

Case Report

Exploring the impact of water soaking on the mechanical, thermal, and physical properties of *Paederia foetida* fiber stem biocomposites: A study in sustainable material innovation

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ARTICLE INFO

Keywords:

Physico-chemical

Paederia foetida fibers

NaOH

Biocomposite

Mechanical properties

Water absorption

ABSTRACT

Biocomposites reinforced with natural fibers have gained significant attention due to their environmental benefits and potential to replace synthetic composites. However, their performance in humid environments remains a concern. This study aims to investigate the mechanical, thermal, and physicochemical properties of *Paederia foetida* fiber-reinforced biocomposites after water immersion, to better understand their durability under such conditions. The biocomposites were prepared by embedding different volume fractions (2.5 %, 5 %, 10 %, 20 %, and 25 %) of chemically treated *Paederia foetida* fibers (PFs) into a polyester matrix. The PFs were extracted from stems, treated with 5 % NaOH, washed, and dried before being incorporated into the polyester and molded by hot press. The biocomposite samples were then immersed in water for 72 and 168 hours, with their properties compared to unsoaked controls. The results revealed that the unsoaked biocomposites exhibited good tensile strength, modulus of elasticity, and flexural strength. Despite increasing the fiber content from 2.5 % to 25 % by volume, the density of the biocomposites remained low. After 72 and 168 hours of water immersion, a reduction in tensile strength, modulus of elasticity, and flexural strength was observed, alongside an increase in density, swelling thickness, and water absorption, attributed to water ingress through the fibers and biocomposite cavities. The thermal stability of the biocomposites was minimally affected by water absorption, maintaining strong resistance at temperatures ranging from 400 °C to 800 °C, even after prolonged water exposure. These findings suggest that the developed PFs/polyester biocomposites are a viable alternative material for building applications, offering a balance of mechanical performance and environmental sustainability, with good thermal resistance even in humid conditions.

1. Introduction

The growing demand for ecologically friendly and sustainable building materials has prompted the development of alternatives to traditional building materials. To address environmental problems, new ecological structural materials are required [1,2]. Materials research and

engineering are putting more attention on developing sustainable, lightweight and high-performance materials [3,4]. The global emphasis on environmental sustainability as well as increased mechanical and thermal properties has fueled research into novel composites.

Cellulose microfibers derived from plant stem fibers have sparked intense attention in materials research due to their appealing inherent

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qualities such as low density, strength, health-friendly, sustainable, and renewable [5,6]. Cellulose fibers are plant-derived biosynthetic products composed of lignin, cellulose, and hemicellulose. They can be extracted into fibers using chemical-mechanical and enzymatic techniques [6,7]. In addition to their unique structure, these natural fibers offer high tensile strengths of 7.5–7.7 GPa, great thermal stability, and a low coefficient of thermal expansion [8–10].

Researchers and scientists are interested in developing fiber from *Paederia* plant stems as a composite reinforcing material since it is abundant, non-toxic, and has great mechanical qualities. *Paederia foetida* is a climbing plant widespread throughout tropical and subtropical climates, including Southeast Asia (Indonesia, Malaysia, Thailand, and the Philippines), India, Bangladesh, and parts of Africa and America. *Paederia foetida* (PF) is a plant that grows wild in Indonesian bushes. This plant grows well in forests, fields, roadsides, and moist environments such as riverbanks. Its stems can grow to be 6 m or longer, and its oval to elliptical leaves exude a foul stench when crushed. This plant's blossoms range in color from light purple to pink, and its fruit is green and turns brown when ripe. *Paederia foetida* is considered an invasive species in some locations due to its rapid growth and capacity to spread and become a weed in agricultural areas [5,11,12]. The *Paederia* plant has long been employed in modern pharmacology and as a source in the pharmaceutical business due to its ability to contain a wide range of phytoconstituents.

Furthermore, researchers retrieved fibers from *Paederia* stems by soaking them in water for ten days. *Paederia* fibers consist of hemicellulose, lignin, and cellulose. These components are known to help *Paederia* maintain its structural integrity and mechanical qualities. *Paederia* fibers' strength depends on their lignin and cellulose content, with stem fibers having a tensile strength of 1710.7 ± 76 MPa. Adding a 5 % NaOH solution to PF fibers increases their tensile strength to 2450.9 ± 84 MPa and crystallinity index to 79.6 % [5]. Several other studies have also reported that other chemical treatments on the surface of different natural fibers, such as flax with sodium bicarbonate (NaHCO_3) at an 8 % concentration, are known to increase the breaking stress and Young's modulus by 40 % and 82 %, respectively, compared to untreated fibers [13]. In addition to NaOH (sodium hydroxide) solution, there are various other chemical or physical treatments that can improve the water resistance of bio composites, particularly fiber surface modification. Some treatments that can be used include: Silane Treatment, Acetylation, Maleic Anhydride Treatment, and Wax Coating; however, each method has disadvantages, namely high costs and a reduction in the mechanical properties of the fiber; on the other hand, chemical treatment with NaOH has more advantages, including NaOH is cheaper and simpler, effectively removes lignin and hemicellulose, increases mechanical strength, and increases bonding with the matrix in the composite [14].

There has been very little research on the physical, mechanical, and thermal properties of *Paederia* fiber-filled composites. Sari et al. (2024) found that the tensile strength and elastic modulus of *Paederia* microfibre bio composite with poly lactic acid matrix were 54.4 ± 4.4 MPa and 6196 ± 142.8 MPa, respectively [15]. According to Sari et al. (2024), combining Al_2O_3 with *Paederia* fiber increases the density, tensile strength, and elastic modulus of PFs- Al_2O_3 hybrid composites to 2.17 g/cm^3 - 1.04 g/cm^3 , 49.085 MPa, and 1.431 GPa, respectively. This hybrid composite's swelling ability has been shown to stabilize after being immersed in water for 820 hours. Several researches have also reported on the usage of PF as a medicinal plant to treat infectious disorders in Bangladesh's central region [16–18] and as a natural corrosion inhibitor for mild steel [19]. However, the usage of fibers extracted from PF stems as a composite filler material has not yet been researched. Given the abundance of PF sources, as well as the fact that this plant is environmentally friendly and safe for human health, PF stem fibers are beneficial in a variety of applications, including building, particularly decking, fencing, siding, and external windows and doors. Biocomposites' dimensional stability is crucial as a construction panel

material, especially for outdoor application [20,21]. Understanding the water absorption process and the impact of absorbed water on changes in dimensions, characteristics, and microstructure of biocomposites is critical for increasing stability. Several researchers have previously reported the absorption properties of different natural fiber-reinforced composites such as date palm fiber in seawater, distilled water, and rainwater environments; they noted that the absorption rate at 15 % reinforcement reached an estimated value of 14.03 % for seawater, 15.42 % for distilled water, and 16.37 % for rainwater, respectively [22]. The weight of date palm fiber biocomposites soaked in distilled water, seawater, and rainwater for more than 670 hours, as determined by artificial neural network (ANN) modeling, rose as the fiber content increased [23]. Incorporating 30 wt% date palm fiber (DPF2) into HDPE biocomposites boosted mechanical characteristics to 499 MPa, meeting criteria for automotive application [14]. After 43 days of testing, alkali treatment of *Arundo donax* L fiber (ArF) for PLA composite reinforcement was found to reduce its water absorption capabilities by 64 % when compared to composites with untreated ArF. Nevertheless, its mechanical strength rose [24]. Meanwhile, extracting *Ampelodesmos mauritanicus* (AM) plant fiber with 2 % NaOH for 48 hours followed by physical and chemical treatments has been shown to enhance fiber density, Young's modulus, and tensile strength to 1.55 g/cm³, 18.6 GPa, and 290 MPa, respectively [25]. Natural fibers can enhance density by 54 % when compared to highly porous natural fibers [26]. From an environmental standpoint, chemically treated of fibers with NaOH and the usage of a polyester matrix can be claimed to have a low environmental impact if carried out properly. The NaOH liquid waste can be neutralized and processed before disposal, preventing it from polluting the environment. Furthermore, the polyester matrix, while not biodegradable, can be recycled or reused in long-term applications, lowering waste generation. Exploring different fiber treatments or surface alterations can be a significant step toward increasing the composite's water resistance and reliability.

The investigation of *Paederia foetida* composites contributes to current understanding by giving new insights into the possibilities of this natural fiber, which has previously been overlooked in the literature. Future research could focus on the properties of *Paederia foetida* fibers (PFs), including mechanical strength, heat resistance, and absorption of water capacity, which could enable their usage in fiber-based composite applications. This study could look into the use of PFs, that are infrequently employed in biocomposites, particularly in terms of water interaction. While polyester-biocomposites often degrade mechanically when immersed in water, this study makes a unique addition by focusing on PFs and their characteristics. Furthermore, this study highlights distinct characteristics of PFs in terms of potential sustainability and thermal resistance, as well as how they react under various environmental situations, particularly in waterlogged areas. Furthermore, this research provides options to change the exterior of PFs to make them less water resistant, as well as to maximize the polymer matrix utilized in composites. This method represents a new avenue in efforts to enhance the mechanical characteristics of PFs-based bio composites, potentially leading to the usage of these fibers in a larger range of applications. Thus, this study not only contributes to the literature on the natural features of PFs, but it also suggests a method to overcome the usual limitations of polyester-biocomposites when exposed to water, making them more suitable for long-term industrial applications.

Therefore, the goal of this work is to provide an in-depth comprehension of the behaviour of PFs-based bio composites following immersion in water. The effects of the percentage of fiber content and the duration of immersion of the biocomposites in a wet environment will be investigated to characterize the composites' behaviour, such as psychophysical behaviour (density, water absorption, and swelling thickness), mechanical behaviour and thermal resistance. SEM was also used to analyze the surface morphology of the composites. For each test, five different specimens were created in order to acquire precise information on the general behaviour of the unique composite material developed

this area.

2. Material and method

2.1. Materials

Paederia plant stems (Fig. 1a) were collected from Lombok, West Nusa Tenggara, Indonesia. Sodium hydroxide with a concentration of 5 %, Polyester resin and catalyst were purchased from PT Justus Kimia Raya, Surabaya, Indonesia. Resin polyester has density, tensile strength, and flexural strength parameters of 2.63 g/cm³, 8 kg/mm², and 2.5 kg/mm², respectively.

2.2. Extraction of PFs

The fiber extraction procedure was carried out according to the method [5] described by Sari et al. (2023). Fresh plant stems were thoroughly cleaned of dirt and leaves (Fig. 1a). The stems were then combed with a plastic comb to obtain fibers with uniform diameters, and the fibers were air-dried before being processed (Fig. 1b). After the plant stem is cut, a plastic comb is used to separate the fibers in the stem as well as smooth out and tidy up the fiber arrangement to ensure a consistent diameter. Following the separation and tidying of the fibers, the following stage is air drying. This drying is done to minimize the moisture content in natural fibers, as moist fibers can degrade their mechanical properties and decrease product quality. *Paederia* fibers are known to have a density of 0.9 g/cm³ and a tensile strength of 1710.7 MPa. Fig. 1 depicts the comprehensive extraction and chemical treatment of the fibers.

2.3. Alkali treatment of PFs

The fibers were produced, then immersed in a 5 % (wt) NaOH solution for 2 hours, as shown in Fig. 1c. To completely remove any left-over NaOH from the fibers' surfaces, they were rinsed with distilled water several times. Following that, the fibers were rinsed three to four times with distilled water, allowed to dry at room temperature, and then preserved in an airtight desiccator until ready to be employed as a biocomposite reinforcement. The 5 % NaOH solution on *Paederia* fiber removes lignin, hemicellulose, and contaminants from the fiber surface,

increasing the contact of hydroxyl groups (-OH) to cellulose. This procedure eliminates hygroscopic polar groups while increasing the roughness of the fiber the outside, resulting in greater mechanical interaction with the resin matrix. As a result, the composite's water resistance can be enhanced because the changed fibers absorb less water. Overall, the strengthened fiber-matrix link not only minimizes water absorption weakness but also improves the composite's mechanical performance, including tensile strength and interfacial strength.

2.4. Biocomposite fabrication

Hot press molding was used to create polyester composites reinforced with PFs. The biocomposite was created by making PFs with a length of 4 cm. The fibers were weighed using the specified ratio, as given in Table 1. In this investigation, the five PF volume fractions (2.5 %, 5 %, 10 %, 20 %, and 25 %) were chosen based on mechanical characteristics, cost, and composite performance factors. Polyester and catalyst (methyl ethyl ketone peroxide): 1 % of the weight of polyester was added and manually agitated for approximately 1 minute. The liquid was then placed into a fiber-containing mold and sealed. A Vecho Vation hot press weighing 15 tons was utilized to press the composite mold for 25 minutes at 200 °C (decreasing non-uniformities in the resin matrix while increasing the composite's strength). The sample was removed from the mold and opened at 105 °C for 60 minutes. Finally, the biocomposite was removed and chilled to room temperature until it met test criteria. In addition, each biocomposite was pre-soaked in water for 72 and 168 hours before being characterized.

Table 1
The fiber-to-polyester ratio in the created biocomposite.

Sample codes	Volume Fraction (%)	
	<i>Paederia f.</i> (PFs)	Polyester
DGC	2.5	97.5
BFC	5	95
HDC	10	90
ZAC	20	80
SAC	25	75

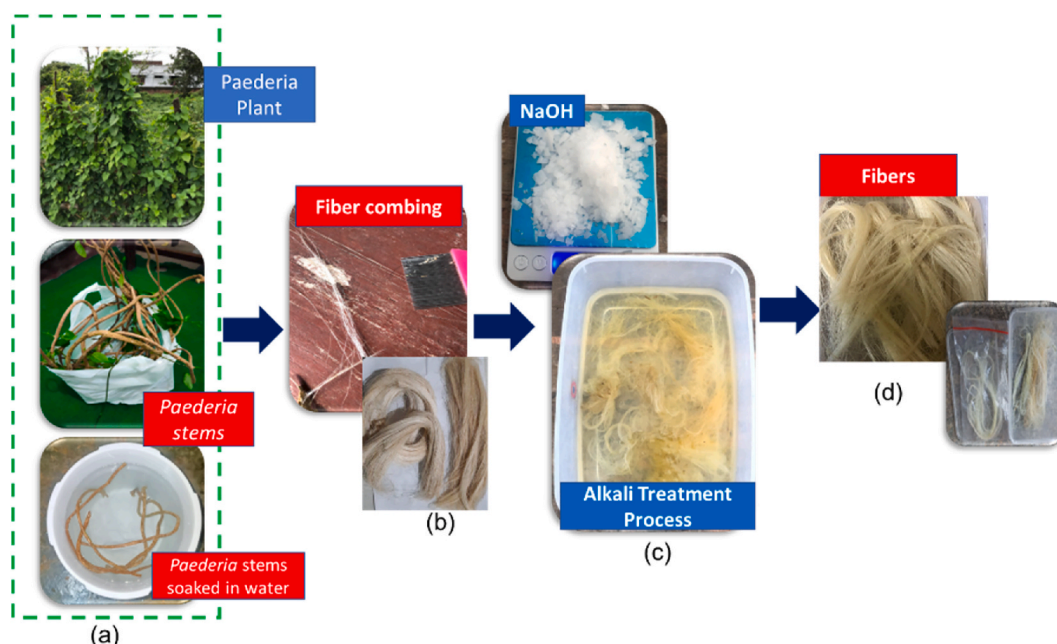


Fig. 1. a. *Paederia* plants and stem selection, b. Fiber extraction process and c. Fiber alkali treatment process.

2.5. Biocomposite characterization

2.5.1. Density

Density were carried out on composites with 25×25 mm according to the Archimedean principle. The cured biocomposite was then weighed in air and then again weighed in a liquid with a known density. The calculated density from measured values was reported in g/cm³ as shown in Equation (1) [27,28].

$$D \left(\frac{g}{cm^3} \right) = \frac{(M_s \times \rho_L)}{(M_U - M_I)} \quad (1)$$

Where, M_U is the wet mass (g), M_s is the dry mass (g), M_I is the immersed mass (g) and ρ_L is the specific mass of water (g/cm³).

2.5.2. Tensile strength test

Tensile tests were conducted on 30 specimens at 26.7 °C (humidity relative 56 %) using a Universal Tensile Machine, model RTG 1310 INSTRON supplied by M/S Microtech Pune with a 5 kN load cell, following ASTM D3039 standards (ASTMD3039M – 17) [29]. The crosshead speed was adjusted to 2 mm/min for all test procedures.

2.5.3. Flexural test

A bending test was carried out to evaluate the composite's flexural strength value using ASTM D790 standard procedures [30]. This was accomplished using a specimen measuring 152 mm long, 25.4 mm broad, and 6 mm thick. A Universal Testing Machine, RTG 1310 INSTRON, 5 tons, was employed, with three-point bending at a speed of 2 mm/s and a spacing of 60 mm between the supports [31].

2.5.4. Water absorption test

Water absorption was tested according to the ASTM D570 standard [32]. The specimen dimensions for this standard are 50 mm \times 15 mm \times 10 mm. The sample was placed in an oven at 50 °C for 24 hours. Then it should be chilled in a desiccant for 24 hours. Finally, it was ready to be immersed in a plastic jar of distilled water (H₂O) at room temperature. A digital weighing balance (W_1) was used to determine the weight of the specimen prior to immersion in water. 30 specimens of each sample were stored for 72 h, and 168 h, each specimen was weighed (W_2). Before weighing, the surfaces of the samples were cleaned using paper towels. The rate of water absorption was determined using the following equation (2) [33,34]:

$$\text{Water Absorption (\%)} = \frac{W_1 - W_0}{W_0} \times 100\% \quad (2)$$

2.5.5. Morphology test

Following mechanical testing of the composite specimen, scanning electron microscopy (SEM) was used to examine the shape and topography of the specimen surface fracture. The observations were conducted using a JEOL JSM-S5200, which produces high resolution in high vacuum mode with an accelerated voltage of 20 kV Energy and 15 mA. Prior to testing, the samples were coated with a thin copper layer of around 30 nm thickness and equipped with a moving magnifier, which was used to capture images in order to examine the structural qualities of the composite material as whole.

2.5.6. Thermal properties

A TG/DTA analyzer was used for thermogravimetric analysis (TGA). The heating operation increased the temperature to 600 °C from the initial ambient level. Temperature was increased at a constant rate of 10 °C per minute in a nitrogen atmosphere between 50 and 1000 °C.

2.5.7. Swelling thickness test

The composite's swelling thickness was determined using a 5 mm thick specimen. When immersed in water, the hydrophilic characteristic of cellulose causes the composite to expand. The sample was soaked in

distilled water to check that the composite material was of the proper thickness. The sample's thickness was then measured at five distinct sites, and an average thickness was derived. Equation (3) was used to calculate the % swelling thickness [34],

$$\text{Swelling Thickness, ST (\%)} = \frac{t_e - t_i}{t_i} \times 100 \quad (3)$$

where, ST = relative thickness of the specimen; t_e = thickness of the specimen; t_i = initial thickness of the specimen.

3. Result and discussion

3.1. Density analysis

Fig. 2 depicts the average density of PFs-reinforced composites. It should be noted that PFs have a density of 0.9 g/cm³, which is somewhat lower than polyester resin's density of 1.26 g/cm³, and that when fibers are added to the resin, the composite density gradually decreases. The composite's density is mostly determined by the fiber density. Before being submerged in water, the density of the composite decreases slightly as the fiber content increases. The DGC sample (2.64 ± 0.07 g/cm³) had the highest density compared to other specimens tested. BFC, HDC, ZAC, and SAC had average densities of 2.6 ± 0.08 g/cm³, 2.58 ± 0.09 g/cm³, 2.56 ± 0.08 g/cm³, and 2.54 ± 0.07 g/cm³, respectively. The decrease in density of this composite is caused by an increase in the number of fibers from 2.5 % to 25 % (% vol). The more fibers there are, the less resin is used; as consequently, the binding of the fibers by the resin is reduced, leaving space between the fibers and the resin, resulting in a low fiber density. After being submerged in water for 72 and 168 hours, the composite's density increased to 2.66 ± 0.09 g/cm³ and 2.73 ± 0.06 , respectively (see in Table 2). When the composite is submerged, water starts to infiltrate into the pores and small spaces in the material structure [34,35]. This water absorption raises the composite's mass without considerably increasing its volume, resulting in a rise in density. Water entering the composite occupies the space previously occupied by air, increasing the material's mass per unit volume.

The phenomenon can happen when the proportion of fiber in the mixture of composites is increased while the quantity of resin utilized is proportionally lowered. Resin acts as a binder, connecting and covering the fibers to provide rigidity and strength to the composite construction. This means that when the number of fibers increases and the resin quantity decreases, the resin's ability to completely bind the fibers decreases. The resin can no longer cover each fiber uniformly and fully, resulting in certain fibers not being effectively bound in the resin matrix. Furthermore, as the resin binding weakens, empty spaces are generated

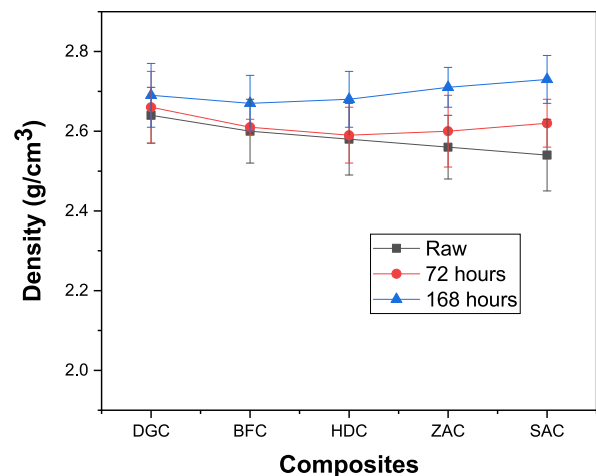


Fig. 2. Density of *Paederia foetida* fiber reinforced polyester composite in distilled water.

Table 2
Average density of different composites.

Sample Codes	Density of composites (g/cm ³)		
	Composite without immersion	Immersion for 72 hours	Immersion for 168 hours
DGC	2.64 ± 0.07	2.66 ± 0.09	2.69 ± 0.08
BFC	2.6 ± 0.08	2.61 ± 0.02	2.67 ± 0.07
HDC	2.58 ± 0.09	2.59 ± 0.07	2.68 ± 0.07
ZAC	2.56 ± 0.08	2.6 ± 0.09	2.71 ± 0.05
SAC	2.54 ± 0.09	2.62 ± 0.06	2.73 ± 0.06

between the fibers and the resin. These empty gaps indicate the existence of voids, which limit binding effectiveness and result in poor stress transfer within the resin and the fibers. This prevents the composite from reaching its full strength. Furthermore, even when more fibers are incorporated, insufficient resin filling diminishes the composite's total density, lowering the composite's strength and structural stability. This approach emphasizes the importance of striking an appropriate balance between the volume of fiber and resin in order to achieve maximal mechanical strength and density.

3.2. Water absorption analysis

Fig. 3 depicts the average Water absorption of PFs composites before and after immersion in water. Fig. 3 shows that SAC has a higher water absorption capacity than the other composites tested. After 72 and 168 hours of immersion, the SAC sample had the highest WA (3.15 % and 3.80 %, respectively), while the DGC sample had the lowest WA (0.59 % and 0.68 %). Meanwhile, the DGC sample consistently shown low WA in all situations. These findings suggest that the DGC sample is more hydrophobic than the other composites under study.

The samples' water absorption (WA) values were consistently higher after 168 hours of immersion compared to 72 hours. The average water absorption (WA) for all composite samples at 72 and 168 hours is shown in Table 3. Water absorption in composites can be explained by the presence of numerous micro voids and micro-cracks in the cross-section of the composites, as well as a large number of polar (hydroxyl) groups on their surface that absorb a large amount of water [3,34,36]. Natural fiber-reinforced composites are susceptible to prolonged water absorption. This prolonged exposure leads the fibers' microvoids and hydroxyl (-OH) groups to absorb a significant amount of water [3,34].

Paederia fibers typically have a structure with small pores and gaps (lumens) [5]. These microholes operate as conduits, allowing water to enter the composite material. When the composite is immersed in water,

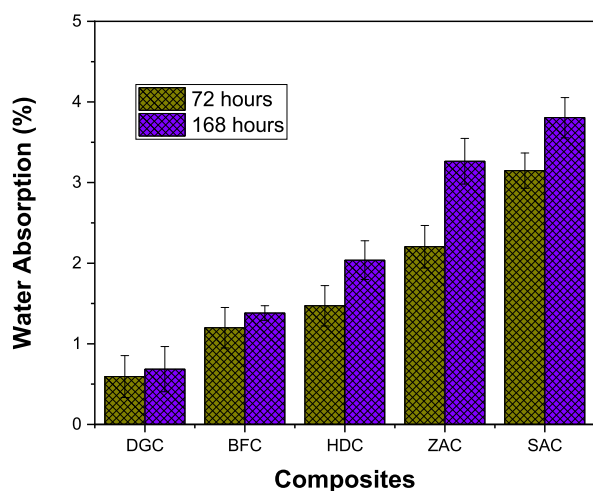


Fig. 3. Water absorption in PF/polyester composites varies before and after immersion in water.

Table 3
Average water absorption and swelling thickness (%) of different composites.

Sample Codes	water absorption (%)		Swelling thickness (%)	
	72 h	168 h	72 h	168 h
DGC	0.59	0.68	0.12	0.14
BFC	1.19	1.38	0.19	0.23
HDC	1.47	2.038	0.25	0.29
ZAC	2.21	3.26	0.35	0.39
SAC	3.15	3.80	0.36	0.42

water readily seeps into these pores, increasing the rate of water absorbed by the material. This improves the possibility for water to spread and fill the empty gaps, resulting in greater overall water absorption. Furthermore, PFs exhibit a high concentration of polar groups, particularly hydroxyl groups (-OH), on their surface. These hydroxyl groups are very hydrophilic, which means they strongly attract and bind water molecules via hydrogen bonds [37]. When the fibers' polar groups come into contact with water, water particles are attracted and bonded to the fiber surface, boosting water absorption. The integration of a physical structure packed with microscopic pores and its chemical structure rich in polar chains makes PF particularly effective in water absorption, which explains why composites containing this fiber absorb so much water.

3.3. Tensile strength analysis

Fig. 4 depicts the PFs composite's tensile strength, Young's modulus, and average strain. Fig. 4a shows that the unsoaked SAC sample had the highest tensile strength at 105.59 ± 6.3 MPa with a 25 % fiber volume percentage, whereas the DGC sample had the lowest strength at 47.46 ± 8.2 MPa. The increase in tensile strength suggests that the fiber acts as the primary reinforcement in the composite matrix. PFs has a greater tensile strength than polyester resin. As the fiber content of the composite improves, more fibers are distributed in the polyester matrix, allowing for more uniform load distribution and improving the composite's capacity to bear tensile stress. These fibers carry the majority of the load, while the polymer matrix distributes it and protects the fibers from mechanical damage [38]. Furthermore, the combination of fiber and polyester contributes significantly to increased tensile strength. Increased fiber content leads to better adhesion between the fiber and matrix due to increased surface area interaction. This tight link facilitates the efficient transfer of load from the matrix to the fiber, boosting the composite's ability to withstand stress without deformation or damage. As a consequence, increasing the amount of fiber in the composite enhances its tensile strength. Fig. 4a also demonstrates that the tensile strength of PFs composites decreased since fibers are the primary component in the composite material that resists tensile loads. As fiber content falls, so does the amount of fibers capable of transferring and dispersing tensile stress. Polyester has less tensile strength than PFs. As a result, with fewer fibers in the composite, the polymer matrix must bear the majority of the tensile load, which is not as effective at resisting load as fibers, lowering the composite's overall tensile strength. Furthermore, as fiber content decreases, mechanical bonding and adhesion between fibers and matrix decrease. The fibers of the composite operate as reinforcements, strengthening the material and providing efficient load transfer routes. If the fiber content is insufficient, the polyester matrix is unable to tightly bound the fibers, decreasing the effectiveness of stress transfer from the matrix to the fibers. As a result, the composite becomes more prone to deformation and failure under tensile loads, reducing its tensile strength.

Furthermore, after water submerging, the tensile strength of the composite decreases dramatically as the number of fibers increases, since water soaked into the composite can destroy the link between the fibers and polymer matrix. Natural fibers, such as *Paederia* fibers, feature hygroscopic hydroxyl groups that allow them to absorb water

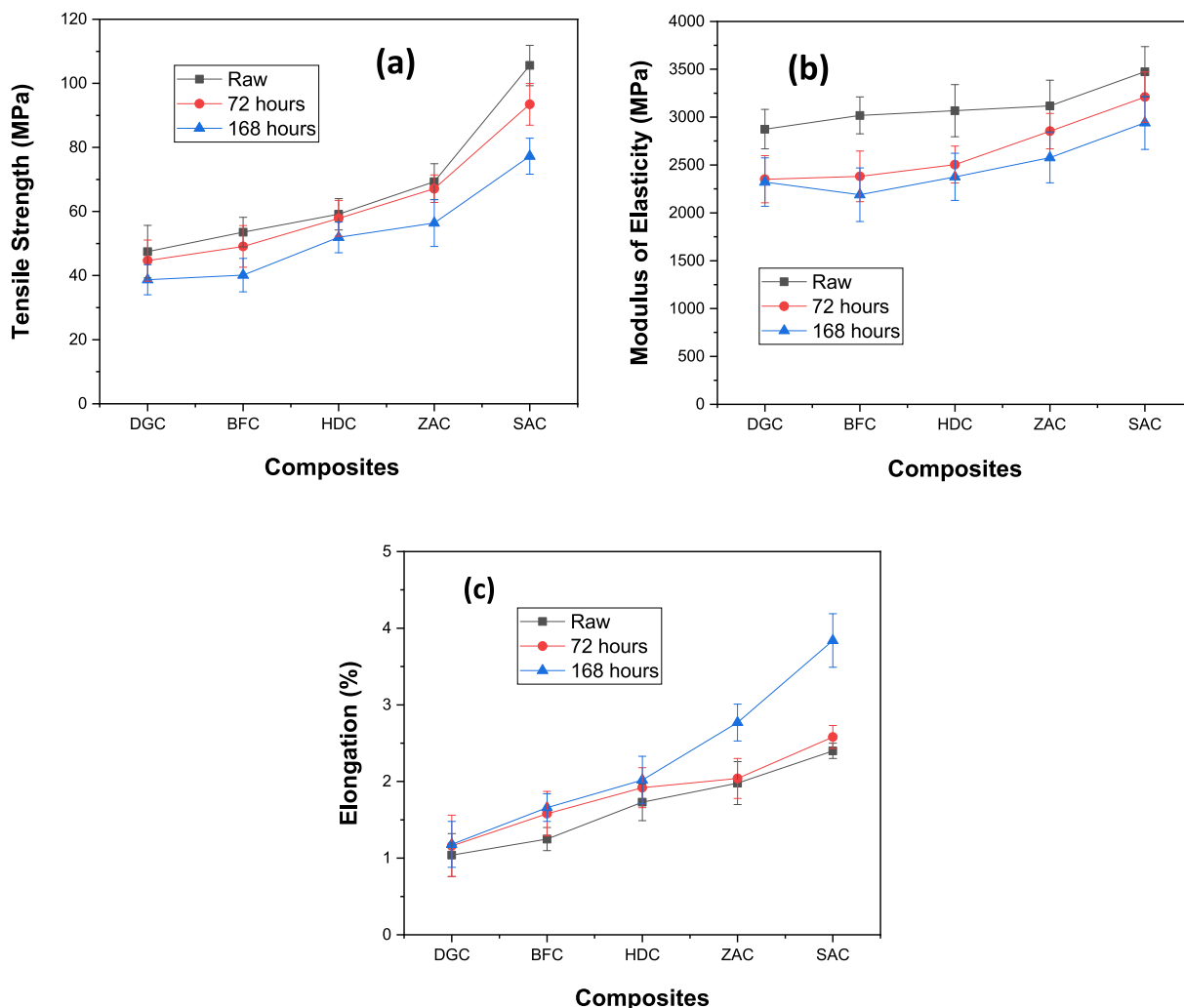


Fig. 4. (a) Tensile strength, (b) Elongation, (c) Elastic modulus of polyester composites raw and after immersion in distilled water for 72 hours and 168 hours.

efficiently. When the composite is submerged in water, the water penetrates the fiber and matrix structure, causing the adhesive bonds between the fibers and matrix to expand and weaken. This reduces the effectiveness of load transfer from the matrix to the fibers, lowering the overall tensile strength of the composite. In addition, wet fibers soften and become less able to endure tensile loads, contributing to the composite’s tensile strength loss. The more significant drop in tensile strength after 168 hours of immersion compared to 72 hours suggests that structural deterioration occurs over time. Longer immersion times allow more water to infiltrate the composite, causing additional deterioration of the polymer matrix and fibers. Water can also hydrolyze chemical bonds in the matrix, lowering the material’s strength and stiffness. The composite’s tensile strength fell from 44.68 ± 6.4 MPa to 93.44 ± 6.5 MPa after 72 hours of immersion, and from 38.72 ± 4.7 MPa to 77.24 ± 5.6 MPa after 168 hours (Table 4). This reduction

represents the slow loss of the composite’s mechanical characteristics caused by prolonged water exposure.

Fig. 4b demonstrates that after water immersion, the modulus of elasticity of the PFs composite decreases dramatically as fiber content increases, owing to structural changes caused by absorbed water. PFs are hygroscopic, meaning they absorb water, causing them to expand and destroy the link between the fibers and the polymer matrix. The absorbed water can also degrade the polymer matrix through the plasticity process, making it softer and less stiff [39]. When the link between the fibers and the matrix weakens, the composite’s ability to endure elastic deformation declines, resulting in a fall in the elastic modulus. Furthermore, the presence of water in the composite structure can result in chemical deterioration of the polymer matrix. Water can cause hydrolysis processes, which disrupt chemical connections in the matrix and reduce the material’s strength and stiffness.

Table 4
Average mechanical properties of different composites.

Samples	Tensile Strength (MPa)			Elongation (%)			Modulus of elasticity (MPa)		
	Raw	72 h	168 h	Raw	72 h	168 h	Raw	72 h	168 h
DGC	47.46 ± 8.2	44.68 ± 6.4	38.72 ± 4.7	1.04 ± 0.28	1.16 ± 0.4	1.18 ± 0.3	2874.32 ± 205	2351.1 ± 247	2321.61 ± 253
BFC	53.56 ± 4.6	49.1 ± 6.5	40.15 ± 5.2	1.25 ± 0.15	1.58 ± 0.29	1.66 ± 0.18	3017.83 ± 193	2380.9 ± 264	2189.01 ± 280
HDC	59.15 ± 4.9	57.85 ± 5.6	51.92 ± 4.8	1.73 ± 0.24	1.92 ± 0.26	2.02 ± 0.31	3067.24 ± 272	2504.2 ± 193	2375.87 ± 247
ZAC	69.32 ± 5.6	67.14 ± 4.3	56.41 ± 7.3	1.98 ± 0.28	2.04 ± 0.26	2.77 ± 0.24	3116.7 ± 270	2853.4 ± 184	2576.21 ± 263
SAC	105.59 ± 6.3	93.44 ± 6.5	77.24 ± 5.6	2.4 ± 0.1	2.58 ± 0.15	3.84 ± 0.35	3473.53 ± 264	3209.8 ± 263	2940.02 ± 277

As the immersion period increases, this degrading effect intensifies, causing the composite's elastic modulus to decrease. This decline is more noticeable in composites with a larger fiber content due to more areas are exposed to water and degrade, particularly at the contact points between the fibers and the matrix, which are crucial for load transfer. After 72 hours of immersion, the elastic modulus of the composite fell from 2351.1 ± 247 MPa to 3209.8 ± 263 MPa. This decline persisted after 168 hours of immersion to 2321.61 ± 253 MPa to 2940.02 ± 277 MPa. This drop implies that water immersion reduces the composite's capacity to recover to its former shape following stress, implying a loss of stiffness and elasticity. This degradation is more evident in composites with higher fiber content because more water may be absorbed, causing structural damage. The modulus of elasticity of the unsoaked composite is higher than that of the composite after immersion because the fibers operate as the primary reinforcing element, providing additional rigidity to the material.

PFs have a higher modulus of elasticity than polyester resins, therefore adding additional fibers to the composite enhances the material's total stiffness. The fibers serve to distribute stress more uniformly throughout the composite, which improves the material's capacity to endure elastic deformation. Increased fiber content leads to stiffer composite structures and higher modulus of elasticity. Also, the composite's fibers act as excellent load-bearing agents, aiding in the material's ability to withstand and transfer stress. When the composite is pulled, these fibers reduce the deformation of the polymer matrix by taking the majority of the load, resulting in less total material deformation [40,41]. As the fiber content grows, so does the number of contact sites, or interfaces, between the PFs and the matrix. These are the locations where the matrix material makes physical contact with the fibers, allowing for mechanically bonding and interaction. The increase in contact points improves the mechanical link between the PFs and their matrix. This increases the adhesion or bond strength of the two components. Better adhesion improves transfer of load from a matrix to the fibers, and that's critical for the composite's stiffness and strength. Besides, the strong link between the fibers and the matrix improves the effectiveness of stress transfer from the matrix to the fibers, contributing to an increase in modulus of elasticity. The more fibers in the composite, the more even the load distribution and the number of contacts between the fibers and the matrix, resulting in a more homogeneous and stronger material structure. Composites with increasing fiber content have higher elastic modulus, ranging from 2874.32 ± 205 MPa to 3473.53 ± 264 MPa, as indicated in Table 3. This represents the stiffness and resistance to elastic deformation that arise from increasing the number and dispersion of fibers in the composite matrix. greater fiber content composites have a greater elastic modulus due to improved fiber strength, better load distribution, and stronger adhesion bonds between the fibers and the matrix.

Furthermore, after 72 hours of immersion, the composites' tensile elongation ranged from 1.16 ± 0.4 % to 2.58 ± 0.15 %, while after 168 hours, it increased to 1.18 ± 0.3 % to 3.84 ± 0.35 % (Fig. 4c). The tensile elongation of composites without immersion ranged from 1.04 ± 0.28 % to 2.4 ± 0.1 %, as shown in Table 4. This rise suggests that water offers internal lubrication, allowing the fibers and matrix to glide and adjust more effectively under load, lowering the likelihood of early breaking and boosting the material's ability to withstand deformation. In other words, water absorption by the fibers and matrix significantly increases the tensile elongation of the composites, particularly as the number of fibers increases, allowing for additional plastic deformation routes. After 72 and 168 hours of immersion in water, the tensile elongation of PFs composites tends to rise dramatically with increasing fiber content (see DGC, BFC, HDC, ZAC, and SAC samples) due to the softening and plasticizing effects of water on the resin and fibers themselves. When water is absorbed into the composite, the polyester matrix softens and becomes more flexible, reducing stiffness and improving its ability to deform before breaking. Hygroscopic PFs absorb water and swell, which increases the composite's overall flexibility. This

softening effect becomes more noticeable as the number of fibers in the composite increases, as fibers that absorb more water provide more routes for deformation. Furthermore, the interaction of water with fibers and resin can create structural changes that boost tensile elongation. Water-containing fibers are more easily distorted, whilst the softened polyester matrix allows for greater fiber mobility within it. This results in a composite that is better able to tolerate plastic deformation under tensile load. As the fiber content in the composite grows, more fibers can absorb water and undergo these structural changes, increasing the material's tensile elongation.

3.4. Flexural strength analysis

Fig. 5 depicts the average flexural strength and modulus of PFs composites. Fig. 5a shows that the flexural strength of the unsoaked SAC sample is 126.9 ± 4.3 MPa with a fiber volume percentage of 25 % (% vol.), whereas the DGC sample has the lowest strength of 43.54 ± 6.1 MPa. Increased fiber content in composites leads to higher flexural strength values, as fibers serve as the primary reinforcement and offer structural support. PFs have better elastic modulus and mechanical strength than the polyester matrix [5]. When more fibers are introduced to a composite, they serve to distribute flexural stress more uniformly throughout the material, improving the composite's capacity to handle

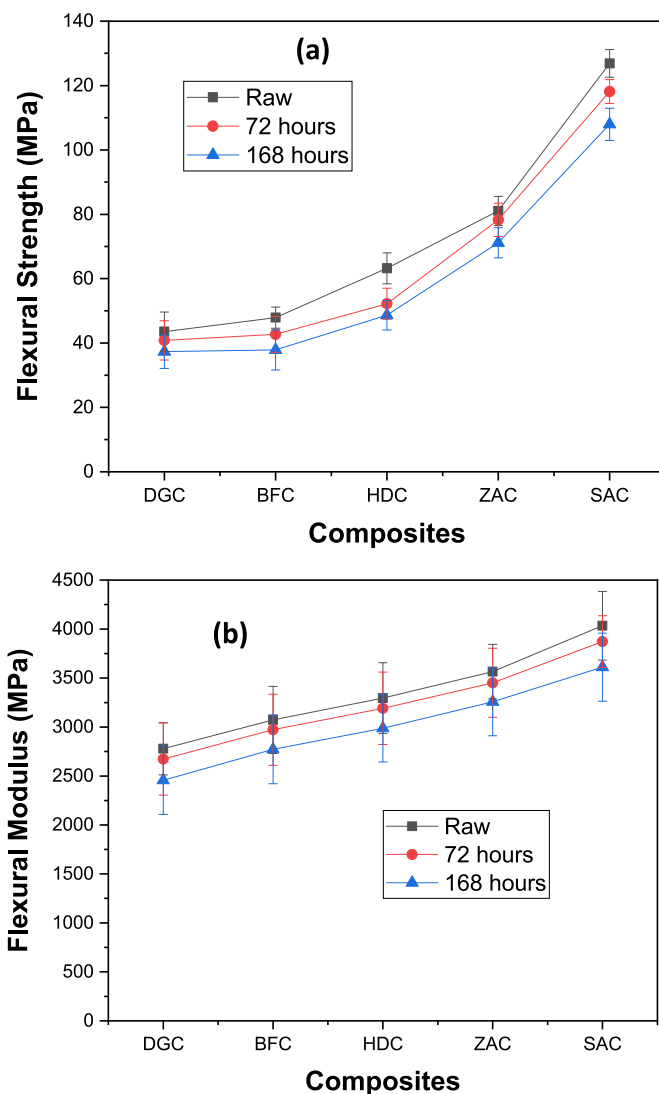


Fig. 5. (a) Bending strength, and (b) bending modulus of polyester composites before and after immersion in water.

bending loads without deformation or fracture. The fibers also stiffen the composite, making it more resistant to bending and fracturing, as evidenced by the increased flexural strength. Conversely, as the fiber content in the composite falls (see DGC sample), so does the flexural strength, as the number of fibers capable of supporting the bending stress reduces. Although the polyester matrix provides structural support, it is less strong and stiff than PFs. When a smaller number of fibers available to distribute and resist bending loads, the polyester matrix bears more of the load, but it is less effective at resisting deformation than the fibers. As a result, the composite is more likely to bend and fracture under bending stresses, lowering overall flexural strength. Without sufficient fiber content, the composite loses many of the fibers' structural advantages, resulting in a considerable drop in mechanical performance.

The composites' flexural strength fell from 43.54 ± 6.1 MPa to 126.9 ± 4.3 MPa (without immersed) to 40.81 ± 6.1 MPa to 118.14 ± 3.7 MPa after 72 hours of immersion, and further decreased to 37.33 ± 5.2 MPa to 107.95 ± 5 MPa after 168 hours of immersion. This reduction shows that the deleterious impact of water absorption on fibers and matrix worsens with immersion time. Although high fiber content can boost initial flexural strength, it also increases the surface exposed to water and potential damage, resulting in a higher loss in flexural strength gradually. After water immersion (Fig. 5a), the flexural strength of PFs composites decreases dramatically as the number of fibers increases, since fibers absorbing water can produce structural changes and degrade the contact between fibers and resin. Water that seeps into the fibers can cause them to swell and change mechanical properties, lowering strength and stiffness. Furthermore, water absorption can degrade the adhesive link between the fibers and the polyester matrix, limiting the composite's capacity to endure bending loads. When the fibers alter, the composite's capacity to withstand bending force declines. Furthermore, as the fiber content increases from 2.5 to 25 %, so does the region affected by water absorption. greater fibers equal greater surface area and pores in the matrix that can be exposed to water. Water can exacerbate matrix degradation and weaken fiber-matrix bonds. When composites with high fiber content are immersed in water, the destructive effect is magnified in comparison to composites with reduced fiber content. As a result, whereas composites with more fibers have a higher initial flexural strength, water immersion causes a greater reduction in flexural strength.

Fig. 5b demonstrates that after 72 and 168 hours of immersion in water, the flexural modulus of the composite increases dramatically with the addition of fibers. This is because an increase in fiber content in the composite can increase the overall stiffness of the material, even after being immersed in water. When fibers absorb water, they may experience physical changes such as swelling, but this effect can be mitigated by increasing the total number of fibers in the composite that act as reinforcing elements. More fibers in the composite assist to distribute and withstand bending forces more uniformly, which increases the material's flexural stiffness.

Furthermore, water absorption by fibers can promote swelling, which improves the mechanical contact between the fibers and the matrix provided the adhesive bond between the two is strong enough. Although immersion may reduce the stiffness of the polymer matrix, water-absorbing fibers that swell can improve or even increase the composite's flexural stiffness. This is because more fibers give more reinforcing elements that resist deformation, lessening the influence of flexural strength loss on the polymer matrix. After 72 hours of immersion, the flexural modulus of the composite with higher fiber content increased significantly, reaching 2672.6 ± 368 MPa to 13872.27 ± 263 MPa and 2456.37 ± 349 MPa to 13610.85 ± 347 MPa after 168 hours, compared to the lower flexural modulus values without immersion, reaching 2778.83 ± 266 MPa to 4033.69 ± 351 MPa (Fig. 5b).

The outcomes of this study, which focused on soaking in water for 72 and 168 hours, may alter if an immersion period is increased or if wet-dry conditions are administered repeatedly. Longer immersion times

cause the composites to absorb more water, that can result in deformation, reduced stiffness, and decreased carrying resistance. Furthermore, increased water absorption can cause hydrolysis in the resin, weakening the link between the fibers and the matrix and increasing the likelihood of cracking or detachment. This is in opposition to previous data, which suggested that degradation was not significant at lower immersion periods. The consequences of recurrent wet-dry situations are crucial for composites' long-term durability in practical applications. Wet-dry cycles can hasten the aging procedure of materials, creating recurrent stress that can result in cracking and structural failure. Outdoor applications, such as building construction or automobile components, require resistance to humidity and temperature variations to ensure the material's lifetime. If composites lack the ability to preserve their rigidity under changing climatic circumstances, they may fail prematurely, reducing the product's overall reliability. As a result, it is critical to study the effects of longer immersion periods and wet-dry situations in order to enhance the design and materials of stronger composites.

In some ways, composites manufactured from PFs function similarly to other natural fibers such as ramie, kenaf, or jute [42,43], however there are significant variances that affect their specialized applications. Tensile strength is typically lower in PFs than in fibers including ramie or kenaf, that are more commonly utilized for engineering uses requiring great strength. However, PFs offer the advantages of being lower in weight and having more elasticity, making them suited for applications that lack a large weight but do require flexibility. The thermal qualities of PFs are also promising, but as previously stated, their water resistance needs to be increased for prolonged use in humid environments.

In contrast, when compared to synthetic substitutes (glass or carbon fibers), PFs-based composites are more cost-effective and sustainable. Synthetic fibers provide significantly higher mechanical strength and superior water and rust resistance, but they are not recyclable and are typically heavier. The usage of PFs as a replacement is more acceptable for applications that value environmental responsibility and low manufacturing costs, such as bio-composite-based automotive, textile, or packaging materials. Although their mechanical performance is lower than that of synthetic fibers, the advancement of processing technology and chemically modifying of PFs can close the performance gap, making PF fibers competitive in the green composite industry.

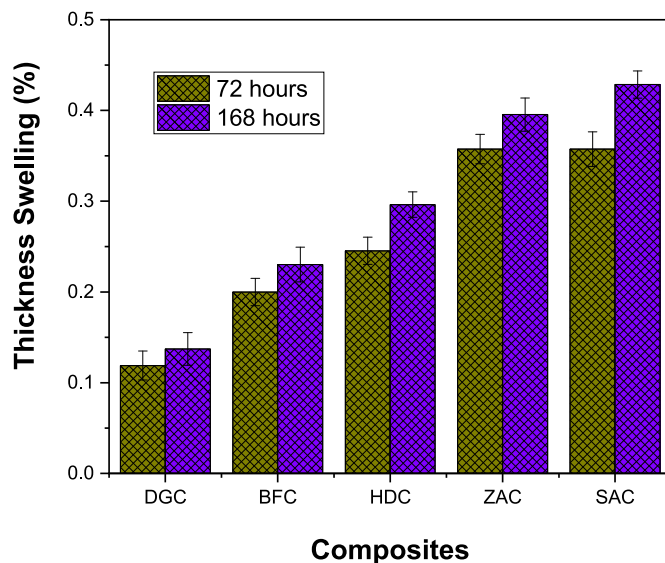


Fig. 6. Swelling thickness of different composites after soaked in water for 72 hours and 168 hours.

3.5. Swelling thickness analysis

Fig. 6 depicts the composite's swelling thickness after 72 and 168 hours of immersion in water; full statistics are provided in Table 5. After 168 hours of immersion, the SAC sample had a maximum swelling thickness (ST) of 0.39 %. Overall, the samples investigated showed an increase in the swelling thickness of the composite after immersion in water. The hygroscopic nature of the fiber itself can explain the considerable increase in swelling thickness of the composite as fiber concentration increases [34]. PFs have been shown to absorb water and swell when immersed in water [5]. As the fiber content of the composite grows, so does the number of fibers that can absorb water. As a result, the fibers in a composite with a high fiber concentration absorb more water, increasing the overall ST. The absorbed water causes the fibers to swell, increasing the overall volume of the composite, as indicated by the larger ST value. Furthermore, as the fiber content grows, the total amount of contact points between the fibers and the matrix increases, allowing more water to enter the composite structure. More fibers increase the number of gaps and pores in the matrix, making it easier to absorb water. When fibers absorb water, they swell and suck water into the matrix, amplifying the swelling effect [34]. This leads in a higher increase in swelling thickness than composites with lower fiber concentration. Composites with lower fiber concentration, such as the DGC sample, had lower swelling thickness (0.12 % and 0.14 % after immersion for 72 and 168 hours, respectively), owing to the lower fiber count resulting in lower water absorption. Furthermore, the polyester matrix in low-fiber composites may be resistant to water absorption, lowering the total swelling effect. With fewer fibers, there is less space for water absorption and swelling, resulting in a reduced swelling thickness when compared to composites with more fibers.

3.6. Thermal analysis

Fig. 7 depicts TGA curves for several composite materials. Fig. 7a depicts the unsoaked composites' weight loss as a function of temperature. The composite deterioration process consists of three stages. During the initial stage (25 °C–200 °C), all composite samples (DGC, BFC, HDC, ZAC, and SAC) lost some weight, which was most likely caused by water evaporation or physical removal of adsorbed water vapor. At this stage, weight loss is usually minor since the primary organic substance has not yet begun to disintegrate. The rapid initial reduction in weight on the TGA curve below 200 °C is typically caused by the loss of water or moisture deposited on the composite surface. Natural fibers, like Paederia fibers, which are commonly used in composites, possess hygroscopic qualities, which means they may absorb water from surroundings owing to the existence of polar hydroxyl chains (-OH) in their cellulosic structure. This absorbed water dissipates quickly in low temperatures, about 100–200 °C, resulting in significant weight loss during the initial stages of heating. This evaporation is mostly a physical process that has no impact on the fiber or composite matrix's primary chemical structure. Further to water evaporation, volatile parts or compounds in polyester resins begin to degrade as temperatures near 200 °C. Polyester resins used as composite matrices may contain volatile components like solvents or plasticizers, which can evaporate or degrade when exposed

to low temperatures. Furthermore, certain gases can be produced during interactions between fibers and matrices. This action results in additional weight loss while also providing vital information regarding the composite's initial thermal stability and the rate to which water or volatile components are present.

The second stage is Main deterioration (200 °C–400 °C), which results in considerable weight loss between 200 °C and 400 °C. This is the major heat deterioration stage of the polyester matrix and PFs. At this temperature, polymer bonds begin to dissolve, and the organic substance decomposes [44,45]. Furthermore, all composite samples demonstrated similar weight loss patterns, with only minor changes in the temperature at which weight loss was most prominent. These could be slight changes in the composition or distribution of fibers in the polyester. Further, The third stage is the ultimate Stability stage (400 °C–800 °C); after the temperature hits approximately 400 °C, the weight loss rate begins to slow and approaches stability. Most volatile elements have been deteriorated at temperatures over 400 °C–800 °C, whereas the remaining materials are more heat stable. Slower weight loss in this temperature range typically suggests further degradation of carbon residues and inorganic compounds [2,35]. At the end of the temperature range (approaching 800 °C), the weight loss curve flattens, indicating that the majority of thermally degradable components have been depleted and only heat-resistant residues remain (Table 5). In general, the degradation patterns were comparable across all samples, however there were minor differences in temperature and weight loss rates, which could be attributed to differences in fiber composition and distribution within the polyester matrix.

Figs. 7b and 8c illustrate thermogravimetric analysis (TGA) of a Paederia fiber composite with a polyester matrix after 72 hours of immersion in water. Fig. 7b and c demonstrate three major stages of heat deterioration. In the early stages (25 °C–200 °C), all composite samples (DGC, BFC, HDC, ZAC, SAC) lost little weight. This weight loss was primarily caused by the evaporation of water ingested while immersed. This shows that water absorbed by the fiber and matrix has no substantial effect on the composite's thermal stability at low temperatures, and that the majority of the absorbed water can be eliminated without causing significant material degradation.

The thermal stability of the composite sample at this temperature (Fig. 7c) demonstrates that immersion in water for 168 hours has no effect on components that do not degrade at low temperatures. In the second stage (200 °C–400 °C). Fig. 7b and c demonstrate significant weight loss, demonstrating that the matrix and fibers are degrading. This dramatic weight decrease suggests that, despite being submerged in water, the composite's essential structure remains consistent with the un-immersed composite. Considerable weight loss in composites following water immersion is generally caused by the discharge of water absorbed during submersion, which has no effect on the material's core structure. This means that, even though the composite collects and releases water, the links among the fibers and the matrix are not permanently damaged. Water only changes the composite's surface or micropores, leaving the core structure unchanged. As a result, water absorption is only transitory and insufficient to alter the mechanical attributes or strength of the composite, allowing it to retain its integrity after drying. Water immersion, on the other hand, may induce a minor fluctuation in the initial degradation temperature, but the overall deterioration pattern stays consistent. This could be due to a minor alteration in the interaction between the fibers and the matrix as a result of moisture absorption. Meanwhile, Fig. 7c demonstrates that even after 168 hours of immersion in water, the thermal deterioration pattern remains consistent with that of the composite that was not submerged or immersed for a shorter period of time, while the starting degradation temperature may have shifted slightly. This implies that the interaction between the fibers and the matrix may have changed slightly as a result of water absorption, but not considerably enough to alter the degradation pattern. In the third phase (400 °C–800 °C) (Fig. 8b and c), the weight loss rate begins to slow and the graph flattens, indicating that the

Table 5
Charcoal residue from various composites.

Sampel Codes	Immersion Period		Composites without immersion Char (%)
	72 h	168 h	
	Char (%)	Char (%)	
DGC	2.36219	2.79219	1.73219
BFC	3.78297	4.22297	3.20297
HDC	6.00827	6.45827	5.44827
ZAC	6.18983	6.57983	5.67983
SAC	8.80127	9.16127	8.37127

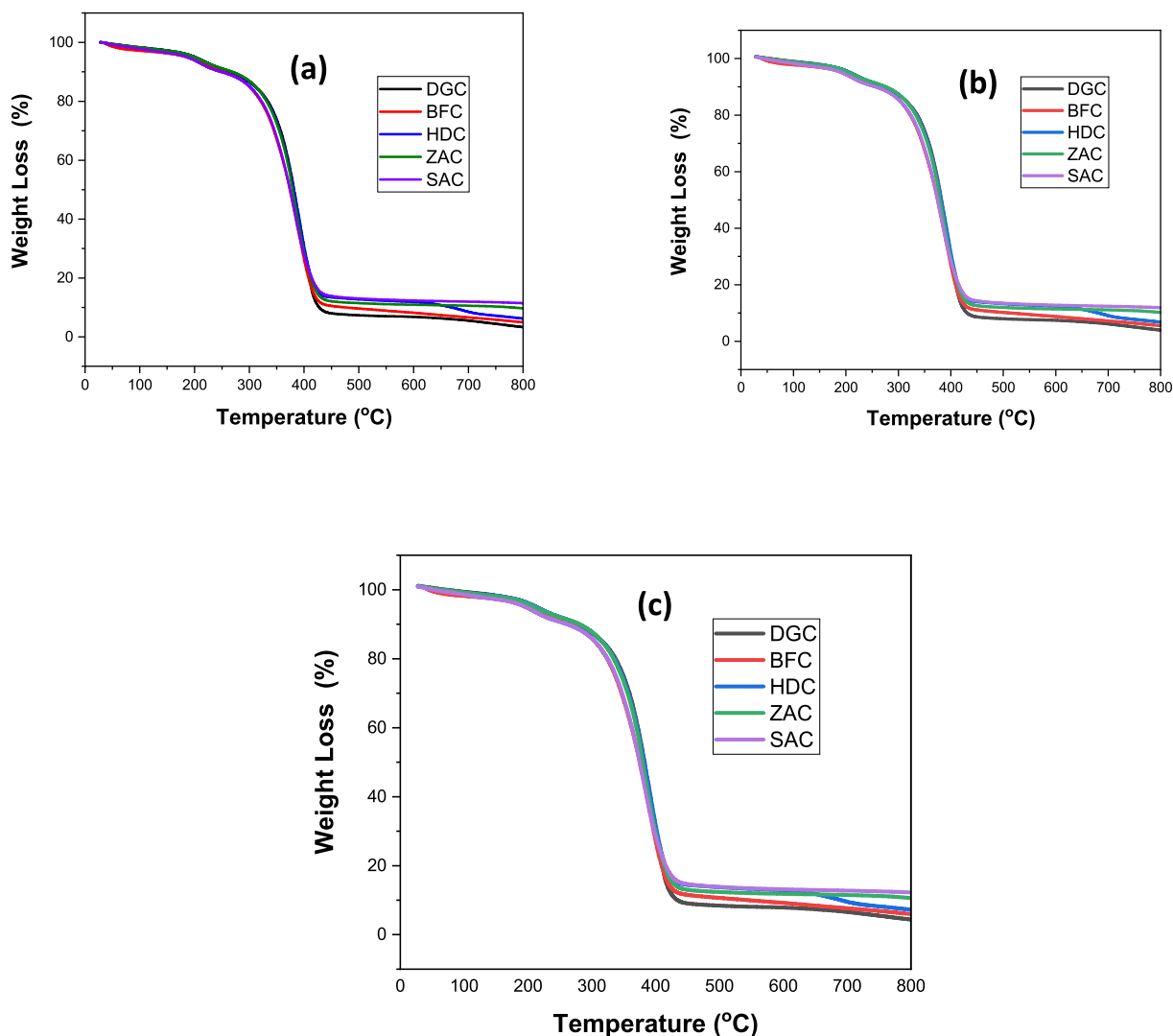


Fig. 7. TGA of PFs composites, (a) Without soaking, (b) after soaking for 72 h, and (c) after soaking for 168 h.

remaining material is more heat stable [45]. The endurance of biocomposites to high temperatures, namely 400 °C–800 °C, demonstrates that all samples (DGC, BFC, HDC, ZAC, SAC) lose low weight in this temperature range. This shows a high degree of thermal stability. The three figures above show that the majority of the weight loss happens at temperatures below 400 °C, that could be due to the first decomposition of organic molecules or the release of absorbed water. After reaching around 400 °C, there is no appreciable weight loss, showing that the biocomposites remain stable at higher temperatures. The biocomposites' low mass change at elevated temperatures suggests that water absorption has little effect on thermal stability, after long exposure to water. At this point, much of the easily degradable organic stuff has been depleted, leaving only the more heat-resistant residue (Table 5). The fact that the weight loss rate at high temperatures stays constant with the unsoaked sample suggests that water immersion for 72 and 168 hours had no meaningful effect on the thermal stability of the remaining material. In other words, while water immersion can change the mechanical and physical properties of the composite, it has no effect on thermal stability at high temperatures. This suggests that the PFs composite with polyester matrix retains good heat resistance even after prolonged exposure to water.

3.7. Morphology analysis

Fig. 8a illustrates a SEM picture. After 72 hours, the surface of sample BFC/72 h shows visible longitudinal fissures and evidence of fiber pull-out, indicating poor interaction between the fiber and matrix. This can reduce the tensile strength and cause early failure. Fig. 8b displays the surface crack of a BFC sample after 168 hours of soaking (or BFC/168 h). The morphology reveals a rougher surface with greater fiber pull-out, implying that the fiber-matrix interface will degrade more with extended exposure times. This could indicate greater void content or decreased adhesion over time. Fig. 8c SEM shot shows a reasonably smooth surface with less evidence of fiber pull-out, which could indicate greater adhesion or less deterioration than the BFC sample. However, some modest interfacial debonding remains observable. Fig. 8d depicts the surface fractures of the HDC/168 h sample, which is comparable to (Fig. 8c), but the appearance of additional fiber pull-out and surface imperfections suggests that the extended exposure (168 h) alters the interface, potentially lowering the mechanical properties over time. Fig. 8e exhibits the fracture of the SAC/72 h sample, indicating that the rough fracture surface reveals fiber pull-out and matrix cracking, that may imply some degree of void formation or inadequate bonding at 72 hours. Meanwhile, Fig. 8f shows considerable fiber pull-out and fissures on the surface, showing that the fiber-matrix adhesion has weakened further, most likely due to extended exposure and consequent stress

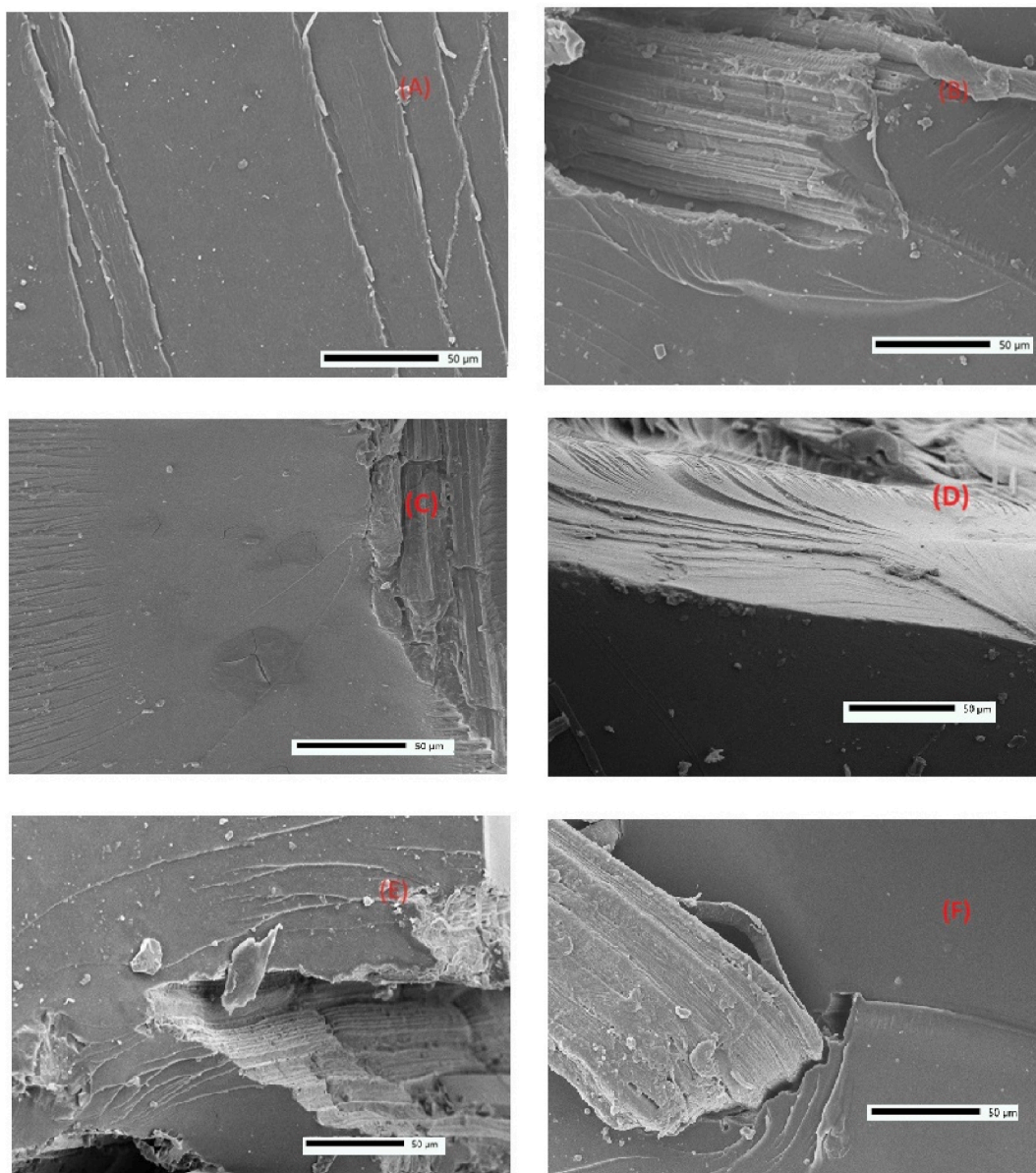


Fig. 8. SEM Micrographs of the fracture surfaces of the composites after tensile testing: (a) sample BFC/72 h (500x); (b) sample BFC/168 h (500x), (c) HDC/72 h (500x), (d) HDC/168 h (500x), and (e) SAC/72 h (500x), and (f) SAC/168 h (500x).

during tensile tests.

The SEM data clearly reveal that water immersion has an effect on the structure and integrity of the PFs composite with a polyester matrix. Water can weaken the adhesion between the components, resulting in material deterioration. After immersion, the fiber-matrix adhesion appeared to be significantly diminished. This can be solved by treating the fiber surface prior to the composite process or by utilizing a more moisture-resistant matrix.

4. Conclusions

This study investigated the thermal, mechanical, and physical properties of *Paederia foetida* (PFs) fiber-reinforced biocomposites following immersion in water. The analyses included thermogravimetric (TG) analysis, water absorption, swelling thickness, tensile and flexural properties, and density measurements. The results revealed that the tensile strength, modulus of elasticity, and flexural strength of the biocomposites without water immersion were relatively high. Notably, as the PFs content increased from 2.5 % to 25 % by volume, the density of

the composites decreased. Specifically, the tensile strength and modulus of elasticity ranged from 47.46 ± 8.2 MPa to 105.59 ± 6.3 MPa and 2874.32 ± 205 MPa to 3473.53 ± 264 MPa, respectively. However, after 72 and 168 hours of water immersion, the mechanical properties—including tensile strength, modulus of elasticity, flexural strength, and flexural modulus—were significantly reduced across all fiber volume fractions. Conversely, there was a noticeable increase in density, swelling thickness, and water absorption, which can be attributed to water ingress through the fiber cavities and composite matrix. While water immersion negatively impacts the mechanical and physical properties of PFs composites, its effect on thermal stability at high temperatures (400 °C– 800 °C) was found to be minimal. This suggests that PFs/polyester composites maintain good thermal resistance even after prolonged exposure to water. Scanning Electron Microscope (SEM) images revealed degradation and cracks in the composite structure post-immersion, which could further compromise the mechanical integrity of the biocomposites. In conclusion, while PFs biocomposites demonstrate potential as sustainable materials with favorable thermal resistance, their mechanical performance in waterlogged conditions is a limiting

factor that needs to be addressed for broader applications, particularly in environments where exposure to moisture is unavoidable. Future study can focus on improving the mechanical stability of PFs bio-composites under saturated circumstances by modifying the exterior of the fibers or matrices. One method is to use hydrophobic treatments or surface grafting techniques to prevent water from being absorbed by fibers and matrices. Furthermore, using polymer matrices with improved water-resistant qualities, for instance modified polyethylene, may be an option.

CRedit authorship contribution statement

Nasmi Hertina Sari: Conceptualization, Writing – original draft preparation. **Suteja:** Data curation. **Sujita:** Methodology, Investigation. **Edi Syafri:** Formal analysis, Investigation. **Buan Anshari:** Resources. **Mounir El Achaby:** Writing – review and editing. **Arridina Susan Sil-itunga:** Formal analysis and editing.

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.

Acknowledgement

The researcher would like to thank the Ministry of Education, Research, Culture, and Technology (Kemdikbudristek) has supported the funding of this research through the Competitive Grant funding of the Indonesian program in 2024 (No. 060/E5/PG.02.00.PL/2024). The authors also wish to thank Strategy Research Support Funding 2024 (No. 324100.2200144) University of Technology Sydney, Australia and Politeknik Negeri Medan, Indonesia.

Data availability

Data will be made available on request.

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