab.* **2009**, *94*, 1151–1162. [\[CrossRef\]](#)
63. Sidia, B.; Bensalah, W. Hygrothermal Aging Effects on Tribological and Mechanical Behaviors of Mollusc Shell-Reinforcement UHMWPE Biocomposites. *J. Thermoplast. Compos. Mater.* **2022**, *36*, 3021–3040. [\[CrossRef\]](#)
64. Campana, C.; Léger, R.; Sonnier, R.; Ienny, P.; Ferry, L. Effect of hygrothermal ageing on the mechanical and fire properties of a flame retardant flax fiber/epoxy composite. *Polymers* **2022**, *14*, 3962. [\[CrossRef\]](#)
65. Hussnain, S.M.; Shah, S.Z.H.; Megat-Yusoff, P.S.M.; Choudhry, R.S.; Hussain, M. Hygrothermal Effects on the Durability of Resin-Infused Thermoplastic E-Glass Fiber-Reinforced Composites in Marine Environment. *Polym. Compos.* **2024**, *45*, 13901–13923. [\[CrossRef\]](#)
66. Han, S.O.; Ahn, H.J.; Cho, D. Hygrothermal effect on henequen or silk fiber reinforced poly(butylene succinate) biocomposites. *Compos. Part B Eng.* **2010**, *41*, 491–497. [\[CrossRef\]](#)
67. Rajkumar, K.; Elen, M.; Sushmita, K.; Overman, N.; Nickerson, E.K.; Murdy, P.; Presuel-Moreno, F.; Fifield, L.S. Hygrothermal Aging and Recycling Effects on Mechanical and Thermal Properties of Recyclable Thermoplastic Glass Fiber Composites. *Polym. Compos.* **2024**, *46*, 4332–4349. [\[CrossRef\]](#)

68. Drouhet, Q.; Touchard, F.; Chocinski-Arnault, L. Influence of hygrothermal aging on mechanical properties and damage mechanisms of hemp-reinforced biocomposites. *J. Nat. Fibers* **2022**, *19*, 15404–15421. [\[CrossRef\]](#)
69. Lu, J.; Zheng, C.; Wang, L.; Dai, Y.; Wang, Z.; Song, Z. T700 Carbon Fiber/Epoxy Resin Composite Material Hygrothermal Aging Model. *Materials* **2025**, *18*, 369. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Qiu, H.; Feng, K.; Gapeeva, A.; Meurisch, K.; Kaps, S.; Li, X.; Yu, L.; Mishra, Y.K.; Adelung, R.; Baum, M. Functional polymer materials for modern marine biofouling control. *Prog. Polym. Sci.* **2022**, *127*, 101516. [\[CrossRef\]](#)
71. Fragassa, C.; Mattiello, S.; Fronduti, M.; Del Gobbo, J.; Gagic, R.; Santulli, C. Prevention of Biofouling Due to Water Absorption of Natural Fiber Composites in the Aquatic Environment: A Critical Review. *J. Compos. Sci.* **2024**, *8*, 532. [\[CrossRef\]](#)
72. Lindholdt, A.; Dam-Johansen, K.; Olsen, S.M.; Yebra, D.M.; Kiil, S. Effects of biofouling development on drag forces of hull coatings for ocean-going ships: A review. *J. Coat. Technol. Res.* **2015**, *12*, 415–444. [\[CrossRef\]](#)
73. Fruleux, T.; Sauleau, P.; Caudal, F.; Champion, M.; Chauvin, L.; Castro, M.; Le Duigou, A. Marine biofilm formation on flax fibre reinforced biocomposites. *Biofouling* **2024**, *40*, 415–430. [\[CrossRef\]](#)
74. Puh, J.S.; Wagner, P.A.; Little, B.J.; Bradley, W.L. The Effect of Biofouling on Graphite/Epoxy Composites. *J. Compos. Technol. Res.* **1998**, *20*, 59–67. [\[CrossRef\]](#)
75. Haque, M.S.; Islam, M.A. Microbial degradation of the waste jute fiber and sawdust fiber-based epoxy composites in drainage system. *Heliyon* **2024**, *10*, e39397. [\[CrossRef\]](#)
76. Ali, A.; Xiao, Y.; Song, L.; Hu, J.; Rao, Q.; Shoaib, M.; Amin, B.U.; Zhan, X.; Zhang, Q. Biodegradable Polyurethane-Based Clay Composite and Their Anti-Biofouling Properties. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *625*, 126946. [\[CrossRef\]](#)
77. Stepczyńska, M.; Rytlewski, P.; Moraczewski, K.; Pawłowska, A.; Karasiewicz, T. Novel biocomposite of starch and flax fiber modified with tannic acid with biocidal properties. *Polymers* **2024**, *16*, 1108. [\[CrossRef\]](#)
78. Santulli, C.; Gabrielli, S.; Roselli, G. Use and Roles of Tannins in Polysaccharide-Based Bioplastics and Biocomposites. *Organics* **2025**, *6*, 19. [\[CrossRef\]](#)
79. Muobom, S.S.; Umar, A.M.S.; Soongseok, Y.; Brolin, A.P. A review on plasticizers and eco-friendly bioplasticizers: Biomass sources and market. *Int. J. Eng. Res.* **2020**, *9*, 1138–1144.
80. Visakh, P.M.; Darie-Nita, R.N. Polyvinylchloride (PVC)-Based Blends: State of Art, New Challenges. In *Polyvinylchloride-Based Blends: Preparation, Characterization and Applications*; Visakh, P.M., Darie-Nita, R.N., Eds.; Springer Nature: London, UK, 2021. [\[CrossRef\]](#)
81. Gulizia, A.M.; Bell, S.C.; Kuek, F.; Santana, M.; Edmunds, R.C.; Yeoh, Y.K.; Sato, Y.; Haikola, P.; van Herwerden, L.; Motti, C.A.; et al. Biofilm Development as a Factor Driving the Degradation of Plasticised Marine Microplastics. *J. Hazard. Mater.* **2024**, *460*, 136975. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Hassaini, L.; Kaci, M.; Dehouche, N.; Bruzaud, S. A Degradation Study of Poly(3-Hydroxybutyrate-co-3-Hydroxyvalerate) and Olive Husk Flour Biocomposites under Marine Environment. *Macromol. Symp.* **2022**, *404*, 2200026. [\[CrossRef\]](#)
83. Jagadeesh, P.; Puttegowda, M.; Thyavihalli Girijappa, Y.G.; Rangappa, S.M.; Siengchin, S. Effect of natural filler materials on fiber reinforced hybrid polymer composites: An Overview. *J. Nat. Fibers* **2020**, *19*, 4132–4147. [\[CrossRef\]](#)
84. Brebu, M. Environmental Degradation of Plastic Composites with Natural Fillers—A Review. *Polymers* **2020**, *12*, 166. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Baier, R.E.; Meyer, A.E. Surface analysis of fouling-resistant marine coatings. *Biofouling* **1992**, *6*, 165–180. [\[CrossRef\]](#)
86. Cao, Z.; Cao, P. Research Progress on Low-Surface-Energy Antifouling Coatings for Ship Hulls: A Review. *Biomimetics* **2023**, *8*, 502. [\[CrossRef\]](#)
87. Muthukumar, T.; Aravinthan, A.; Lakshmi, K.; Venkatesan, R.; Vedaprakash, L.; Doble, M. Fouling and Stability of Polymers and Composites in Marine Environment. *Int. Biodeterior. Biodegrad.* **2011**, *65*, 276–284. [\[CrossRef\]](#)
88. Palanisamy, S.; Kalimuthu, M.; Nagarajan, R.; Fernandes Marlet, J.M.; Santulli, C. Physical, chemical, and mechanical characterization of natural bark fibers (NBFs) reinforced polymer composites: A bibliographic review. *Fibers* **2023**, *11*, 13. [\[CrossRef\]](#)
89. More, A.P. Flax fiber-based polymer composites: A review. *Adv. Compos. Hybrid Mater.* **2022**, *5*, 1–20. [\[CrossRef\]](#)
90. Deshmukh, G.S. Advancement in hemp fibre polymer composites: A comprehensive review. *J. Polym. Eng.* **2022**, *42*, 575–598. [\[CrossRef\]](#)
91. Gogna, E.; Kumar, R.; Anurag; Sahoo, A.K.; Panda, A. A comprehensive review on jute fiber reinforced composites. In *Advances in Industrial and Production Engineering: Select Proceedings of FLAME*; Shanker, K., Shankar, R., Sindhwani, R., Eds.; Springer Nature: London, UK, 2019; pp. 459–467. [\[CrossRef\]](#)
92. Sumi, S.; Unnikrishnan, N.; Mathew, L. Experimental investigations on biological resistance of surface modified coir geotextiles. *Int. J. Geosynth. Ground Eng.* **2016**, *2*, 31. [\[CrossRef\]](#)
93. Elfaleh, I.; Abbassi, F.; Habibi, M.; Ahmad, F.; Guedri, M.; Nasri, M.; Garnier, C. A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials. *Results Eng.* **2023**, *19*, 101271. [\[CrossRef\]](#)

94. Chandramohan, D.; Murali, B.; Vasantha-Srinivasan, P.; Dinesh Kumar, S. Mechanical, moisture absorption, and abrasion resistance properties of bamboo–jute–glass fiber composites. *J. Bio-Tribo-Corros.* **2019**, *5*, 66. [\[CrossRef\]](#)
95. Teixidó, H.; Staal, J.; Caglar, B.; Michaud, V. Capillary effects in fiber reinforced polymer composite processing: A review. *Front. Mater.* **2022**, *9*, 809226. [\[CrossRef\]](#)
96. Rangappa, S.M.; Siengchin, S.; Parameswaranpillai, J.; Jawaid, M.; Ozbakkaloglu, T. Lignocellulosic fiber reinforced composites: Progress, performance, properties, applications, and future perspectives. *Polym. Compos.* **2022**, *43*, 645–691. [\[CrossRef\]](#)
97. Feng, Y.; Hao, H.; Lu, H.; Chow, C.L.; Lau, D. Exploring the development and applications of sustainable natural fiber composites: A review from a nanoscale perspective. *Compos. Part B Eng.* **2024**, *276*, 111369. [\[CrossRef\]](#)
98. Fragassa, C. Marine applications of natural fibre-reinforced composites: A manufacturing case study. In *Advances in Applications of Industrial Biomaterials*; Pellicer, E., Nikolic, D., Sort, J., Baró, M., Zivic, F., Grujovic, N., Grujic, R., Pelemis, S., Eds.; Springer: Cham, Switzerland, 2017; pp. 21–47. [\[CrossRef\]](#)
99. Narayana, V.L.; Rao, L.B. A brief review on the effect of alkali treatment on mechanical properties of various natural fiber reinforced polymer composites. *Mater. Today Proc.* **2021**, *44*, 1988–1994. [\[CrossRef\]](#)
100. Fang, X.; Xu, J.; Guo, H.; Liu, Y. The effect of alkali treatment on the crystallinity, thermal stability, and surface roughness of bamboo fibers. *Fibers Polym.* **2023**, *24*, 505–514. [\[CrossRef\]](#)
101. Mohammed, M.; Mohammed, A.M.M.; Oleiwi, J.K.; Adam, T.; Betar, B.O.; Gopinath, S.C.; Ihmedee, F.H.; Anton, K. Influence of Fiber Treatments on Water Absorption Behavior in Natural Fiber-Reinforced Polymer Composites: A Review. *Al-Rafidain J. Eng. Sci.* **2025**, *3*, 410–430. [\[CrossRef\]](#)
102. Tserki, V.; Zafeiropoulos, N.E.; Simon, F.; Panayiotou, C. A study of the effect of acetylation and propionylation surface treatments on natural fibres. *Compos. Part A Appl. Sci. Manuf.* **2005**, *36*, 1110–1118. [\[CrossRef\]](#)
103. Zaman, H.U.; Khan, R.A. Acetylation used for natural fiber/polymer composites. *J. Thermoplast. Compos. Mater.* **2021**, *34*, 3–23. [\[CrossRef\]](#)
104. Abd Halip, J.; Hua, L.S.; Ashaari, Z.; Tahir, P.M.; Chen, L.W.; Uyup, M.K.A. Effect of treatment on water absorption behavior of natural fiber–reinforced polymer composites. In *Mechanical and Physical Testing of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*; Jawaid, M., Thariq, M., Saba, N., Eds.; Woodhead Publishing: Cambridge, UK, 2019; pp. 141–156. [\[CrossRef\]](#)
105. Fragassa, C.; Pesic, A.; Mattiello, S.; Pavlovic, A.; Santulli, C. Exploring the Potential of *Posidonia oceanica* Fibers in Eco-Friendly Composite Materials: A Review. *J. Mar. Sci. Eng.* **2025**, *13*, 177. [\[CrossRef\]](#)
106. Garcia-Garcia, D.; Quiles-Carrillo, L.; Montanes, N.; Fombuena, V.; Balart, R. Manufacturing and characterization of composite fibreboards with *Posidonia oceanica* wastes with an environmentally-friendly binder from epoxy resin. *Materials* **2017**, *11*, 35. [\[CrossRef\]](#) [\[PubMed\]](#)
107. Seggiani, M.; Cinelli, P.; Mallegni, N.; Balestri, E.; Puccini, M.; Vitolo, S.; Lardicci, C.; Lazzeri, A. New bio-composites based on polyhydroxyalkanoates and *posidonia oceanica* fibres for applications in a marine environment. *Materials* **2017**, *10*, 326. [\[CrossRef\]](#)
108. Chauhan, V.; Kärki, T.; Varis, J. Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques. *J. Thermoplast. Compos. Mater.* **2022**, *35*, 1169–1209. [\[CrossRef\]](#)
109. Wataniyakun, W.; Le Gall, M.; El Rakwe, M.; Karl, C.W.; Larsen, R.B. Biodegradable fishing gears: A potential solution to ghost fishing and marine plastic pollution. *Mar. Pollut. Bull.* **2025**, *212*, 117607. [\[CrossRef\]](#) [\[PubMed\]](#)
110. Jagadeesh, P.; Puttegowda, M.; Mavinkere Rangappa, S.; Siengchin, S. A review on extraction, chemical treatment, characterization of natural fibers and its composites for potential applications. *Polym. Compos.* **2021**, *42*, 6239–6264. [\[CrossRef\]](#)
111. Miller, S.A.; Srubar III, W.V.; Billington, S.L.; Lepech, M.D. Integrating durability-based service-life predictions with environmental impact assessments of natural fiber–reinforced composite materials. *Resour. Conserv. Recycl.* **2015**, *99*, 72–83. [\[CrossRef\]](#)
112. Summerscales, J. Durability of composites in the marine environment. In *Durability of Composites in a Marine Environment*; Davies, P., Rajapakse, Y., Eds.; Springer: Dordrecht, The Netherlands, 2014; pp. 1–13.
113. Santulli, C. Fabrication and characterization of a filament for 3D printing from polylactic acid with *Cryptostegia grandiflora* fiber. *Mater. Sci.* **2024**, *42*, 1–10. [\[CrossRef\]](#)
114. Chandrasekar, M.; Ishak, M.R.; Sapuan, S.M.; Leman, Z.; Jawaid, M. A review on the characterisation of natural fibres and their composites after alkali treatment and water absorption. *Plast. Rubber Compos.* **2017**, *46*, 119–136. [\[CrossRef\]](#)
115. Sahu, P.; Gupta, M.K. A review on the properties of natural fibres and its bio-composites: Effect of alkali treatment. *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* **2020**, *234*, 198–217. [\[CrossRef\]](#)
116. Punyamurthy, R.; Sampathkumar, D.; Srinivasa, C.V.; Bennehalli, B. Effect of alkali treatment on water absorption of single cellulosic abaca fiber. *BioResources* **2012**, *7*, 3515–3524.
117. Chen, Y.; Su, N.; Zhang, K.; Zhu, S.; Zhu, Z.; Qin, W.; Yang, Y.; Shi, Y.; Fan, S.; Wang, Z.; et al. Effect of fiber surface treatment on structure, moisture absorption and mechanical properties of luffa sponge fiber bundles. *Ind. Crops Prod.* **2018**, *123*, 341–352. [\[CrossRef\]](#)

118. Kamali Moghaddam, M.; Karimi, E. The effect of oxidative bleaching treatment on Yucca fiber for potential composite application. *Cellulose* **2020**, *27*, 9383–9396. [\[CrossRef\]](#)
119. Palaniappan, M.; Palanisamy, S.; Murugesan, T.; Tadepalli, S.; Khan, R.; Ataya, S.; Santulli, C. Influence of washing with sodium lauryl sulphate (SLS) surfactant on different properties of ramie fibres. *BioResources* **2024**, *19*, 2609–2625. [\[CrossRef\]](#)
120. Sayeb, S.; Marzoug, I.; Hassen, M.B.; Sakli, F.; Rodesli, S. Study of water sorption properties for esparto grass ultimate fibre (ALFA fibre). *J. Text. Inst.* **2010**, *101*, 19–27. [\[CrossRef\]](#)
121. Hu, W.; Wang, X.; Cai, M.; Zhang, C.; Zhong, D.; Wang, X.; Zhou, Y.; Xia, L.; Zhou, S.; Xu, W. Environmentally friendly salt-free and low-alkaline coloration of lyocell fibers in an ethanol–water mixture with excellent exhaustion. *Green Chem.* **2025**, *27*, 3751–3763. [\[CrossRef\]](#)
122. Varma, V.K.; Sarangi, S.K. Characterization of *Bauhinia variegata* natural fiber treated with bleaching, benzylation, and alkalization. *Eng. Res. Expr.* **2024**, *6*, 025528. [\[CrossRef\]](#)
123. Ladaci, N.; Saadia, A.; Belaadi, A.; Boumaaza, M.; Chai, B.X.; Abdullah, M.M.; Al-Khawlani, A.; Ghernaout, D. ANN and RSM prediction of water uptake of recycled HDPE biocomposite reinforced with treated palm waste *W. filifera*. *J. Nat. Fibers* **2024**, *21*, 2356697. [\[CrossRef\]](#)
124. Fiore, V.; Scalici, T.; Valenza, A. Effect of sodium bicarbonate treatment on mechanical properties of flax-reinforced epoxy composite materials. *J. Compos. Mater.* **2018**, *52*, 1061–1072. [\[CrossRef\]](#)
125. Fiore, V.; Scalici, T.; Nicoletti, F.; Vitale, G.; Prestipino, M.; Valenza, A. A new eco-friendly chemical treatment of natural fibres: Effect of sodium bicarbonate on properties of sisal fibre and its epoxy composites. *Compos. Part B Eng.* **2016**, *85*, 150–160. [\[CrossRef\]](#)
126. Lee, Y.J.; Chung, C.H. Study on the mechanical properties of marine FRP laminates. *J. Compos. Mater.* **2003**, *37*, 967–983. [\[CrossRef\]](#)
127. Oladele, I.O.; Adelani, S.O.; Makinde-Isola, B.A.; Omotosho, T.F. Coconut/coir fibers, their composites and applications. In *Plant Fibers, Their Composites, and Applications*; Sanjay, M.R., Siengchin, S., Parameswaranpillai, J., Ozbakkaloglu, T., Wang, H., Eds.; Woodhead Publishing: Cambridge, UK, 2022; pp. 181–208. [\[CrossRef\]](#)
128. Nguyen, D.T.; Le, H.C. Potential of jute fiber-reinforced composites in the manufacture of components and equipment used on ships and hulls. *J. Emerg. Sci. Eng.* **2023**, *1*, 14–21. [\[CrossRef\]](#)
129. Blier, T.; Troalen, W.; Baley, C.; Baral, N. Flax Fiber Reinforced Composites in Boat Building: A Comprehensive Review and Application-Oriented Testing. In *SNAME Chesapeake Sailing Yacht Symposium, Proceedings of the SNAME 25th Chesapeake Sailing Yacht Symposium, Annapolis, MD, USA, 14–15 March 2025*; SNAME: Annapolis, MD, USA, 2025; p. D021S006R001. [\[CrossRef\]](#)
130. Jasti, A.; Biswas, S. Effect of ocean water absorption on flexural properties of *Cannabis sativa* L. hemp fibre reinforced polymer composites for marine applications. *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* **2023**, *237*, 3894–3907. [\[CrossRef\]](#)
131. Yu, C. Sisal. In *Bast and Other Plant Fibres*; Franck, R.E., Ed.; Woodhead Publishing: Cambridge, UK, 2005; pp. 228–273. [\[CrossRef\]](#)
132. Salazar, V.L.P.; Leão, A.L.; Rosa, D.S.; Gomez, J.G.C.; Alli, R.C.P. Biodegradation of coir and sisal applied in the automotive industry. *J. Polym. Environ.* **2011**, *19*, 677–688. [\[CrossRef\]](#)
133. Rajan, R.K.; Zulkifli, R.; Tahir, M.F.M.; Ude, A.U. Tensile properties and water absorption of Gigantochloa Scortechinii bamboo strip with epoxy layer coating under sea water conditions. *Results Eng.* **2024**, *24*, 102969. [\[CrossRef\]](#)
134. Huang, P.; Chang, W.S.; Ansell, M.P.; John, C.Y.; Shea, A. Porosity estimation of Phyllostachys edulis (Moso bamboo) by computed tomography and backscattered electron imaging. *Wood Sci. Technol.* **2017**, *51*, 11–27. [\[CrossRef\]](#)
135. Hamidon, M.H.; Sultan, M.T.; Ariffin, A.H.; Shah, A.U. Effects of fibre treatment on mechanical properties of kenaf fibre reinforced composites: A review. *J. Mater. Res. Technol.* **2019**, *8*, 3327–3337. [\[CrossRef\]](#)
136. Yusof, Y.; Yahya, S.A.B. Pineapple leaf fiber as a new potential natural fiber in rope making. *Adv. Mater. Res.* **2013**, *785*, 628–633. [\[CrossRef\]](#)
137. Dhanenderan, N.; Uvaraja, V.C.; Bensam Raj, J.; Malarkodi, P. Physical, chemical and thermal analysis of banana flower pistil fiber for the potential application of composite manufacturing. *Proc. Inst. Mech. Eng. Part E* **2023**, *237*, 1344–1353. [\[CrossRef\]](#)
138. Peng, B.Y.; Su, Y.; Chen, Z.; Chen, J.; Zhou, X.; Benbow, M.E.; Criddle, C.S.; Wu, W.-M.; Zhang, Y. Biodegradation of polystyrene by dark (*Tenebrio obscurus*) and yellow (*Tenebrio molitor*) mealworms (Coleoptera: Tenebrionidae). *Environ. Sci. Technol.* **2019**, *53*, 5256–5265. [\[CrossRef\]](#)
139. Klose, L.; Meyer-Heydecke, N.; Wongwattanasarat, S.; Chow, J.; Pérez García, P.; Carré, C.; Streit, W.; Antranikian, G.; Romero, A.M.; Liese, A. Towards sustainable recycling of epoxy-based polymers: Approaches and challenges of epoxy biodegradation. *Polymers* **2023**, *15*, 2653. [\[CrossRef\]](#) [\[PubMed\]](#)
140. Haramina, T.; Hadžić, N.; Keran, Z. Epoxy resin biocomposites reinforced with flax and hemp fibers for marine applications. *J. Mar. Sci. Eng.* **2023**, *11*, 382. [\[CrossRef\]](#)
141. Nash, N.H.; Egan, L.; Bachour, C.; Manolakis, I.; Comer, A.J. Bio-Based Epoxy Resin Systems as Potential Alternatives to Petroleum Based Epoxy Matrices in Marine Fibre-Reinforced Polymer Composites. *SciSpace* **2019**, 296534488. Available online: https://www.scipedia.com/public/Nash_et_al_2019a (accessed on 24 June 2025).

142. Ramon, E.; Sguazzo, C.; Moreira, P.M. A review of recent research on bio-based epoxy systems for engineering applications and potentialities in the aviation sector. *Aerospace* **2018**, *5*, 110. [\[CrossRef\]](#)
143. Capretti, M.; Giammaria, V.; Santulli, C.; Boria, S.; Del Bianco, G. Use of bio-epoxies and their effect on the performance of polymer composites: A critical review. *Polymers* **2023**, *15*, 4733. [\[CrossRef\]](#)
144. Gopalakrishna, K.G.; Reddy, N.; Zhao, Y. Biocomposites from Biofibers and Biopolymers. In *Biopolymer Composites in Electronics*; Khan, A., Mavinkere Rangappa, S., Siengchin, S., Asiri, A., Eds.; Springer: Cham, Switzerland, 2020; pp. 95–123. [\[CrossRef\]](#)
145. Raffaele, M.; Corigliano, P.; Cucinotta, F.; Palomba, G.; Salmeri, F. Life Cycle Assessment and Experimental Mechanical Investigation of Test Samples for High-Performance Racing Boats. *J. Mar. Sci. Eng.* **2024**, *12*, 2028. [\[CrossRef\]](#)
146. Lopez-Arraiza, A.; Essamari, L.; Iturrondobeitia, M.; Boullosa-Falces, D.; Justel, D. Life cycle assessment of glass fibre versus flax fibre reinforced composite ship hulls. *Sci. Rep.* **2025**, *15*, 16283. [\[CrossRef\]](#)
147. Liu, J.; Zhang, L.; Shun, W.; Dai, J.; Peng, Y.; Liu, X. Recent development on bio-based thermosetting resins. *J. Polym. Sci.* **2021**, *59*, 1474–1490. [\[CrossRef\]](#)
148. Čuk, N.; Štular, D.; Očepek, M.; Langerholc, J.; Venturini, P. Development of Renewable Polyester Resins for Coil Coatings Based on 2, 5-Furandicarboxylic Acid. *Coatings* **2025**, *15*, 350. [\[CrossRef\]](#)
149. Meng, J.; Li, Z.; Bai, X.; Gao, X.; Dong, Y.; Sheng, L.; Sun, J.; Guo, K. Design evolution towards sustainability: From dual furan and eugenol biomass to functional epoxy resin and its upgrading. *Chem. Eng. J.* **2025**, *506*, 159604. [\[CrossRef\]](#)
150. Medina, R.; Hauptert, F.; Schlarb, A.K. Improvement of tensile properties and toughness of an epoxy resin by nanozirconium-dioxide reinforcement. *J. Mater. Sci.* **2008**, *43*, 3245–3252. [\[CrossRef\]](#)
151. Zhang, X.; Bitaraf, V.; Wei, S.; Guo, Z.; Zhang, X.; Wei, S.; Colorado, H.A. Vinyl ester resin: Rheological behaviors, curing kinetics, thermomechanical, and tensile properties. *AIChE J.* **2014**, *60*, 266–274. [\[CrossRef\]](#)
152. Misumi, J.; Ganesh, R.; Sockalingam, S.; Gillespie, J.W., Jr. Experimental characterization of tensile properties of epoxy resin by using micro-fiber specimens. *J. Reinf. Plast. Compos.* **2016**, *35*, 1792–1801. [\[CrossRef\]](#)
153. Hanon, M.M.; Marcziš, R.; Zsidai, L. Influence of the 3D printing process settings on tensile strength of PLA and HT-PLA. *Period. Polytech. Mech. Eng.* **2021**, *65*, 38–46. [\[CrossRef\]](#)
154. Kainulainen, T.P.; Hukka, T.I.; Ozeren, H.D.; Sirviö, J.A.; Hedenqvist, M.S.; Heiskanen, J.P. Utilizing furfural-based bifuran diester as monomer and comonomer for high-performance bioplastics: Properties of poly(butylene furanoate), poly(butylene bifuranoate), and their copolyesters. *Biomacromolecules* **2019**, *21*, 743–752. [\[CrossRef\]](#)
155. Najah, M.I.; Aisyah, R.; Adzila, S.; Haq, R.H.A. Mechanical properties of calcium phosphate reinforced polyhydroxyalkanoate (PHA) biocomposite. *J. Thermoplast. Compos. Mater.* **2023**, *36*, 3294–3311. [\[CrossRef\]](#)
156. Xiao, G.Z.; Shanahan, M.E.R. Water absorption and desorption in an epoxy resin with degradation. *J. Polym. Sci. B Polym. Phys.* **1997**, *35*, 2659–2670. [\[CrossRef\]](#)
157. Kalenda, P. Chemical-resistance values of epoxy resins hardened with polyamines. *Pigment Resin Technol.* **2001**, *30*, 150–158. [\[CrossRef\]](#)
158. Feng, L.; Li, R.; Yang, H.; Chen, S.; Yang, W. The hyperbranched polyester reinforced unsaturated polyester resin. *Polymers* **2022**, *14*, 1127. [\[CrossRef\]](#)
159. Ching, Y.C.; Gunathilake, T.U.; Ching, K.Y.; Chuah, C.H.; Sandu, V.; Singh, R.; Liou, N.S. Effects of high temperature and ultraviolet radiation on polymer composites. In *Durability and Life Prediction in Biocomposites, Fibre-Reinforced Composites and Hybrid Composites*; Jawaid, M., Sultan, M.T.H., Saba, N., Eds.; Woodhead Publishing: Cambridge, UK, 2018; pp. 407–426.
160. Rahman, M.I.A.M.; Ariffin, A.H. The Development of Pineapple Leaves Fibre Composite Material for Marine Application Using Hand Lay-Up Method. *Res. Progr. Mech. Manufact. Eng.* **2024**, *5*, 70–78.
161. Biswas, S. Mechanical properties of bamboo-epoxy composites a structural application. *Adv. Mater. Res.* **2012**, *1*, 221–231. [\[CrossRef\]](#)
162. Fitriadi, N.; Rizal, M.; Fonna, S. Physical and Thermal Characteristics of Coco Peat Fibre Reinforced Polyurethane Composite for Insulation Box in Marine Application. *J. Eng. Sci. Technol.* **2022**, *17*, 3787–3799.
163. Dhanenderan, N.; Rajasekaran, P.; Pauldoss, S.P.; Arumuganainar, K. Innovative development of sustainable epoxy toughened through banana flower pistil: Mechanical along with water absorption performance evaluation. *Phys. Scr.* **2025**, *100*, 035980. [\[CrossRef\]](#)
164. Huang, Y.; Sultan, M.T.H.; Shahar, F.S.; Łukaszewicz, A.; Oksiuta, Z.; Grzejda, R. Kenaf Fiber-Reinforced Biocomposites for Marine Applications: A Review. *Materials* **2025**, *18*, 999. [\[CrossRef\]](#)
165. Taj, A.; Swamy, R.P.; Naik, K.; Bharat, K.N. Physical effects of nanoaluminum oxide and nanographene on kenaf epoxy composite; vacuum bagging process. *J. Appl. Polym. Sci.* **2023**, *140*, e53374. [\[CrossRef\]](#)
166. Raj, R.R.; Sathish, S.; Mansadevi, T.L.D.; Supriya, R.; Sekar, S.; Patil, P.P.; Tonmoy, M.M. Effect of Graphene Fillers on the Water Absorption and Mechanical Properties of NaOH-Treated Kenaf Fiber-Reinforced Epoxy Composites. *J. Nanomater.* **2022**, *2022*, 1748121. [\[CrossRef\]](#)

167. Palmiyanto, M.H.; Surojo, E.; Ariawan, D.; Imaduddin, F. E-glass/kenaf fibre reinforced thermoset composites filled with MCC and immersion in a different fluid. *Sci. Rep.* **2022**, *12*, 20332. [[CrossRef](#)]
168. Manik, P.; Samuel, S.; Tuswan, T.; Jokosisworo, S.; Nadapdap, R.K. Mechanical properties of laminated bamboo composite as a sustainable green material for fishing vessel: Correlation of layer configuration in various mechanical tests. *J. Mech. Behav. Mater.* **2022**, *31*, 673–690. [[CrossRef](#)]
169. Corradi, S.; Isidori, T.; Corradi, M.; Soleri, F.; Olivari, L. Composite boat hulls with bamboo natural fibres. *Int. J. Mater. Prod. Technol.* **2009**, *36*, 73–89. [[CrossRef](#)]
170. Mentari, P.R.A.; Suharti, S.; Andreansyah, I.; Pratama, A.W.; Agustina, S.; Suhartana, S.; Syamani, F.A. Characterization of High-Density Polyethylene (HDPE)-based Biocomposite with Green Seaweed *Caulerpa lentillifera* as Filler and Polyethylene-grafted-Maleic Anhydride (PE-g-MA) as Coupling Agent. *Biointerface Res. Appl. Chem.* **2024**, *14*, 136. [[CrossRef](#)]
171. Fragassa, C.; Mattiello, S.; Latini, M.; Pesic, A.; Santulli, C. Saltwater immersion effects on bio-composites reinforced with seashell powders. *Appl. Compos. Mater.* **2025**, *32*, 123–138. [[CrossRef](#)]
172. Li, L.; Yu, H.; Gui, C.; Hu, L.; Zou, M.; Ren, S.; Huan, W.; Yu, X.; Wang, X. Bio-marine shell powder-filled jute fabric/epoxy composites: Chemical, combustion, and mechanical properties. *Polym. Compos.* **2025**, *46*, 4853–4862. [[CrossRef](#)]
173. Echeverria, C.A.; Pahlevani, F.; Gaikwad, V.; Sahajwalla, V. The effect of microstructure, filler load and surface adhesion of marine bio-fillers, in the performance of Hybrid Wood-Polypropylene Particulate Bio-composite. *J. Clean. Prod.* **2017**, *154*, 284–294. [[CrossRef](#)]
174. Essabir, H.; Bensalah, M.O.; Rodrigue, D.; Bouhfid, R.; Qaiss, A.E.K. Biocomposites based on argan nut shell and a polymer matrix: Effect of filler content and coupling agent. *Carbohydr. Polym.* **2016**, *143*, 70–83. [[CrossRef](#)]
175. Cardon, L.; Ragaert, K.; Koster, R. Design and fabrication of biocomposites. In *Biopolymers—Processing and Products*; Niaounakis, M., Ed.; Elsevier: Amsterdam, The Netherlands, 2010; Chapter 2; pp. 25–43. [[CrossRef](#)]
176. Siraj, M.T.; Alshybani, I.; Payel, S.B.; Shahadat, M.R.B.; Rahman, M.Z. Advances in biocomposite fabrication: Emerging technologies and their potential applications. In *Sustainable Composites for Aerospace Applications*; Jawaaid, M., Sultan, M.T.H., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; Chapter 76. [[CrossRef](#)]
177. Paolucci, M.; Fasulo, G.; Volpe, M.G. Employment of marine polysaccharides to manufacture functional biocomposites for aquaculture feeding applications. *Mar. Drugs* **2015**, *13*, 2680–2693. [[CrossRef](#)] [[PubMed](#)]
178. Roy, H.; Pahlevani, F.; Cholake, S.T.; Echeverria, C.A.; Banerjee, A.; Sahajwalla, V. Simulation of marine bio-composite using empirical data combined with finite element technique. *J. Compos. Sci.* **2018**, *2*, 48. [[CrossRef](#)]
179. Kim, S.; Lee, S.; Choi, D.; Lee, K.H.; Park, H.; Hwang, W. Fabrication of metal nanohoneycomb structures and their tribological behavior. *Adv. Compos. Mater.* **2008**, *17*, 101–110. [[CrossRef](#)]
180. Popineau, V.; Céline, A.; Le Gall, M.; Martineau, L.; Baley, C.; Le Duigou, A. Vacuum-bag-only (VBO) molding of flax fiber-reinforced thermoplastic composites for naval shipyards. *Appl. Compos. Mater.* **2021**, *28*, 791–808. [[CrossRef](#)]
181. Qin, Y.; Summerscales, J.; Graham-Jones, J.; Meng, M.; Pemberton, R. Monomer selection for in situ polymerization infusion manufacture of natural-fiber reinforced thermoplastic-matrix marine composites. *Polymers* **2020**, *12*, 2928. [[CrossRef](#)] [[PubMed](#)]
182. Ait Talaoul, A.; Assarar, M.; Zouari, W.; Ayad, R.; Mazian, B.; Behlouli, K. Investigation of the Flexural Behavior and Damage Mechanisms of Flax/Cork Sandwich Panels Manufactured by Liquid Thermoplastic Resin. *J. Compos. Sci.* **2024**, *8*, 539. [[CrossRef](#)]
183. Summerscales, J. Composites manufacturing for marine structures. In *Marine Applications of Advanced Fibre-Reinforced Composites*; Graham-Jones, J., Summerscales, J., Eds.; Woodhead Publishing: Cambridge, UK, 2016; pp. 19–55, ISBN 0081002009.
184. Cesur, S.; Oktar, F.N.; Ekren, N.; Kilic, O.; Alkaya, D.B.; Seyhan, S.A.; Ege, Z.R.; Lin, C.-C.; Kuruca, S.E.; Erdemir, G.; et al. Preparation and characterization of electrospun polylactic acid/sodium alginate/orange oyster shell composite nanofiber for biomedical application. *J. Aust. Ceram. Soc.* **2020**, *56*, 533–543. [[CrossRef](#)]
185. Chaudhary, B.; Li, H.; Matos, H. Long-term mechanical performance of 3D printed thermoplastics in seawater environments. *Results Mater.* **2023**, *17*, 100381. [[CrossRef](#)]
186. Varghese, A.M.; Mittal, V. Surface modification of natural fibers. In *Biodegradable and Biocompatible Polymer Composites: Processing, Properties and Applications*; Shimpi, N.G., Ed.; Woodhead Publishing: Cambridge, UK, 2017; p. 115.
187. Cheng, X.Q.; Baig, Y.; Li, Z.N. Effects of stitching parameters on tensile strength of FRPs under hygrothermal conditions. *Adv. Mater. Res.* **2012**, *570*, 63–77. [[CrossRef](#)]
188. Gupta, U.S.; Dhamarika, M.; Dharkar, A.; Chaturvedi, S.; Kumrawat, A.; Giri, N.; Tiwari, S.; Namdeo, R. Plasma modification of natural fiber: A review. *Mater. Today Proc.* **2021**, *43*, 451–457. [[CrossRef](#)]
189. Fan, H.; Wang, J.; Tao, Z.; Huang, J.; Rao, P.; Kurokawa, T.; Gong, J.P. Adjacent Cationic–Aromatic Sequences Yield Strong Electrostatic Adhesion of Hydrogels in Seawater. *Nat. Commun.* **2019**, *10*, 5127. [[CrossRef](#)] [[PubMed](#)]
190. Hu, H.; Bai, Z.; Sun, Y.; Gao, Y.; Zhang, K.; Wang, H. Solvent-free preparation of bio-based composite coating with improved crystallinity and unique corrosion resistance. *Prog. Org. Coat.* **2023**, *179*, 107520. [[CrossRef](#)]
191. Şükür, E.F.; Önal, G. Long-term salt-water durability of GNPs reinforced basalt-epoxy multiscale composites for marine applications. *Tribol. Int.* **2021**, *158*, 106910. [[CrossRef](#)]

192. Tian, H.; Zhan, Y.; Tian, L.; Sun, J. Corrosion resistance self-healing coating with bioinspired interfacial structure. *Prog. Org. Coat.* **2023**, *174*, 107303. [\[CrossRef\]](#)
193. Hudda, A.; Singh, S.; Tiwari, S.; Kumar, H.V.; Vesh, A.; Imamuddin, M.; Roy, D.; Prasad, N.E. Unravelling the Role of Nanofillers Towards the Stability of Polymer Matrix Composite in Marine Environment. *Adv. Compos. Mater.* **2022**, *32*, 268–282. [\[CrossRef\]](#)
194. Seo, E.; Seong, M.R.; Lee, J.W.; Lim, H.; Park, J.W.; Kim, H.; Hwang, H.; Lee, D.; Kim, J.; Kim, G.H.; et al. Anti-Biofouling Features of Eco-Friendly Oleamide-PDMS Copolymers. *ACS Omega* **2020**, *5*, 11515–11521. [\[CrossRef\]](#)
195. Sankaran, S.; Palani, G.; Yang, Y.L.; Trilaksana, H. Enhancing natural fiber-based polymeric composites with biochar filler particles derived from groundnut shell biomass waste. *Biomass Convers. Biorefin.* **2025**, *15*, 14399–14410. [\[CrossRef\]](#)
196. Post, W.; Kuijpers, L.J.; Zijlstra, M.; Van Der Zee, M.; Molenveld, K. Effect of mineral fillers on the mechanical properties of commercially available biodegradable polymers. *Polymers* **2021**, *13*, 394. [\[CrossRef\]](#)
197. Wang, D.; Liu, Y.; Zhou, F. Anti-Biofouling Friction Power Generation Coating Material and Application Thereof. Korean Patent n. KR101489640B1, 4 February 2015.
198. Sharma, M.; Sharma, H.; Shannigrahi, S. Tribology of Advanced Composites/Biocomposites Materials. In *Green Tribology*; Bhushan, B., Ed.; Woodhead Publishing: Cambridge, UK, 2017; Chapter 18. [\[CrossRef\]](#)
199. Lee, B.P.; Messersmith, P.B.; Israelachvili, J.N.; Waite, J.H. Mussel-inspired adhesives and coatings. *Annu. Rev. Mater. Res.* **2011**, *41*, 99–132. [\[CrossRef\]](#) [\[PubMed\]](#)
200. Pulikkalparambil, H.; Babu, A.; Thilak, A.; Vighnesh, N.P.; Rangappa, S.M.; Siengchin, S. A review on sliding wear properties of sustainable biocomposites: Classifications, fabrication and discussions. *Heliyon* **2023**, *9*, e14381. [\[CrossRef\]](#)
201. Seshadhri, V.; Alagarsamy, S.V.; Rajagopal, M. Tribological behaviour of AZ31 Mg hybrid bio-composite reinforced with zirconium dioxide and seashell bio-ceramics. *Phys. Scr.* **2024**, *100*, 015043. [\[CrossRef\]](#)
202. Curto, M.; Le Gall, M.; Catarino, A.I.; Niu, Z.; Davies, P.; Everaert, G.; Dhakal, H.N. Long-term durability and ecotoxicity of biocomposites in marine environments: A review. *RSC Adv.* **2021**, *11*, 32917–32941. [\[CrossRef\]](#)
203. Chang, B.P.; Mohanty, A.K.; Misra, M. Studies on durability of sustainable biobased composites: A review. *RSC Adv.* **2020**, *10*, 17955–17999. [\[CrossRef\]](#)
204. Santulli, C.; Fiore, V. Seawater aging and its degradation effects on the mechanical properties of biocomposites. In *Handbook of Bioplastics and Biocomposites Engineering Applications*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 423–440. [\[CrossRef\]](#)
205. Sekaran, J.J.G.; Thirumurugan, P.; Kandavalli, S.R.; Swarnalatha, K. Dynamic mechanical, tensile fatigue and water absorption behaviour of polyester composites comprises of *Amaranthus dubius* stem natural fiber and its root waste crystalline cellulose. *Biomass Convers. Biorefin.* **2024**, *14*, 32499–32507. [\[CrossRef\]](#)
206. Strangis, G.; Rossi, D.; Cinelli, P.; Seggiani, M. Seawater biodegradable poly (butylene succinate-co-adipate)—Wheat bran biocomposites. *Materials* **2023**, *16*, 2593. [\[CrossRef\]](#) [\[PubMed\]](#)
207. Snowdon, A.A.; Dennington, S.P.; Longyear, J.E.; Wharton, J.A.; Stoodley, P. Surface properties influence marine biofilm rheology, with implications for ship drag. *Soft Matter* **2023**, *19*, 3675–3687. [\[CrossRef\]](#)
208. Gandini, A.; Lacerda, T.M. Furan polymers: State of the art and perspectives. *Macromol. Mater. Eng.* **2022**, *307*, 2100902. [\[CrossRef\]](#)
209. Paul, R.; Zindani, D.; Bhowmik, S. Investigation on physicomechanical, tribological and optimality condition for coir filler-reinforced polymeric composites. *Arab. J. Sci. Eng.* **2023**, *48*, 3615–3630. [\[CrossRef\]](#)
210. Woolnough, C.A.; Yee, L.H.; Charlton, T.; Foster, L.J.R. Environmental degradation and biofouling of ‘green’ plastics including short and medium chain length polyhydroxyalkanoates. *Polym. Int.* **2010**, *59*, 658–667. [\[CrossRef\]](#)
211. Piras, S.; Salathia, S.; Guzzini, A.; Zovi, A.; Jackson, S.; Smirnov, A.; Fragassa, C.; Santulli, C. Biomimetic use of food-waste sources of calcium carbonate and phosphate for sustainable materials—A review. *Materials* **2024**, *17*, 843. [\[CrossRef\]](#) [\[PubMed\]](#)
212. Taghaddosi, S.; Akbari, A.; Yegani, R. Preparation, characterization and anti-fouling properties of nanoclays embedded polypropylene mixed matrix membranes. *Chem. Eng. Res. Des.* **2017**, *125*, 35–45. [\[CrossRef\]](#)
213. Kumar, S.V.; Singh, H. Wear, morphological and thermal behavior of flax fibre reinforced epoxy composites. *Indian J. Fibre. Text. Res.* **2023**, *48*, 326–335. [\[CrossRef\]](#)
214. Sumesh, K.R.; Ajithram, A.; Anjumol, K.S.; Sai Krishnan, G. Influence of natural fiber addition and fiber length in determining the wear resistance of epoxy-based composites. *Polym. Compos.* **2024**, *45*, 3029–3042. [\[CrossRef\]](#)
215. Taha, I. Investigation of flax fibre reinforced epoxy friction composites. *Mater. Werkst.* **2012**, *43*, 1059–1066. [\[CrossRef\]](#)
216. Afshar, A.; Alkhader, M.; Korach, C.S.; Chiang, F.P. Effect of long-term exposure to marine environments on the flexural properties of carbon fiber vinylester composites. *Compos. Struct.* **2015**, *126*, 72–77. [\[CrossRef\]](#)
217. Oluwoye, I.; Machuca, L.L.; Higgins, S.; Suh, S.; Galloway, T.S.; Halley, P.; Tanaka, S.; Iannuzzi, M. Degradation and lifetime prediction of plastics in subsea and offshore infrastructures. *Sci. Total Environ.* **2023**, *904*, 166719. [\[CrossRef\]](#) [\[PubMed\]](#)
218. Weber, F.; Esmaeili, N. Marine biofouling and the role of biocidal coatings in balancing environmental impacts. *Biofouling* **2023**, *39*, 661–681. [\[CrossRef\]](#) [\[PubMed\]](#)

219. Sathish, T.; Mohanavel, V.; Raja, T.; Djearmane, S.; Velmurugan, P.; Nasif, O.; Alfarraj, S.; Wong, L.S.; Manikandan, V.; Ravichandran, M. Influence of compression molding process parameters in mechanical and tribological behavior of hybrid polymer matrix composites. *Polymers* **2021**, *13*, 4195. [[CrossRef](#)]
220. Huang, X.; Ye, R.; Zhao, L. Research progresses of composites with natural fibers recycled from textiles waste. *J. Eng. Fibers Fabr.* **2025**, *20*, 15589250251338265. [[CrossRef](#)]
221. Otoni, C.G.; Azeredo, H.M.; Mattos, B.D.; Beaumont, M.; Correa, D.S.; Rojas, O.J. The food–materials nexus: Next generation bioplastics and advanced materials from agri-food residues. *Adv. Mater.* **2021**, *33*, 2102520. [[CrossRef](#)]

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