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Review of state-of-the-art studies on the water absorption capacity of agricultural fiber-reinforced polymer composites for sustainable construction

Nur Syafiqaz Nor Arman, Ruey Shan Chen *, Sahrim Ahmad

Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor Darul Ehsan, Malaysia

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ABSTRACT

With the growing environmental impact related to the production, disposal, and recycling of synthetic fiber based polymeric matrix composites, environmentally friendly composites have been developed using materials based on natural resources. Of late, the disposal of agro-waste from industrial crops is another serious concern in developing countries. Based on the availability of agro-wastes, its usage for the development of sustainable composite materials is on the rise which constitutes a very interesting option for the construction industry. However, the water uptake characteristic of these natural fibers is established to be the most critical factor for the progressive deterioration of resultant composites' properties over time. Present review article attempts to comprehensively report studies related to water absorption properties of agricultural fiber reinforced polymer composites. This study is divided into three sections: The first section highlights the water absorption mechanism including the experimental measurement and prediction using Fickian modelling. The second part outlines the experimental results of water absorption capacity for various composites with different types of thermosets, thermoplastics and agro-wastes. The last section analyses the potentiality of agro-waste materials to partly replace the conventional composites in building material research. The impact of water absorption on the mechanical properties of composites is also demonstrated. The literature survey compares the moisture/water content level of previous findings with the existing wood-based products in service and the established standard requirement for industrial building materials. This review article will provide a comprehensive data source for further research in this topic to explore the application of agricultural fiber-reinforced polymer composites as cheap, primary building construction materials.

1. Introduction

Chronic scarcity of building materials due to increasing population and housing demand has become a problem in building and construction industry [1]. Another major challenge in developed and developing countries is sustainable development [2]. During the production of traditional construction materials such as bricks, cement, and steel, enormous amounts of thermal and electrical energy are consumed and thus contribute to air, water, and land pollutions [1]. Recent serious problems related to environmental issues have endorsed extensive research efforts to establish sustainable building design such as developing new green building materials in order to minimize the negative impacts induced from construction [3]. In consideration of wood shortage and the demerits of synthetic materials, the use of natural fibers obtained from renewable vegetable (agricultural) sources in composite materials has been explored [4,5]. Natural fibers or vegetable fibers have important advantages, such as abundant availability at relatively low cost, bio renewability, biodegradability, non-toxicity and environmentally friendly, recyclability, zero carbon footprint, and fascinating performances (low density and well-balanced strength, stiffness, and toughness) [4,6]. In developing countries, industrial and agricultural production activities have generated large amounts of wastes and a consequent disposal problem of solid waste. A feasible solution is the reuse of agricultural wastes or agro-wastes such as rice husk, sugarcane bagasse, coconut husk, jute fiber, and cotton stalk as a sustainable construction material [1]. These agricultural wastes have been proven to be a good reinforcing filler in polymeric matrices to reduce the density and cost of the resultant composites [1,7]. Applying locally available

* Corresponding author.
E-mail address: chen@ukm.edu.my (R.S. Chen).

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agro-waste material in composites can solve problems on pollution, land-filling, depleting petroleum sources, and high cost of building materials [1,8].

Moisture and water absorption is a critical concern in the application of agricultural fiber or agro-waste reinforced composites for building and construction purposes especially outdoor use [9]. Most of the natural fibers are prone to humidity and moisture owing to the presence of hydrophilic constituent materials such as cellulose, hemicellulose, and other soluble components in relatively high amounts [10–12]. Thus, water absorption is important in determining the performance and durability of natural fiber composites [9]. As shown in Fig. 1, water absorption is the main drawback to the performance deterioration and long-term durability of these composite materials; materials with high water absorption swell in all dimensions, and the absorbed water molecules will adversely affect the matrix-natural fibers interaction and stimulate bacterial growth [4,13,14]. Therefore, comprehensively understanding the water absorption behavior of materials is crucial in evaluating their suitability for internal or external construction.

The water absorption properties of natural fiber composites are governed by internal factors (Fig. 2), such as fiber inherent characteristics, fiber loading and orientation, types of plastics (viscosity of matrix), fiber–matrix interaction, additive used, area of exposed surfaces, void content, lumen size, and external factors such as humidity and temperature of soaking medium and surface protection [15–19]. Considerable efforts have been attempted to effectively minimize water absorption capacity, such as the prospective use of modification methods including surface treatment on fiber, inclusion of additives such as compatibilizer or coupling agent, and incorporation of nanoparticles [20,21]. Analysis of water absorption properties has become a routine characterization for natural fiber polymer composites, as evidenced by the increasing number of publications (Fig. 3). The number of published journals related to natural fiber polymer composites (NFPCs) or even specifically agro-waste polymer composites (AWPCs) showed a steady increment from 2011 to 2021. The increased interest in this research area has been focused on exploring new bio or green composite material as alternatives for conventional materials to compromise with environmental friendliness. A total of 7980 and 521 papers were published on NFPCs and AWPCs, respectively, up to early July 2021. Throughout the years, about half of these studies were involved with water absorption properties. This finding drives further interest in this topic.

This review addresses current studies on polymer matrix composites reinforced with agricultural fibers conducted during the past decade. The specific objective is to collect and review research studies on the water absorption behavior and capacity of various agricultural fibers composite to provide fundamental basis for possible industrial applications such as building construction. This review article is divided into three different sections: the first section addresses in great details of the water absorption behaviour, measurement and prediction; the second section focuses on the water absorption properties of single and hybrid agricultural fibers based on thermosets, thermoplastics, and biopolymer matrix composites, and the third section analyses the water absorption data concerning its impact on the mechanical properties of composites, and their potential applications for alternate wood-based products.

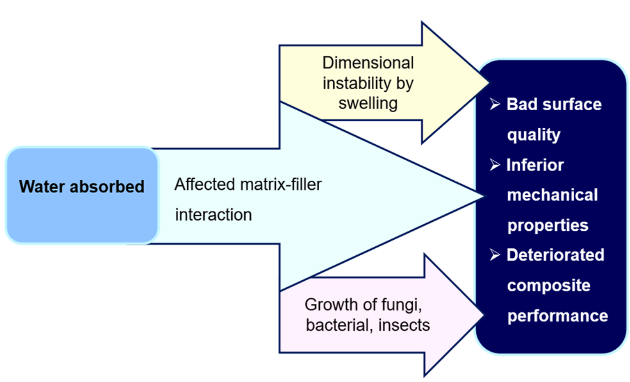

Fig. 1. Importance of water absorption characteristics on the performance and durability of composites.

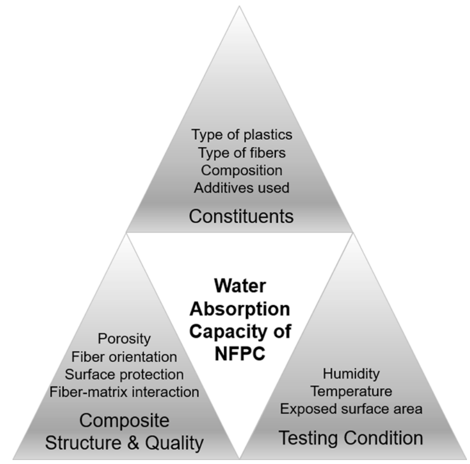

Fig. 2. Relation of the water absorption properties of natural fiber polymer composites (NFPCs) to internal and external factors.

2. Water absorption behaviour and measurement

The general moisture/water absorption of natural fiber polymer composites is governed by three major mechanisms, namely, the diffusion, capillary, and transport of water molecules as illustrated in Fig. 4. Diffusion occurs within the micro-gaps between polymers chains [9]. Capillary transport transpires in the gaps and flaws at the fiber–matrix interface in the case of the incomplete impregnation of the reinforcement with polymer matrix during manufacturing and under poor wettability [22]. Hence, the increase in fiber loading increases the water absorption of composites [22,23]. Another transport mechanism occurs through the micro-cracks appearing in the matrix and stems from the fiber swelling as a consequence of water storage [9,22]. Fiber swelling could be induced by the penetration of water molecules into the fibers, thus leading to dilapidation and crack formation in the bulk material and fiber–polymer interface debonding [24]. The absorbed water-soluble substances start leaching from the fiber surfaces and eventually cause the debonding and delamination of fiber–matrix, thereby reducing the tensile strength of the composites [25].

The water uptake or water absorption (WA) by natural fiber polymer composites is calculated using the following equation [12,26–29]:

$$WA(\%) = \frac{W_t - W_i}{W_i} \times 100 \tag{1}$$

where W_t represents the weight of the specimen at a certain immersion time t and W_i represents the initial weight of the specimen before soaking in water.

Literature revealed the measurement of water absorption capacity in the composites was presented in either short term (2 h until few days) or long term (from weeks up to months). In composites, water absorption increases almost linearly with immersion time until the equilibrium (saturation level) state has achieved. In the early (linear) stage of water absorption, the water absorption behaviour can be presented by a parameter, namely, diffusion coefficient (D), which is computed using equation (2) [9].

$$D = \pi\left[\frac{\theta h}{4M_{equilibrium}}\right]^2 \tag{2}$$

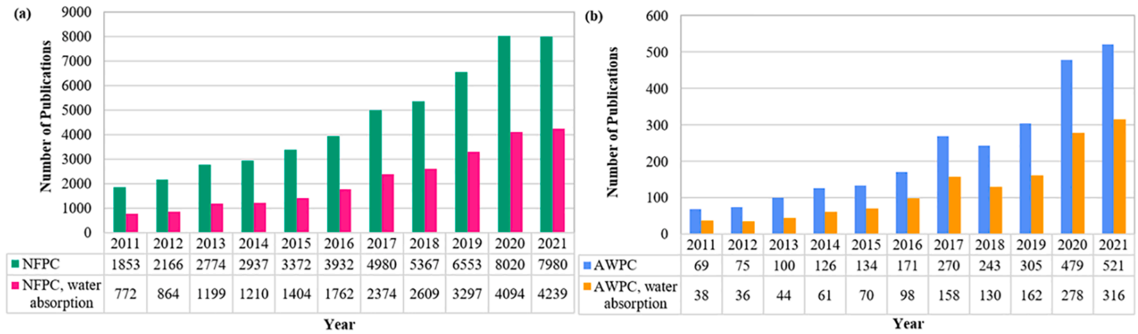

Fig. 3. Number of publications on (a) NFPCs and (b) agro-waste polymer composites (AWPCs) with focus on characterization by water uptake analysis. Source: www.sciencedirect.com, 4 July 2021; Keywords: natural fiber polymer composite, agro-waste polymer composite, water absorption.

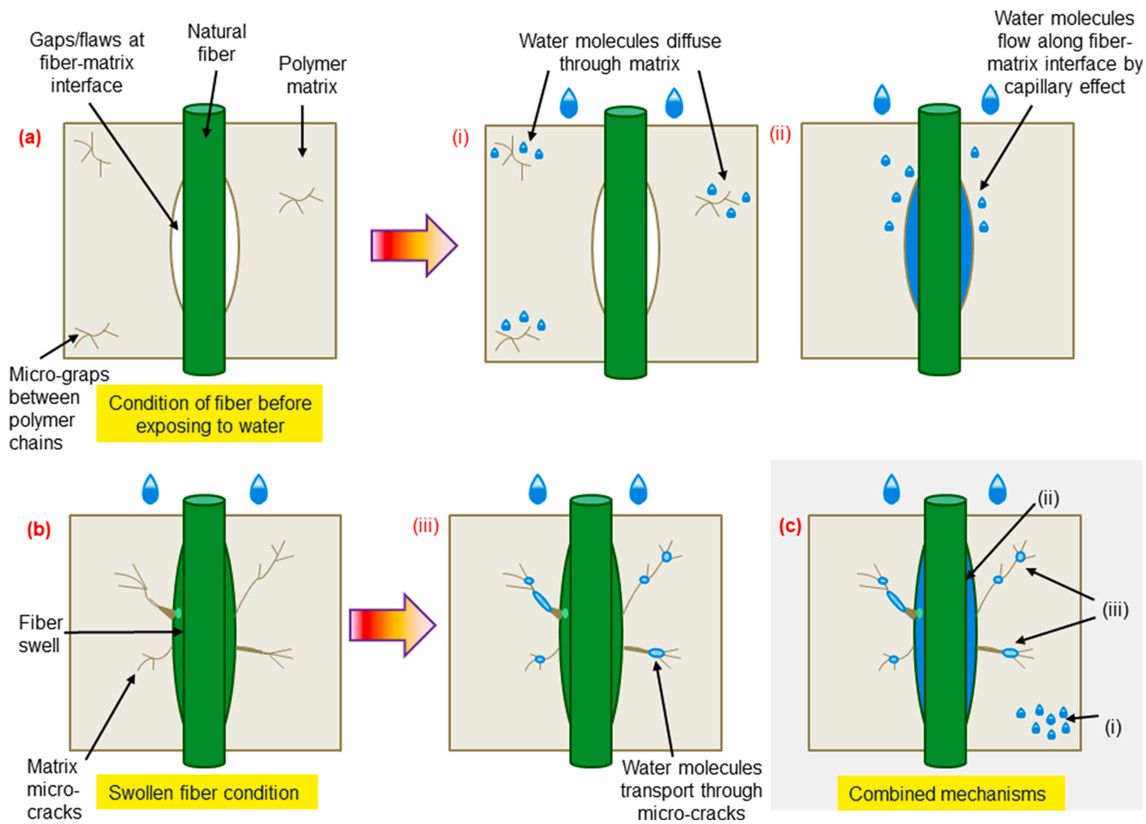

Fig. 4. Probable water absorption mechanism. (i) Diffusion of water molecules through polymer chains, (ii) capillary flow of water molecules along the fiber–matrix interface, and (iii) transport of water molecules through micro-cracks.

where θ is the slope of M_t (water absorption at certain t time) versus $t^{1/2}$ curve, $M_{equilibrium}$ is the water absorption at equilibrium state and h is the composite thickness. D determines the rate of water molecules diffuse into the composite materials, which does not correspondingly represent to the capacity of water absorption (measured using equation (1)).

It is established that almost all of the natural fiber reinforced composites are claimed to conform typical Fickian diffusion behaviour by using Fick's equation: $\log (M_t/M_m) = \log (k) + n \log (t)$, to determine the diffusion kinetic parameters (n and k constants) [30,31]. In this regard, Fickian modelling equations have been proven as a useful tool to predict the water absorption process based on the satisfactory fitting obtained between the experimental results and the Fickian modelling [9,29,31]. The prediction of the first portion of water absorption (M_{t1}) where M_t is 0.6 lower than $M_{equilibrium}$ can be implemented by equation (3), whereas the second portion of water absorption (M_{t2}) prediction where M_t is 0.6 higher than $M_{equilibrium}$ can be computed using equation (4) [9,31]. This prediction approach could play an important role in determining the performances such as mechanical properties of the natural fiber-reinforced polymer composites.

$$M_{t1} = \frac{4M_m}{h}\sqrt{\frac{D.t}{\pi}} \tag{3}$$

$$M_{t2} = M_m \cdot \left[1 - \exp\left(- 7.3\left(\frac{D.t}{h^2}\right)^{0.75}\right)\right] \tag{4}$$

3. Analysis of water absorption tests

Many studies in the literature have attributed reasonable water absorption capacity of agricultural fibers incorporated in the biocomposites, even though agricultural fibers are highly sensitive to water absorption. The hygroscopicity of these composites is determined by the composite formulation which can be improved by additives presence, composite modification and secondary nanofillers. Recent works from year 2015 to 2020 on the water absorption properties of composites with single and hybrid agricultural fibers are shown in Tables 1-3.

3.1. Single agricultural fiber-based thermoset composites

In a study of Sair et al. [32], water absorption of polyurethane composites increased with the hemp fiber loading up to 30 % with the largest water uptake (64.3 %), diffusion coefficient (7.45×10^{-11} m^2/s), and permeability coefficient (1.10×10^{-10} m^2/s). The extremely high water absorption capacity due to highly hydrophilic characteristic of hemp fiber limits the use of natural fibers to high percentages. Pujari and coauthors [33] compared the water absorption properties of jute fiber and banana fiber filled epoxy composites with various filler loadings (20% – 60%) and found that regardless of the fiber content, the banana fibers had higher water absorption coefficient than the jute fibers. Drastic difference in water absorption coefficients of 9.3 % and 56.1 %, was obtained for 60% jute and banana fibers, respectively. The water absorption capacity of flax fiber/epoxy composites rapidly increased up to 25.7 %, due to the high content of hydrophilic fiber (68.1 %) and the presence of voids in the composite [34]. Sodoke et al. [35] analyzed cyclic water absorption involving wetting and drying for 104 days and found similar water absorption behavior for each cycle; however, the water uptake rates were different for each cycle. At the first cycle, the saturated water absorption was achieved at 14%, which slightly increased with the increasing cyclic time, such as 16 % for the 7th cycle.

Another work showed that after adding a high percentage of jute fiber, the water absorption rate increased, and the highest water absorption was measured for 40% fibers in epoxy and bio-epoxy composites. The higher water absorption of bio-epoxy composites than that of traditional epoxy composites is attributed to the use of cellulose component and hydroxyl group in the former [28]. Another reason for the increasing water absorption with the increment in fiber content is the high number of fiber-to-fiber contacts within the composites that induces a great wicking effect [36]. The effect of maleic anhydride-grafted polycaprolactone (PCL-g-MA) compatibilizer on the water resistance of bamboo fiber (BF) composites was also investigated. When the BF content is constant, the water resistance of PCL-g-MA/BF was better than that of PCL/BF due to the increased hydrophobicity of BF as a result of the interaction of PCL-g-MA with BF [37]. This result is in agreement with another research by the same co-researcher, in which the polybutyleneterephthalate (PBT)/ sisal fiber composites containing acrylic acid-grafted PBT shows an increased matrix–filler compatibility and provides better water resistance than PBT/BF [38]. Mohamed and coauthors [39] also investigated the water absorption properties of pineapple leaf fiber (PALF)/vinyl ester composites. The bleached PALF exhibited lower water absorption than the untreated PALF due to the close packing of cellulose molecules and the increase in crystallinity resulting from the sodium hypochlorite aqueous solution. Salim et al. [40] showed that alkalization substantially reduces the equilibrium water uptake of kenaf fiber filled acrylic-based polyester composites by the elimination of hemicellulose and lignin and the activation of hydroxyl groups of cellulose unit for good fiber matrix interaction. Another water absorption study was performed on the influence of alkali treatment concentrations from 3 wt% to 7 wt%. The reducing sequence of water absorption is ordered as follows: 0 wt% (untreated) > 7 wt% > 3 wt% > 5 wt%. The higher water absorption rate of 7 wt% than the 3 wt% or 5 wt% alkali treatment could be explained by the removal of hydrophobic greasy material, which in turn generates an inefficient interfacial bonding between the matrix and fiber with cracks at the interface; this process served as a pathway for the absorption of water molecules [41]. Stalin and Ramkumar [42] investigated the water absorption experiment for polyester composites incorporated with 10–50 wt% Aati fiber under different temperature conditions, namely, normal water, hot water, and cold water. The results showed that 10 wt% of fiber absorbed the least water content, irrespective of water types, and water absorption was dependent on the water condition in the following sequence: hot water (3.7–8.1%) > normal water (2.2–4.1%) > cold water (1.6–2.2%).

3.2. Single agricultural fiber-based thermoplastic composites

Fardausy et al. [43] reported the increasing water absorption with an increment of soaking time (4 h) and loading of jute fiber up 20% (~2% in 4 h immersion) in polyvinyl chloride (PVC) composites. This is anticipated as due to the cellulosic and lignin effects, and the presence of defects such as lumens, fine pores and void spaces in the composites [43,44]. The construction and nature characteristic of lignocellulosic fibers primarily contribute to the water absorption [44]. As reported in Mazur et al. [44], the formation of microtunnels in hydrophilic lignocellulosic fibers such as wood flour, flax fibers and walnut shell flour allows a more intense flow of water deep into bio-polyethylene matrix as compared to composite with basalt fiber which is natural fiber of inorganic origin.

In linear low-density polyethylene (LLDPE)/sisal fiber composites, the mass percentages of absorbed water increased with the sisal fiber loading from 10% up to 50% because of the hydrophilicity of the cellulose component. Treatment with 1%-3% dicumpy peroxide, which acted as crosslinking agent in the composites, significantly reduced the water absorption compared with that of untreated ones. This behavior resulted from the grafting reaction that reduces the number of voids between polyethylene (PE) matrix and sisal fiber, and partially prevents the contact between fibers and water [45]. Water absorption study on coir fiber (CF)/PE composites showed that chemical treatment using sodium hydroxide (OH) and hydrogen peroxide reduced the number of hydroxyl functional groups which are responsible for water absorption, thus leading to lower water absorption capacity in comparison to the untreated fibers [46]. Sari and co-researchers [47] reported that plasma-modified polyethylene (PPE)/bleached CF had the lowest water absorption among other types of interface (PE/CF, PE/bleached CF and PPE/CF). This result is attributed to the good fiber/matrix interaction where a considerable amount of accessible OH groups have bonded to the polar groups on the PPE surface and the composite lacks of microvoids. Moreover, the percentage of water absorption of the treated and untreated CFs or agave fiber green PE composites was investigated. For the 30 wt% treated fibers, the maximum water absorption was reduced to 55% due to the reduced water affinity of the composites and the improved interfacial compatibility by MAPE surface treatment. Hence, the number of voids where the water can diffuse was reduced compared with those in the untreated fiber composites. This effective reduction in water absorption proved that agricultural fiber addition positively affects the mechanical properties and generates a sustainable and economic point of view [21].

Aggarwal and co-researchers [48] investigated the water uptakes of jute fiber/ polypropylene (PP) composite and reported that the coupled composites with 10%–50% fiber absorbed a low amount of water at merely 0.2%−1.4% compared with the uncoupled composites with 0.4%−3.8%. This water resistance effect is related to the effective wetting by polymer and the encapsulation of jute fibers that prevents the penetration of water to the fibers. A similar result of decreasing water uptake was found in PP/old newspaper fiber by coupling with maleic anhydride PP (MAPP) via the formation of ester bonds between MAPP and fiber surface hydroxyl groups, thereby increasing the interfacial adhesion, reducing the voids in the interfacial area, and hindering the diffusion [30]. In another work, the loading approaches of coupling agent (maleated PE) with PE/hemp fiber composites were found to affect the water resistance. The findings showed that composites from treated fibers whose coupling agent was added during fiber treatment had higher water diffusion coefficient than those whose coupling agent was directly introduced during compounding. This result can be interpreted by two possible reasons, namely, the random orientation of fibers

Table 1
Reported water absorption analysis work of single agricultural fiber polymer composites.

Agricultural fiber	Fiber loading	Matrix	Water uptake testing			Water absorption results		Mechanical results		Application	Ref.
			Condition	Period	Standard	*Maximum water content (%)	Diffusion coefficient (m^2s^{-1})	Before water absorption	After water absorption		
Cotton fiber extracted from textile waste	0.1, 0.2, 0.3 and 0.4 fiber volume fraction (FVF))	Epoxy	Distilled water, RT	7 days	ASTM D570-98	4.6–8.3	(1.940–1.98) $\times 10^{-11}$	[a]49.5–75.4 MPa, [b]1.5–3.3 GPa, [c]46.4–108.4 MPa, [d]2.6–7.1 GPa, [e]2.1–7.6 kJ/m^2	–	Furniture materials, automotive components	[36]
Kenaf fiber	45 vol%	Acrylic based polyester	Distilled water, RT	7 days	ASTM D570	38.9–54.3	(1.25–1.42) $\times 10^{-11}$	[c]49.5–58.4 MPa, [d]4.3–5.7 GPa	[c]20.7–33.0 MPa, [d]1.9–2.7 GPa	Automotive	[40]
Flax	(laminate)	Epoxy	Distilled water, 60 °C	104 days	–	14–16	(0–12) $\times 10^{-12}$	[a] ~ 125 MPa	[a] ~ 110–120 MPa	Long-term structural applications	[35]
Hemp fiber	5, 10, 15, 20, 25, 30 wt%	Polyurethane	Distilled water, RT	7 days	ASTM D 2842–01	29.0–64.3	(1.47–7.45) $\times 10^{-11}$	[a]0.7–1.4 MPa, [b]6.5–14.4 GPa, [c]1.4–3.8 MPa, [d]8.7–21.1 GPa	–	Building insulation	[32]
Jute fiber	20, 40, 60, 100 vol%	Epoxy	Distilled water, RT	27 days	ASTM D570	5.7–14.0	–	–	–	Automotive, household and architectural	[33]
Banana fiber						9.7–83.1					
Rice husk particle(3, 5, 7 wt% NaOH)	10 wt%	Unsaturated polyester	–	9 days	ASTM D570-98	1.2–2.9	–	[a]18.0–21.6 MPa, [b]780-860 MPa, [c]28-39 MPa, [d]3.9–5.1 GPa	–	–	[41]
Pineapple fiber	10, 20, 30, 40 wt%	Polyester	Rain water, RT	14 days	ASTM D5229M-12	0.2–0.3	–	[a] ~ 7–29 MPa, [b] ~ 510–767 MPa, [c] ~ 18–31 MPa, [d] ~ 390–705 MPa	–	–	[27]
Oil palm empty fruit bunch fiber	10, 20, 30, 40, 50, 60, 70 wt%	Polyester	Distilled water, 23 °C	24 h	BS EN 993–1:1995	3.1–9.0	–	[a]0.1–3.9 MPa, [b]2.0–22.7 MPa	–	–	[96]
Flax	undefined	Epoxy	Water, 60 °C	13 days	–	25.7	3.98 $\times 10^{-12}$	[b]18.6–20.4 GPa	[b]14.2–18.1 GPa	–	[34]
Aati fiber	10, 20, 30, 40 and 50 wt%	Polyester	Normal water, 23 °C Hot water, 50–100 °C Cold water	2–24 h	ASTM D 570–99	2.2–4.1 3.7–8.1 1.6-2.2	–	[a]4.8–18.8 MPa, [c]9.8–34.1 MPa	–	Aerospace, automobile parts, electronic packages, building construction, and sport goods	[42]
Agave fiber	20 and 30 wt%	Linear low-density polyethylene	Distilled water, 50 °C	42 days	ASTM D570	11.7–20.0	(1.83–2.13) $\times 10^{-8}$	[a] ~ 7–12 MPa, [b] ~ 200–350 MPa, [c] ~ 8–11 MPa, [d] ~ 380–470 MPa, [e] ~ 60–70 J/m	–	Automotive and packaging	[14]
Coir fiber						7.5–16.9	(1.49–2.72) $\times 10^{-8}$	[a] ~ 7–15 MPa, [b] ~ 250–350 MPa, [c] ~ 7–20 MPa, [d] ~ 440–657 MPa, [e] ~ 80–120 J/m			
Coir fiber	5 wt%	Polyethylene	Distilled water, RT	–	–	0.1–0.2	–	[a] ~ 13–18 MPa, [b] ~ 360–780 MPa, [e] ~ 6–11 kJ/m^2	–	–	[47]
Waste rice husk ash(with 0–1 wt% silane)	60 phr	Polyvinyl chloride	Water, RT	90 days	ASTM D570	38	–	[a]36.1–51.9 MPa, [b]2.2–2.6 GPa, [e]52.1–74.9 J/m	–	–	[52]
Coir fiber	5, 10, 15 and 20 phr	Polyethylene	Distilled water, RT	–	–	< 0.1	–	[a]9.5–21.5 MPa, [b]650-1100 MPa, [d]550-780 MPa	–	–	[46]

(*continued on next page*)

Table 1 (*continued*)

Agricultural fiber	Fiber loading	Matrix	Water uptake testing			Water absorption results		Mechanical results		Application	Ref.
			Condition	Period	Standard	*Maximum water content (%)	Diffusion coefficient (m^2s^{-1})	Before water absorption	After water absorption		
Rice husk	40, 60 and 80 wt%	Recycled (HDPE/PET) blend	Distilled water Seawater, RT	116 days	ASTM D570-98	(i) 6.2–14.7 (ii) 5.7–22.9	(1.6–42.5) × 10^{-13} (1.7–23.7) × 10^{-13}	[a] ~ 18–23 MPa, [b] ~ 600–1700 MPa, [c] ~ 28–48 MPa, [d] ~ 2200–5300 MPa, [e]1.9–2.5 kJm^{-2}	–	Outdoor use like building	[9]
Cellulose Sawdust Wheat straw fiber	30 wt%	Polypropylene	Distilled water, RT	–	ASTM D570	~0.5 ~0.9–1.2 ~2.5–3.8	–	–	–	–	[97]
Rice husk	10, 20, 30 and 40 wt%	Polylactic acid	Water, 25 ± 2 °C	120 days	ASTM D570	8–12	–	[a] ~ 20–50 MPa	–	Filaments for 3D printing	[59]
Basalt	40 wt%	Bio-polyethylene	Distilled water, ambient temperature	30 days	ISO: 62	0.1	–	[a]48 MPa, [b]6.5 GPa	[a]40 MPa, [b]5.9 GPa	Automotive, sport, footwear application, daily products (kitchen utensils, countertops, cutting boards)	[44]
Wood flour						3.7		[a]18 MPa, [b]2.8 GPa	[a]17 MPa, [b]2.4 GPa		
Flax						4.3		[a]22 MPa, [b]4.6 GPa	[a]19 MPa, [b]3.2 GPa		
Walnut shell flour						5.4		[a]13 MPa, [b]1.7 GPa	[a]12 MPa, [b]1.4 GPa		
Kenaf	30 wt%	Polylactic acid	Distilled water, RT	35 days	–	~2–7	–	[a] ~ 51–70 MPa, [c] ~ 100–135 MPa	–	–	[58]
Recycled denim fabric	38–60 wt%	Acrylated epoxidized soybean oil resin	Water, RT	30 days	ASTM 570–98	~5–16	–	[a] ~ 15–38 MPa, [b] ~ 1–8 GPa, [c] ~ 18–42 MPa, [d] ~ 0.6–3.0 GPa, [e] ~ 20–44 kJ/m^2	–	Structural	[69]
Sisal fiber	10–15 wt%	Polyhydroxybutyrate	Cooling chamber, temperature 60 °C	7 days	ASTM D5229M-92	2.4–3.2	–	[a]18.2 MPa, [b]958 MPa,[c]35.3 MPa, [d]2898 MPa	[a]8.4 MPa, [b]579 MPa, [c]13.3 MPa, [d]661 MPa	Little tubes and plastic bags for planting seedlings, disposable packaging trays	[68]
Coconut fiber						4.6–6.1		[a]11.9 MPa, [b]828 MPa, [c]34.0 MPa, [d]2045 MPa	[a]12.2 MPa, [b]457 MPa, [c]13.6 MPa, [d]999 MPa		
Kenaf	5 and 10 wt%	Polylactic acid	Distilled water	63 days	ASTM D570-98	4.6–5.7	–	[a]15.1–18.9 MPa, [b]1.4–2.1 GPa, [c]59-72 MPa, [d]2.5–2.6 GPa, [e]11.5–17.0 J/m^2	–	–	[54]
Elephant grass	5, 10, 15, 20 and 25 wt%	Polylactic acid	Water, 23 °C	48 h	ASTM D570-98	~1.1–11.2	–	[a] ~ 60–66 MPa, [b] ~ 2.5–2.8 GPa, [c] ~ 90–115 MPa, [d] ~ 4.5–9.2 GPa, [e] ~ 2.6–6.0 kJ/m^2	–	–	[55]
Jute	5, 10, 15, 20 and 25 wt%	Polylactic acid	Distilled water, 25 °C	48 h	ASTM D570	~1.5–6.5	–	[c] ~ 35–110 MPa, [d] ~ 2.8–6.5 GPa, [e] ~ 0.9–3.5 kJ/m^2	–	–	[56]
Silk fibroin	10, 20, 30 and 40 wt%	Poly(butylene succinate)	Distilled water, ambient temperature	21 days	–	1.5–3.2	–	[a]42-60 MPa, [b]1.3–2.5 GPa, [c]32-61 MPa, [d]1.3–3.0 GPa, [e]52-99 J/m	–	Environmentally-friendly products	[64]
Oil palm mesocarp	70 wt%	Poly(butylene succinate)	Distilled water, 25 °C	24 h	ASTM D570, EN317	18.8–22.2	–	[c]27.3–30.3 MPa, [d]2191-2368 MPa, [e]65.8–77.2 J/m	–	–	[66]

Note: *Based on the immersion period in the particular study, [a]Tensile strength, [b]Young's modulus, [c]Flexural strength, [d]Flexural modulus, [e]Impact strength, ~ means estimation value, HDPE: high-density polyethylene, PET: polyethylene terephthalate, RT: room temperature.

Table 2
Reported water absorption analysis work of bionanocomposites.

Agricultural fiber/ nanofiller	Fibers loading ratio	Matrix	Water uptake testing			Water absorption results		Mechanical results		Application	Ref.
			Condition	Period	Standard	*Maximum water content (%)	Diffusion coefficient (m^2s^{-1})	Before water absorption	After water absorption		
Agave fiber/nanoclay	30/3–5 (wt%)	Polylactic acid	Distilled water, 55 °C	28 days	ASTM D570	~7–13	–	[a]51–52 MPa, [b] ~ 1800–2300 MPa, [c]70–77 MPa, [d]4117–5486 MPa, [e] ~ 37–41 J/m	–	–	[21]
Kenaf fiber/ montmorillonite clay	30/1, 2 and 3 (wt%)	Polylactic acid	Normal water, RT	30 days	–	6.2–9.1	–	[a] ~ 42–51 MPa, [b] ~ 3.1–3.7 GPa, [c] ~ 59–100 MPa, [d] ~ 6–7 GPa, [e] ~ 45–55 kJ/m^2	–	–	[72]
Eupatoriumfiber/ carbon nanotube	2, 4 and 6 vol%(ratio of 99.8/0.2–99.0/ 1.0)	Epoxy	Sea water	45 days	ASTM D-570	1.4–4.5	–	–	–	–	[75]
Rice husk/ montmorillonite	20 wt%/ 4 phc	Polypropylene	Distilled water, RT	10 days	–	~0.2	–	[a] ~ 20.0–27.5 MPa, [b] ~ 1.9–2.2 GPa, [c] ~ 25–30 MPa, [d] ~ 1.8–2.0 GPa	[a] ~ 17.5–25.0 MPa, [b] ~ 1.8–2.0 GPa, [c] ~ 22.5–27.5 MPa, [d] ~ 1.5–1.8 GPa	–	[71]
Wood flour/ organoclay	40/2, 4 and 6 (wt%)	Recycled HDPE	Distilled water	10 days	ASTM D570-98	~3.0–7.3	–	[a] ~ 11–15 MPa, [e] ~ 2.6–3.8 J/cm^2	–	–	[73]
Rice husk/organoclay	70 wt%/3 phc	Recycled (HDPE/PET)	Distilled water, RT	1 day	ASTM D 570–98	~2–4	–	[a] ~ 13–19 MPa, [b] ~ 1400–1800 MPa	–	Decking	[70]
Rice husk particle/ nanoclay	10/1, 3 and 5 (wt%)	Unsaturated polyester	–	9 days	ASTM D570-98	~0.9–1.3	–	[a] ~ 20–24 MPa, [b]891–926 MPa, [c] ~ 30.0–60.0 MPa, [d]4900–5300 MPa	–	–	[41]
Sisal fiber/clay	5, 10, 20 and 30/5 (wt%)	PHBV	Water	14 days	ASTM D570-98	~0.8–6.8	(4.27–4.65) × 10^{-9}	[a] ~ 26–30 MPa, [b] ~ 1500–1600 MPa, [e] ~ 3–23 kJ/m^2	–	–	[76]

Note: *Based on the immersion period in the particular study, [a]Tensile strength, [b]Young's modulus, [c]Flexural strength, [d]Flexural modulus, [e]Impact strength, ~ means estimation value, phc: parts per hundred parts of composite, HDPE: high-density polyethylene, PET: polyethylene terephthalate, PHBV: Poly(hydroxy butyrate-co-hydroxyvalerate), RT: room temperature.

Table 3
Reported water absorption analysis work of hybrid agricultural fibers polymer composites.

Hybrid agricultural fibers	Fiber loadingratio	Matrix	Water uptake testing			*Maximum water content (%)	Mechanical results (Before water absorption)	Application	Ref.
			Condition	Period	Standard				
Kenaf fiber/sisal fiber	13.33/6.66 and 6.66/13.33 (wt%)	Bioepoxy	Normal water, 23 °C	120 days	ASTM D570	~5	[a]26.8–34.3 MPa, [b]1035.6–1053.9 MPa, [e]7.3–8.6 kJ/mm^2	Semi-structural	[98]
Oil palm empty fruit bunch/ sugarcane bagasse	35/15, 25/25, 15/35 (wt%)	Phenolic	Distilled water	2–22 h	ASTM D1037	5.8–18.7	[a]5.3–5.6 MPa, [b] ~ 599.0–661.3 MPa	–	[19]
Roselle/sugar palm fiber	75/25, 50/50, 25/75based on 40 wt%	Polyurethane	Water, RT	7 days	–	7.4–8.5	–	–	[99]
Roselle/sugar palm fiber	60/30 (wt%)	Polyurethane	Water	7 days	ASTM D570	8.0–8.5	[a]13.5–14.3 MPa, b ~ 190–210 MPa	Automotive part - battery holder	[100]
Bauhinia-vahlii-weight/sisal fiber with rice husk	3/3 (wt%) with 2, 4, 6 wt%	Epoxy	–	–	ASTM D570-99	0.2–0.5	[a] ~ 22–25 MPa, [c] ~ 20–23 MPa	–	[101]
Kenaf / pineapple leaf fibers	15/35, 25/25 and 35/15 (wt%)	Phenolic	Distilled water, RT	7 days	ASTM D570	~5–20	–	–	[80]
Banana/sisal fiber	30/20,20/30, 25/25(wt%)	Epoxy	Distilled water, room temperature	–	ASTM D570	~33–39	–	–	[78]
Jute/kenaf fiber	56 wt%	Epoxy	Distilled water, room temperature Boiled water	–	ASTM standard D570-98	0.2–0.3 0.2–0.5	[a]32.6–53.6 MPa, [c]440.9–866.3 MPa, [e]0.5–0.8 kJ/m^2	Aerospace, automobile and sports, building products	[102]
Sisal/bamboo fiber	10, 15 and 20 wt % (weight ratio 25/75, 50/50, 75/25)	Unsaturated polyester resin	–	–	ASTM D570	19.6–27.5	[a]21.5–23.5 MPa, [c]53.1–57.8 MPa, [e]17.0–19.7 kJ/m^2	–	[79]
Banana/coir fiber	5/15, 10/10, 15/5 (wt%)	Polypropylene	Water, ambient temperature	24 h 48 h 72 h	ASTM D570	0.7–1.0 1.2–1.3 1.3	[a]28.1–31.3 MPa, [b]597.5–760.3 MPa, [c]28.1–31.3 MPa, [d]598.3–762.3 MPa, [e]50.6–73.2 J/m	–	[103]
Corn stalk/sisal fiber	25/5 phc (5–20 mm fiber length)	Polyvinyl chloride	–	16 days	ASTM D570-98	~6.5–9.7	[a] ~ 13–17 MPa, [b]1000–1400 MPa, [c] ~ 35–51 MPa, [d] ~ 1750–4500 MPa	–	[86]
Bagasse flour/ bagasse ash Rice husk flour/ rice husk ash	50/5, 50/10 (wt %)50/5, 50/10 (wt%)	HDPE	–	–	ASTM D570	~20–25 ~10–13	[c] ~ 32–38 MPa, [d] ~ 2000–3200 MPa, [e] ~ 0.68–0.75 J/m	–	[82]
Coir/jute fiber	5,10 and 15 wt% (ratio 1:1)	Polyethylene	Hot distilled water	2 h	ASTM D 570–99	~5–18	[a] ~ 4.5–5.5 MPa, [b] ~ 200–310 MPa, [c] ~ 14–18 MPa, [d] ~ 600–710 MPa, [e]400-700 J/m	–	[10]
Kenaf fiber/coir fiber	15/15 wt% (0, 2 phc MMT)	Polypropylene	Distilled water, RT	10 days	ASTM D570-99	~20	[a]9.82–10.70 MPa, [b]345-368 MPa	–	[83]
Jute/coir fibers	30, 40 and 50 wt %	Polylactic acid	Distilled water	7.5 days	ASTM D570	~10–20	[a]40-50 MPa, [b] ~ 1000–1250 MPa, [c] ~ 13–18 MPa, [d]~2000–2500 MPa, [e] ~ 11–16 kJ/m^2	–	[91]
Basalt/flax fiber	5/25, 10/20, 15/15, 20/10, 25/5 (wt%)	Polylactic acid	Water, RT	30 days	ASTM D570	~2–30	[a]26.7–54.8 MPa, [b]0.5–1.4 GPa, [e]2.88–6.24 kJ/m^2	–	[87]
Coir/pineapple leaf fiber	15/15, 9/21, 21/9 (wt%)	Polylactic acid	Distilled water, RT	7 days	–	~4–7	–	–	[88]
Oil palm fiber/ kenaf core fiber	55/5, 50/10, 45/15 (wt%)	Polylactic acid	Distilled water, 25 °C	24 h	ASTM D570 and EN 317	~7.50–8.00	[a] ~ 20–36 MPa, [b] ~ 310–480 MPa, [c] ~ 16–27 MPa, [d]2–62/GPa, [e] ~ 7–13 J/m	–	[89]

Note: *Based on the immersion period in the particular study, [a]Tensile strength, [b]Young's modulus, [c]Flexural strength, [d]Flexural modulus, [e]Impact strength, ~ means estimation value, phc: parts per hundred parts of composite, MMT: montmorillonite, RT: room temperature.

and the incomplete encapsulation of fiber particles by plastic matrix [49]. Sultana and their co-workers [50] found that the water absorption of sodium periodate oxidized jute/PP composites was lower than that of untreated fiber composites because the hydroxyl groups of raw jute fiber absorb more water than the aldehyde groups (less affinity for water molecules) of oxidized jute.

Law and Ishak [51] investigated the water absorption of kenaf fiber (KF)/PP and achieved the highest water absorption at 40% KF (compared with 20% and 30% fiber loadings), the largest diffusion coefficient (6.52×10^{-12} m^2/s), and the maximum thickness swelling (21.9%). This increment can be related to the high amount of accessible hydroxyl groups in KF with respect to its loading that increases the initial rate and level of water uptake. Similar to other findings, the incorporation of MAPP in PP/KF composites could reduce the water absorption capacity via the formation of ester linkages between the hydrophilic hydroxyl groups of KF and the acid anhydride groups of MAPP. The water absorption percentage of the solid and foamed PVC/rice hull composites was also investigated. For the unfoamed composite, the water uptake was minimum at approximately 1% due to the hydrophobicity and non-porous structure of PVC matrix; for the foamed composite, the maximum water absorption of 12.1% was recorded for 2.0 wt% modified with azodicarbonamide chemical blowing agent [29]. The same researcher conducted another analysis on the effect of γ-aminopropyltrimethoxysilane compatibilizer on the water absorption of PVC/rice husk ash for 90 days. The water absorption of the composite was reduced by 38% because of the addition of 1 wt% silane that reduced the interfacial voids of fiber [52].

In our previous research on the high loading fiber of rice husk-reinforced recycled HDPE/PET blend, the water absorption resistance was improved by compatibilizing the immiscible polymer blend. The water uptake in seawater was more pronounced than in distilled water due to the presence of salt in seawater that forms microcavities in the crosslink network of the compatibilized blend material [9]. In addition, our recent research reported that the gamma radiation post-treatment on the same composites of recycled HDPE/PET blend containing 40 wt % rice husk was found to decrease the water absorption (3.7–4.5% for irradiated composites with 25–150 kGy as compared to 4.7% for non-irradiated composites) as attributed to the reduced amount of hydroxyl group and improved matrix-fiber adhesion [31].

3.3. Single agricultural fiber-based biopolymer composites

Dehbari et al. [53] studied the water absorption of polylactic acid (PLA) composites with 15%−70% of kenaf core and reported an increasing trend of up to 8.5% for 70% filler due to the hydrophilicity of kenaf plant, especially in the core and bast. The increasing water absorption with the fiber content is aggravated by the existence of high voids and gaps between the PLA matrix and kenaf fiber as evidenced by scanning electron micrographs [54]. In the research of Gunti et al. [55], PLA composites filled with 25% of untreated elephant grass fibers obtained the largest amount of water absorption (11.2%) compared with the loadings of 5%−20%. For the successively alkali-treated (mercerization followed by bleaching) elephant grass fiber, the rate of water absorption was reduced to 6.1%. This result was in agreement with another PLA-based composite study by the same main researcher that obtained the same fiber loading of 25%. The composite with untreated jute fibers had the highest water absorption of 9.9%, which was lower than that with elephant grass fibers. Similarly, the alkali-treated jute/PLA composites exhibited reduced water uptakes of 6.5%, 5.6% and 4.4% for 5%, 10% and 15% NaOH concentrations, respectively. This behavior is imparted by the hydrophobic nature of fibers resulting from the reaction of alkali with their hydroxyl groups [56]. Except for surface treatment, only a few studies were conducted on the effect of coupling agent in the biocomposites. PLA/kenaf biocomposites introduced with 3-glycidoxypropyl trimethoxy silane (GPS) coupling agent showed a continuous reduction in water absorption with respect to GPS contents from 1% to 5% compared with non-treated bio-composites. Two mechanisms were proposed for this behavior, namely, the reaction of silanes with hydroxyl groups prevalent in cellulosic fibers and the improved wetting of polymer onto fibers due to coupling effect that causes less void space [57]. Chung and co-authors [58] studied the water absorption properties of PLA composites of acetylated kenaf fibers and reported a low rate of water uptake due to the replacement of hydroxyl groups of kenaf with acetyl groups. Meanwhile, the untreated kenaf/PLA composites showed the faster and highest water absorption because of the high amount of available hydroxyl groups from the untreated kenaf fibers and the poor affinity (interface) between kenaf and PLA. Another study on PLA composites reinforced rice husk showed that the use of acrylic acid-grafted polylactic acid (PLA-g-AA) and treated rice husk (TRH) with cross-linking agent mixture (solution of tetraethyl orthosilicate, water, lactic acid catalyst) produces a great water resistance due to the enhanced hydrophobicity of TRH while interacting with PLA-g-AA [59].

A high fiber loading is generally desired for biocomposites to achieve good mechanical performances. Unfortunately, this characteristic adversely affects the dimensional stability with the increasing water absorption of composites. In high fiber loading, the consolidation factors of molding temperature and molding period are crucial in reducing the water uptake capacity. Lee et al. [60] stated that the water absorption rate of PLA/flax biocomposites showed a linear relationship with fiber loading, molding temperature, and molding period. For example, the water absorption increased from 28% to 42% at 50% of flax content and from 58% to 63% at 60% of flax content. At the same fiber content (40%), the water absorption increased by 27% for 200 °C and 15 min compared with under low molding temperature and time (180 °C and 5 min). The high temperature and long molding time allow many water molecules to enter the biocomposites via the pore path formed between the fiber and matrix interface due to fiber degradation under this condition. Anuar [61] investigated the water absorption of PLA composites reinforced with 5–20 wt% of kenaf fiber in different types of immersion medium, namely, river water (pH 6), tap water (pH 7), and sea water (pH 7.5). The results showed that biocomposites absorbed more water in tap water than in river and sea water.

In addition to PLA, poly(butylene succinate) (PBS) is another common biopolymer used in preparing biocomposites. In PBS/kenaf bast fiber composites, the equilibrium water absorption increased with the fiber content up to 40% with the highest water uptake (9.8%) and diffusion coefficient (9.34×10^{-12} m^2/s) [62]. The increasing water uptakes with the fiber content was also reported in other previous studies of PBS composites with kenaf fiber [63] and silk fibroin fiber [64]. This increment is typically due to the presence of highly hydrophilic sites in the fibers that promotes hydrogen bonding formation with water molecules [62–64]. Tran Huu Nam and co-researchers [65] investigated the water absorption of surface-treated jute fiber/PBS biodegradable composites and reported their lower water absorption compared with the untreated composites because of the improved interfacial adhesion between the PBS matrix and jute fiber upon chemical surface treatment. The lowest water absorption was achieved for the composite with combined alkaline-silane treatment, followed by silane and alkali treatment on jute fiber. Then et al. [66] reported that the PBS composites with oil palm mesocarp fiber (OPMF) treated in 5% NaOH solution showed reduced water absorption by 15% compared with the untreated OPMF. This behavior is due to the elimination of hemicellulose (the most hydrophilic component than cellulose and lignin) during NaOH treatment that led to a reduction in the hygroscopicity of composites.

In another study of PBS with various lignocellulosic fibers, the maximum water absorption increased from 0.2% for pristine PBS up to 1.7% for PBS/curaua, 2.6% for PBS/sisal, 3.4% for PBS/coconut, and 4.6% for PBS/bagasse fiber composites after 8 h. Morphological images showed the incomplete filling of the internal hollow structure of bagasse and coconut fibers by the matrix, which favored the storage of water molecules; in addition, curaua and sisal fibers have close contact with the polymer and thus reduce the penetration of water in the bulk material [67]. Some of these results agreed to the study of Hosokawa et al. [68] who showed that sisal fiber-reinforced polyhydroxybutyrate (PHB) had lower moisture content than that of coconut fiber/PHB composites. Manufacturing techniques also affect the water absorption percentage; less water resistant was exhibited by compressed AESO samples as compared with vacuum infused samples due to the long impregnation time for the latter [69].

3.4. Agricultural fiber/nanofiller-reinforced polymer bionanocomposites

Chen and co-researchers [70] investigated the short-term water absorption for 24 h of organoclay-incorporated recycled high-density polyethylene/polyethylene terephthalate (rHDPE/rPET) based composites. The result showed that the percentage of water absorption increased up to 4% and was accompanied by the thickness swelling of 7% after the addition of high loading rice husk (RH) at 70 wt%. Compared with that of the sample without RH (<0.1% for water absorption and ~ 2% for swelling in thickness direction), this increment was fairly high due to the OH groups on the RH surface that bonded with water molecules to absorb additional water via the formation of hydrogen bonding. However, with the presence of compatibilizer in the rHDPE/rPET blend or the use of coupling agent together with RH in the composites, the water resistance was improved. Omid and their co-workers [41] studied the influence of nanoclay content on the water absorption of 10 wt% RH particles filled with unsaturated polyester (UP) composites. The results revealed that the increasing nanoclay addition from 1 wt% to 5 wt% decreased the water absorption. This phenomenon occurred because the high aspect ratio and naturally impermeable clay nanolayers enhanced the barrier properties by creating a tortuous path to delay or prevent the penetration and diffusivity of water molecules into the composites. The decrease in water uptake with the incorporation of montmorillonite (MMT) clay may also be due to the occupation of voids or gaps at the interphase between polymer and filler (i.e., PP and RH) and the restricted capillary effect in RH by MMT (acted as obstruction) [71].

In another clay bionanocomposite made from PLA, 30 wt% NaOH-treated kenaf fiber and 1–3 wt% MMT clay, the water resistance increased with the continuous addition of MMT, whereas the water absorption decreased from 2.2% to 1.5% and 9.5% to 6.2% after 3 and 30 days of immersion, respectively [72]. Martín del Campo et al. [21] stated that the water absorption reduced by the nanoclay addition in the PLA/agave fiber biocomposite was due to the intercalation or exfoliation of nanoclay layers in the composite material. Neat PLA and PLA biocomposites exhibited increasing water absorption, followed by slight decrement after reaching the saturation level; however, the biocomposites containing nanoclay particles did not experience such decrement due to the increase in crystallinity caused by the clay particles in the biocomposites. In rHDPE/wood flour composites incorporated with 2 wt% modified bentonite (mBNT), the water absorption capacity was decreased by 27.3% after 5 days of immersion compared with that of control specimen without clays (approximately 3.3%). The high amount of water absorbed in control composite is related to the presence of lumens, fine pores, gaps and micro-cracks at the interfaces generated during mixing. These structures permitted water diffusion throughout the polymer matrix. Meanwhile, the improved water resistance can also be attributed to the hydrophobicity of mBNT acting as a water repellent; and the tortuous pathway generated by the clay layers [73]. Organoclay-treated Kraft fiber/HDPE composites showed higher water absorption at 15 wt% filler due to the voids between the fiber and matrix where much water is absorbed through voids via the capillary effect compared with untreated Kraft fiber composites. However, the water absorption was 30% lower when 5 wt% of MAPE was added as compatibilizer compared with that of the composites without MAPE. The decreased water absorption was caused by the improved interaction between the plastic matrix and the fibers through coupling effect by MAPE. When the Kraft fiber treatment was increased to 40 wt%, the water diffusion rate was lowered by 25%, which could be attributed to the barrier effect of organoclay particles and the improved fiber–matrix adhesion [74].

In another work, the water absorption of hybrid eupatorium fiber/carbon nanotube (CNT)/epoxy polymer composites was lower at 2.4% compared with that of eupatorium/epoxy (without CNT) at 4.4%. This behavior is attributed to the ability of CNT (merely 0.2%) to resist water absorption [75]. Dangtungee and co-authors [76] studied the water absorption of poly(hydroxybutyrate-co-hydroxyvalerate) (PHBV)/sisal composite and showed its reduced water absorption when incorporated with clay particles. The decreased diffusion coefficient (D) may be linked to the sensitivity of D to the barrier effect induced by nanoparticles.

3.5. Hybrid agricultural fibers-based thermoset composites

Venkateshwaran and co-researchers [77] investigated the moisture absorption of banana fiber/sisal fiber/epoxy and showed that the lowest percentages of water uptake were achieved at 18.8% (50:50 wt% of banana and sisal fiber) with the sorption coefficient of 1.204 S, diffusion coefficient of 1.69×10^{-11} m^2/s, and permeability coefficient of 2.04×10^{-11} m^2/s. At the same ratio of 1:1 (banana fiber/sisal fiber), the epoxy composites with high fiber content (50 wt%) exhibited doubled water absorption capacity of approximately 35% [78]. Prasanna Venkatesh and co-workers [79] investigated the water absorption of sisal fiber/bamboo fiber/unsaturated polyester composites and reported that the composite containing sisal single fiber (20.9%) had higher water absorption than the single bamboo fiber composite (16.8%). With regard to the hybridization effect, the water uptake with 50% hybridization of fibers (sisal/bamboo at 50/50 wt%) absorbed low water content at 19.6% with lowest permeability coefficient, followed by water absorption of 23.3% (25/75 wt%) and 27.5% (75/25 wt%).

Upon the surface treatment of hybrid fibers with silane, the kenaf fiber/ PALF/phenolic composites exhibited lower water absorption than the untreated fibers. This result proved that silane effectively evacuates hydroxyl groups from the fiber surface and creates a layer on the fiber to prevent the penetration of water molecules into the fibers. For untreated hybrid composites, the highly presence of voids and pores on surface of hybrid composite consequently led to the increase in composite weight with the water trapped inside voids. The water absorption capacity of the treated hybrid composites followed the sequence of the fiber weight ratio of 15/35 < 35/15 < 25/25. The higher water absorption of 35/15 than that of 15/35 was possibly due to the high fiber fraction of PALF and the lowest water resistance in 25/25 may be attributed to the development of micro-cracks and voids as a result of poor interfacial bonding [80]. The same range of hybrid fiber weight ratio was studied for phenolic composites based on oil palm empty fruit bunch (OPEFB) and sugarcane bagasse (SCB). The lowest water absorption (15.4%) was obtained in the hybrid fiber composites of 15 wt% OPEFB/35 wt% SCB, followed by 25/25 and 35/15 in weight percentage. The OPEFB fiber has good mechanical strength due to the high cellulosic content of SCB and ratio. This behavior is closely related to the intrinsic characteristic and structure. OPEFB fiber has a great tendency to absorb water as indicated by the higher percentage of water absorbed in pure OPEFB fiber

Table 4
Moisture content values for various materials used in building construction.

Material	Moisture contents in service	References
Wood	19%	[95]
Structural wood-based panels/ composite lumber	<16%	[95]
Fired clay brick	<20% (IS 1077:1992)	[1]
Fibreboard	<30% (European standard EN317)	[5]

Fig. 5. Some application from plastic composites made of agricultural or wood fibers.
Source: https://www.greenbuildingsolutions.org/blog/composites-high-performance-building-solutions/

composite (22.3% for 24 h) than in pure SCB composite (18.7% for 24 h). Therefore, SCB fiber has a compact structure that could reduce the porosity and void of surface area exposed to the composites [19].

In addition to the composition ratio of hybrid fillers, the arrangement of layers affects the water absorption properties of a composite sandwich. For instance, Abdul Khalil et al. [81] showed that the sandwich structure of jute/OPEFB/jute (6%) in hybrid composites had lower water absorption percentage than the structure of OPEFB/jute/OPEFB (10%) because of the effective void filling during the formation of composites.

3.6. Hybrid agricultural fibers-based thermoplastic composites

Sheykh and their co-researchers [82] reported that the water uptakes of RH fiber/HDPE and bagasse fiber/HDPE composites increased by approximately 40% and 60% with the addition of 10% of bagasse ash and RH ash, respectively. This increment is mainly due to the hydrophilic lignocellulosic fiber component in composites, the presence of voids and micro-gaps at the interface, and the presence of ashes to diminish the bonding strength and homogeneity of composite compounds. A similar increasing trend of water absorption up to 15% was reported by Ahmed and co-workers [10] in CF/jute fiber/PE composites with 15 wt% fiber content due to the increasing amount of hydrophilic hydroxyl groups of cellulose, hemicellulose, and lignin. Islam and co-researchers [83] investigated and compared the water absorption of single fiber (kenaf and coir) PP and hybrid fiber PP composites with a fixed fiber loading of 30 wt%. Their findings showed that the highest water absorption was achieved for hybrid fiber composites due to the hydrophilicity of the two different fibers that were mixed together.

Aji et al. [84] stated that the synergistic bonding and compatibility between hybrid fibers can help to reduce the water absorption of natural fiber composite in the absence of any chemical treatment. This finding was verified by a study, which reported that the kenaf fibers absorbed less water than PALF, but the hybrid with an appropriate ratio (3:7) obtained the least percentage of absorbed water. Hassan and co-authors [85] reported that the alkali-treated hybrid fibers of jute and betel nut reinforced in PP composites absorbed less water than the untreated fibers because the good interaction of alkali-treated hybrid fibers with PP matrix could block the cellulose OH groups of the fibers and thus hinder the access of water molecules. Comparison between wood flour plastic composite (WPC) and agricultural or natural fiber composites [86] showed that WPC and corn stalk fiber composites (at 30 phr) had similar water content level, and the hybridization with 5 mm sisal fiber promoted a low water absorption value. This finding suggests that corn stalk and sisal fibers exhibited a network-like structure, which led to a strong interface and compact microstructure and few pores and gaps in the composites. However, long sisal fiber easily caused agglomeration and entanglement and thereby increased the tendency to form holes and gaps between the fibers and the polymer.

3.7. Hybrid agricultural fiber-based biopolymer composites

Water absorption property was examined for three composite systems based on PLA, namely, single basalt fiber (BF) composite, flax fiber (FF) composite, and hybrid fiber composites with various composition ratios at a fix loading of 30 wt%. The results showed that FF with highly hydrophilic character is the only main component responsible for increasing the water uptake capacity (causing a remarkable increase up to 30%) in hybrid composites and BF is independent on water (showing almost the same water absorption level as neat matrix) [87]. Another similar study was conducted on single and hybrid fibers reinforced PLA composites with CF and PALF. The pure CF/PALF composites showed higher water absorption content than the single PALF composite. This finding could be attributed to the high shallowness of fiber structure and the porosity of the coir [88].

Birnin-Yauri et al. [89] reported the intermediate water absorption capacity for hybrid fibers composites of oil palm/kenaf core, the highest water uptake percentage for single kenaf core, and the lowest for single oil palm fiber. An interesting result of devaluation in water absorption (5 days immersion) was reported by Ramasubbu and their co-workers [90] on the hybrid sisal/kenaf fiber reinforced with epoxy matrix composite with 3.3% as compared to single fiber composites, i.e. sisal fiber composite (4.2%) and kenaf fiber composite (5.4%). This shows that the hybridization could decrease the water absorption characteristics if the fiber–matrix bonding was significantly improved. In another hybrid composites based on PLA matrix, the use of chemical treatment (alkali-peroxide and alkali-silane) on the fillers of jute and coir fibers could restrict the moisture absorption within the fiber and at the interface with matrix because of the filling up of voids and pores during composite fabrication [91].

3.8. Impact of water absorption on the mechanical performance of agricultural fiber composites

Few studies have been published on the deterioration in mechanical properties of agricultural fibers-polymer composites by approximately 30–50% after the samples were exposed to the water at a certain period [40,49,68,92]. The adverse effect of mechanical strength and modulus in wet composites could be associated with debonding and weakening of interfacial adhesion that rendered by fiber swelling [40]. In a case of flax/epoxy composite laminates, the mechanical properties showed low reduction of about 20% and below [34,35]. A study from Majeed et al. [71] reported that slightly better retention tensile and flexural properties in PP/rice husk fiber with the presence of clay particles and coupling agent. These constituents minimized the detrimental impact of the interfacial region by the water molecules penetration. It is worthy to note that a significant in the impact resistance of PP/kenaf fiber composites in wet state was reported by Law and Ishak [51]. This improvement is related to the enhanced frictional work of swelled fiber pull-out from matrix. Petchwattana et al. [29] also presented the increased flexural properties in PVC/rice hull foamed composites; it is believed to be as a result of the leaching of PVC additive (dioctyl phthalate plasticizer) from PVC structure and making the soaked composite foam stiffer.

4. Application of agricultural fiber composites in construction industry

This literature review mainly focused on the different types of agricultural fiber reinforcement for various polymeric matrices that signify huge variation in water absorption capacity. The water absorption capacity of biocomposites or green composites was generally in the acceptable level of moisture content for in-service construction materials including wood, wood-based products, fired clay brick, and fiberboard (Table 4). For instance, Zandvliet et al. [93] reported better water resistance of the prepared jute fiber reinforced PLA composite compared with medium-density fiberboard (MDF), particleboard, and hardboard; the water absorption capacity is far below the minimum requirement of ISO 16983. This finding shows that agricultural fiber composites could serve as a good candidate to replace wood-based material or products because their water absorption capacity is comparable or even better than that of wood species (with moisture content fluctuates between 8% and 40% for exterior use [94]) and the wood supply is getting limited. Agricultural fiber composites can be used as high performance building materials, such as partition wall, false ceiling, furniture, decorative items, roof, kitchen, and decking (Fig. 5). Those interior and exterior products signify a broad variation in equilibrium moisture content that is highly pronounced at high levels of humidity [95]. International benchmarking can be established for the potential commercial application of these innovative construction materials. The generated database of benchmarking will be beneficial to the manufacturers to design and develop suitable innovative construction materials for indoor or outdoor applications.

5. Conclusion

The use of agricultural fibers in composite production has attracted extensive concerns owing to their various benefits. This review comprehensively reported the current state-of-the-art studies on the water absorption characteristics of agricultural (agro-waste) fiber-reinforced polymer matrix composites. Various modifications to improve water resistance were also highlighted. Introducing agricultural fibers into polymeric matrix can increase the water absorption capacity and the water uptake level depending on the types of matrices and fiber used, fiber loading, inclusion of different additives, fiber treatment or matrix modification, and hybridization. Based on the various literatures, the following conclusions can be reached: (a) water absorption of composites increased with the fiber loading up to a certain extent, (b) chemical treatments such as NaOH at appropriate concentration on agricultural fiber decreased the water absorption, (c) the additives added such as coupling agent, compatibilizer or interfacial modifier effectively improved the water absorption resistance of composites, and (d) hybridization with nanofillers optimally lowered the water absorption until an optimum weight fraction, whereas hybridization with secondary agricultural fibers provided a synergistic effect in water absorption level. Different water absorption properties were reported for various agricultural fibers reinforced thermoset and thermoplastic polymers, but the overall treated or modified composites displayed comparable or even better water penetration resistance than conventional construction products/composites.

Future works should focus on the production of fully green composite using recycled plastics or biodegradable resin polymeric matrix and high loading agricultural especially agro-waste fibers and incorporation of multifunctional nanofillers to develop eco-friendly innovative materials in building construction or other potential sectors. In particular, further research and investigation are required to control or minimize the water absorption penetration which can improve durability and long-term stability for commercial outdoor applications.

Declaration of Competing Interest

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

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