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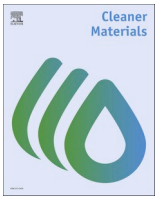

A critical review: Recent developments of natural fiber/rubber reinforced polymer composites

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ABSTRACT

Recent advancements in the development of low-emission materials have become a global imperative to achieve net-zero emissions in efforts to limit the effects of climate change. The materials transition agenda not only aims to substitute emission-intensive materials but also incorporates emission reduction efforts into goods and applications. Natural fiber composites have received attention from both commercial and research communities because of their inherent eco-friendliness, lower cost, and lower energy consumption during processing than their synthetic counterparts. Additionally, rubber-reinforced polymer composites have generally shown promising results, particularly in resisting sudden deformation. Although studies combining waste rubber with natural fibers in polymer composites are nascent, with limited existing literature, this area demonstrates remarkable potential for the substitution of traditional synthetic composites. Therefore, this review outlines the recent developments in polymer composites incorporating the use of natural fibers and rubber in various forms. The use of rubber as a filler has been shown to enhance tensile strength and impact performance while enhancing the surface finish, however, conflicting studies were identified. Hybridizing waste rubber and natural fibers presents a promising path to further enhance the mechanical performance of composite materials. Emphasis has been placed on the use of fillers in various forms and on their inclusion in thermoset matrices. The future outlook and research opportunities are also presented in this review.

1. Introduction

Currently, the global fiber industry is dominated by synthetic fibers, with a share of 62 %, whereas natural fibers make up 38 % of the market (Kwak et al., 2022). Synthetic fibers not only require more energy for processing but also contribute more to environmental burdens (Akter et al., 2024; de Queiroz et al., 2024). This is due to the release of harmful chemicals such as sulfuric acid and blended petroleum products (Gonzalez et al., 2023). Environmental concerns and potential health hazards have motivated researchers to develop eco-friendly and sustainable materials for various applications. By 2025, the global market for biocomposites is expected to be worth USD 41 billion, with the two primary industries lying within the automobile and construction sectors (Zwawi, 2021). Natural fiber-reinforced composites (NFRCs) display great potential for various applications owing to their low cost and low environmental impact (Palmiyanto et al., 2022; Neto et al., 2022; Nabinejad et al., 2017). The high demand for sustainable and environment-friendly materials has allowed natural fiber polymer composites to emerge as a key research area (Ganguly et al., 2022; Murugesan et al., 2022) (see Table 1).

In the last few years, researchers have started to explore the energy impact capabilities of NFRCs (Faizi, 2017), with the ability to protect the main structural components from catastrophic failure (Mahesh et al., 2021); and utilize natural fiber composites as a new material for safety helmets (Rahman, 2023). Owing to the possibility of brittle fracture upon impact, impact loads are often the determining factor in material selection in many engineering applications involving polymer composites (Bucknall, 1977; Agunsoye et al., 2012).

Additionally, composites incorporating waste materials have also gained traction owing to landfill issues and other potential hazards upon disposal. According to a World Bank report (Hoornweg and Bhada-Tata, 2012), 2.2 billion tons of municipal solid waste (MSW) will be generated

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Table 1
Worldwide Palm Oil Fruit and Sugarcane Production (Hussain, 2023).

Year	Fiber Production in Million Tons	
	Palm Oil Fruit	Sugarcane
2009	216	1,673
2019	411	1,950

annually by the year 2025 and is expected to increase to 4.54 billion tons by 2050 (Maalouf and Mavropoulos, 2023). The transport industry (automobiles, trucks, and motorcycles) generates a primary source of rubber waste in the form of tires. In 2022, it accounted for more than 70 % of the global rubber consumption and is expected to increase further owing to new growth opportunities (Rubber, 2023). Due to its complex nature, a bare 1.5 % of the total waste generated is reused and recycled (Chittella et al., 2021). The stockpiling of this waste could promote the spread of deadly diseases, such as dengue and malaria (Chittella et al., 2021; Ramarad et al., 2015). Hence, these issues are recognized as significant global problems. The valorization of waste materials can offer a triple-win solution by reducing greenhouse gas emissions, conserving resources, and generating new economic opportunities through the production of valuable products (Sathish Kumar et al., 2024).

In the study of composite materials, the matrix binds the filler particles to form a new material. Reinforcing materials are a form of filler added to the matrix of the parent material to enhance its mechanical properties. Fillers can impart unique properties such as wear, thermal, flammability, and fatigue resistance (Prakash and Gnanavel, 2024). They are categorized into primary and secondary reinforcing materials, wherein the former fibers are commonly used to reinforce a certain material; in the latter, the properties of the composite are further enhanced (Bharath et al., 2019). Hybrid composites offer a synergistic effect, where the beneficial properties of one filler material counteract the drawbacks of the other, resulting in significant enhancements in mechanical performance (Dehury et al., 2024).

The mechanical properties of polymers and polymer composites depend on many structural and molecular factors such as molecular weight, cross-linking and branching, molecular orientation, crystallinity, crystal morphology, and etc (Landel and Nielsen, 1993). These factors not only influence the physical properties of the polymer but also its molecular behavior, even in the absence of fillers (Danielsen, 2021). For example, increased molecular weight increases tensile strength as it is a product of the degree of polymerization, as does the presence of cross-linking, which restricts the motion of the polymer chains (Balani et al., 2014).

In all-polymer composites, mechanical failure is initiated through debonding of the filler and polymer matrix (Cho et al., 2006). Interfacial adhesion is a critical factor in dictating mechanical strength performance, which stems from a combination of interfacial bonding mechanisms such as physical adhesion, electrostatic adhesion, chemical adhesion, and mechanical interlocking (Lee et al., 2021). This highlights the importance of improving the interfacial bonds between the filler and matrix, which can be achieved through surface modification by improving the compatibility of the filler with the polymer matrix (Linda et al., 2023; Ntimugura et al., 2023). Physical modifications alter the structural and surface properties of the filler, whereas chemical modifications alter the surface topography and remove surface impurities by introducing chemical functionalities (Ernest and Peter, 2022; Halip et al., 2019). Both methods can be used to enhance the overall effectiveness of the fillers (see Table 2).

Over the last 20 years, there has been a steady increase in the development of polymer composite materials. Apart from 2023, the number of published documents in this area has increased annually, reaching 17,068 documents annually. This indicates that there is substantial interest in its development. Combining natural fibers and waste rubber as fillers can be an alternative to presently used synthetic fillers. The utilization of this waste has the potential to offer economic and environmental benefits. The data used to produce Fig. 1A and 1B were obtained via the Scopus database. Fig. 1A depicts the number of materials published over the last 20 years. Over the last five years, this area of research has consistently garnered more than 20 published works annually, almost doubling the number of years prior to 2018, with the exception of 2013 and 2014. Fig. 1B presents the number of publications in polymer composite in 2023 focusing on the terms “natural fiber,” “rubber,” and “natural fiber rubber”; it is shown that the hybridization of both natural fiber and rubber in polymer composite has less than 2 %, a relatively unexplored area. Therefore, the development of sustainable, environmentally friendly, and competent materials warrants further investigation.

The lack of comprehensive reviews on the recent advances in polymer composites utilizing natural fibers and rubber as fillers highlights the need for this work. This review aims to cover the topics of polymeric composites, focusing on the incorporation of plant-derived natural fibers and waste rubber, specifically emphasizing their mechanical performance. In addition, to encourage the future development of natural fiber-based polymer composites, this review outlines the current research gaps as potential opportunities for future work.

2. Natural Fiber-Reinforced polymer composites

Over the past decade, the automotive sector and lightweight structural applications have experienced rapid growth in the use of natural fiber composite materials (Brailson Mansingh et al., 2023). Natural fibers can be employed to reinforce polymers to reduce the negative environmental impacts associated with their synthetic counterparts (Islam et al., 2022). Such materials have mainly been used as vehicle interior components, resulting in a weight reduction of up to 25 % (Adlie et al., 2023). These composites have also been used in windows, doors, frames, ceilings, beams, pipes, and tanks (Zwawi, 2021). To further add to their potential benefits, it was reported that the presence of natural fibers in a composite can absorb incident UV radiation. This provides protection to the polymer matrix and reduces the effects of material degradation caused by aging (Moreno et al., 2018).

Natural fibers are readily available, cheaper, simpler to manufacture, and more likely to create environmentally friendly biocomposites. Natural plant fibers, such as oil palm empty fruit bunch, sugarcane bagasse, and water hyacinth, are considered lightweight, cheap, and readily available. Despite being organic materials, such fibers can negatively impact the environment by contaminating the air, soil, and aquatic environments (Wang, 2016; Ifrani et al., 2021; Rama Rao and Ramakrishna, 2022). Malaysia is the second-largest global palm oil producer, supplying up to 26 % of the world’s palm oil demand (Mohd Hanafiah et al., 2022). Oil palm (*Elaeis guineensis*) fiber is one of the most abundantly available natural fibers in the local Borneo region.

Similarly, the sugar-processing industry in tropical countries produces abundant sugarcane bagasse (*Saccharum officinarum*) waste; approximately 30 % of the fibrous material is a byproduct (Mahmud and

Table 2
Main Components and Density of Selected Natural Fiber.

Type of Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Untreated Density (g/cm^3)	References
Water Hyacinth (Petiole)	65.4	12.8	7.2	>0.837	(Arivendan et al., 2022; Davies and Mohammed, 2011)
Sugarcane Bagasse	55.2	16.8	25.3	0.91	(Hussain, 2023; Faruk et al., 2012)
Oil Palm Empty Fruit Bunch	43.3	20.3	13.8	1.1972	(Thanapimmetha et al., 2023; Zuhaimi, 2023)

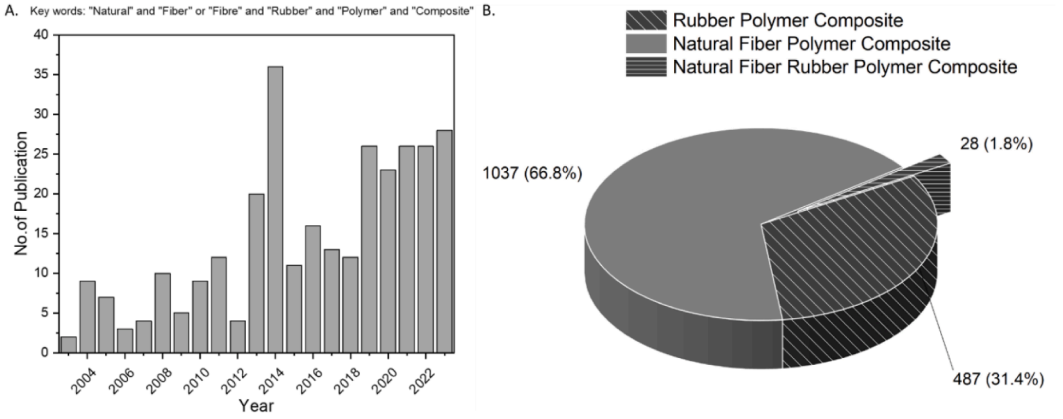

Fig. 1. A: Number of Publications between 2003 to 2023. B: Number of Publication of Polymer Composite with Specific Terms in 2023.

Anannya, 2021). Bagasse fibers can be found in abundance but are rarely used optimally (Kusuma et al., 2023). The following table presents the palm oil fruit and sugarcane production worldwide.

Unlike previous fibers, water hyacinth (*Eichornia crassipes*) (WH) is an extremely fast-growing aquatic plant that can double its population within 12 days (Shariff and Bakar, 2006). A single plant produces 28,000 tons of fresh biomass and 140 million daughter plants annually (Thuyen et al., 2017; Ruan et al., 2016; Lu et al., 2007). Due to its high reproduction and widespread growth rate, it has caused ecological disruption and severe environmental and economic problems. It is not only found to restrict water flow and deprive the water of oxygen (Rama Rao and Ramakrishna, 2022); but also forms a thick mat of roots that have been reported to be impossible to penetrate by aquatic vehicles (Shariff and Bakar, 2006). Negative attitudes and lack of funding have been the main obstacles to eliminating this weed from water bodies worldwide (WasteMoney, 2023). Among the discussed fibers, water-hyacinth-based polymer composites exhibit the least mature development, which is reflected in the scarcity of currently available publications. Nandiyanto et al. (Nandiyanto et al., 2024) has also indicated that the WH development period is still classified under the acceleration period. This implies that the utilization of this fiber has yet to be fully realized and requires further consideration.

The table below presents the content of the natural fibers discussed along with their inherited density.

The following section presents recent investigations incorporating natural fibers as fillers in polymer matrices, with the majority focused on epoxy as a matrix. A recent study by Arivenda et al. (Arivendan et al., 2022) showed that the incorporation of WH fibers into an epoxy matrix could simultaneously improve the tensile impact and flexural strength. The composites were fabricated using hot compression molding at a temperature of 100 °C and a pressure of 10.34 MPa. Their work experimented with various fiber contents (15, 20, 25, 30, and 35 wt%). It was revealed that the addition of 30 % was the most effective, yielding a tensile strength of 39.65 MPa, flexural strength of 60.12 MPa, and breaking energy of approximately 0.81 J. The addition of WH fibers increased the tensile strength, flexural strength, and breaking energy by 192.8 %, 167.8 %, and approximately 700 %, respectively. The authors found that fiber loadings of 35 % created agglomeration in both phases (matrix and dispersed) of the composite, which led to debonding of the filler and matrix. This resulted in poorer mechanical performance. Based on these promising results, they are strongly recommended for light-weight materials and commercial product applications. However, upon further review, their work did not report the final density of the WH epoxy composite alongside the associated commercialization costs. Additionally, their work did not provide an in-depth analysis of the reinforcement mechanisms with an increase in fiber loading. Furthermore, based on the information provided regarding the novel fiber extraction method, replicating the composite would be challenging. Finally, despite the authors' claims that they followed ASTM testing standards, such as D3030, D790, and D256, which require the use of at least five test specimens, their work only conducted tests on three specimens without reporting their uncertainties in any of their graphs. To further add on, the ASTM D256 test method and specimen size were not listed. This raises additional questions about the reliability and consistency of the results.

In 2023, Sulardjaka et al. (Thuyen et al., 2017) conducted a study to determine the effects of fiber treatment on the mechanical properties of WH-reinforced epoxy. The fibers were treated for 24 h via immersion in three different solutions (acetate anhydride, 5 %, and 10 % sodium hydroxide). The composites were fabricated via hand layup in combination with 5 MPa of compression. It has been reported that esterification is more effective than alkalization because it results in fibers with a lower thickness and does not significantly increase the porosity of the composites. During the alkaline treatment, the fiber surface became rougher, increasing air entrapment, which led to an increase in porosity. This may also lead to the formation of defects/weak zones. The highest tensile strength was obtained with 25 wt% fiber loading at 61 MPa using acetate anhydride, followed by 58 MPa using 5 % NaOH, and 41 MPa using 10 % NaOH. Notably, it was also stated that WH treated with acetate anhydride displayed the least number of debonded fibers compared to the other treatment methods. The effects of replicating this acetate anhydride treatment will be challenging as its concentration was not mentioned, and the researchers highlighted the use of "CH_3COOH" instead of $C_4H_6O_3$, which is known to be acetic acid. Upon a deeper review, it was found that this work incorporated the use of several tensile testing standards, which raises doubts in comparing their results; ASTM D638 was used to evaluate the epoxy resin, while ASTM D3039 was used to test the composite. Therefore, the values for neat epoxy were excluded from this review in view of data reliability. Lastly, it was also shown that the developed composites mainly displayed brittle failure mode.

Owen et al. (2022) fabricated epoxy composites using WH fibers and investigated the effects of alkali surface treatment on mechanical performance. Two types were used: untreated and treated with 6 % NaOH at room temperature. Both the fibers were then dried using a dehumidifier with an average relative humidity of 40 %. The fibers were then pulverized into fiber particles using a 5.0 mm mesh aperture. Fillers (10 wt%) were added to the resin and mixed at a speed of 120 rpm for 30 min. The mixtures were then manually compressed and cured at room temperature. It was found that the incorporation of untreated fibers resulted in a reduced mechanical strength across the board for tensile, flexural, and impact. This is due to poor interaction bonding and a weak fiber interface with the matrix. It was also observed that the composite surface displayed poor wettability, microvoids, and fiber pullout. Consequently, its performance was reduced because of the ineffective transfer of stress. In contrast, the addition of alkaline-treated fiber

provided an increasing order of reinforcement for tensile, impact, and flexural strengths by 0.5 %, 6.6 %, and 10.6 %, respectively. The authors explained that such improvements via alkaline treatment are due to the enhancement of weak interfacial bonding between the hydrophilic fiber and the hydrophobic polymer matrix. The good distribution and dispersion of the treated fibers also contributed to stress transfer and provided effective resistance to crack propagation. Owen et al. (2022) also highlighted that both particle size and concentration of NaOH play a major role in improving tensile properties. However, more data are needed to support their claim that a 5.0 mm mesh size and 6 % NaOH with 10 wt% loading are the optimized parameters. In particular, smaller particles have various size distributions and can pass through the sieve. Owen et al. (2022) reported extremely high impact strength values of up to 128 kJ/m^2. The authors likely intended to report impact resistance values (J/m) instead of incorrect data. Lastly, they acknowledged that WH fiber can be used like other natural fibers, while simultaneously enhancing the economic value and elevating associated issues. However, claims for load-bearing applications require further in-depth testing and analysis.

Much research has also been conducted on the use of oil palm fibers (OPF) as a composite reinforcement. Suriani et al. (2021) investigated the effect of fiber loading of Oil Palm Empty Fruit Bunch (OPEFB) fibers on the tensile strength of epoxy. In the researchers' work, the OPEFB fibers were cut to 22 cm in length. They were then added to the epoxy at fiber loadings of 20, 35, and 50 wt% via the hand lay-up method. 5 wt% Polyethylene Terephthalate (PET) yarn and 5 wt% Magnesium Hydroxide powders were also added to all sample types, including the neat epoxy samples. Undergoing ASTM D638 tensile tests, it was found that the neat epoxy sample exhibited the greatest tensile strength at 10.79 MPa, gradually decreasing as the content of OPFs increased. Based on this trend, the samples containing 50 wt% OPF had the lowest tensile strength value of 3.88 MPa. According to the researchers, the reduction in tensile strength was due to inefficient fiber–matrix stress transfer caused by the fiber's hydrophilicity and poor fiber–matrix adhesion. The poor adhesion was further proven when scanning electron microscopy (SEM) images showed that fiber pull-out and fiber–matrix debonding occurred at the fracture surfaces of the composites. Lastly, poor fiber dispersion was also noted to contribute to the reduction.

Awad (2022) studied the effect of OPFs and Pineapple Fibers (PALF) of size 0.8–1 mm, on the mechanical performance of biophenolic resin hybrid composites. In this work, the researchers also studied the effect of alkali treatment, wherein the treated fibers were immersed in 5 % NaOH for 3 h. The total fiber loading was maintained at 50 wt% for both the pure and hybrid composites. The hybrid composites were composed of OPF/PALF ratios of 3:7, 1:1, and 7:3. All composites were fabricated via hot compression molding and their tensile and impact properties were tested under ASTM D3039 and ASTM D256 standards, respectively. The tensile tests showed that the treated samples exhibited higher strength, with the 50 wt% treated PALF samples having the highest at 33.3 MPa. According to researchers, this was due to the enhanced fiber–matrix interactions caused by NaOH. This was verified through SEM, where untreated fibers showed higher porosity, void content, and fiber pullouts on the fracture surface, whereas treated fibers had smaller voids. However, the strength of the samples containing 50 wt% OPF decreased from ~30 to 18 MPa after treatment. Considering that NaOH immersion lasted for 3 h at 5 % concentration, it is possible that changes in the fiber diameter through alkali treatment may have affected the fiber strength (Anggawan et al., 2019). Therefore, further research on effective treatment conditions for OPF is required. Regarding the impact test, it was found that alkali treatment led to higher performance for all sample types, with the highest performance achieved by samples containing 50 wt% PALF at ~6.5 kJ/m^2. No discernible trend was observed in the strengths of the hybrid composites in terms of the fiber ratios. Finally, neat sample data were not presented, leaving ambiguity on the effect of OPF and PALF fiber loading and hybridization on the biophenolic resin.

Meanwhile, Hanan et al. (Hanan et al., 2020) also investigated the effect of OPEFB and Kenaf mats on the impact properties of epoxy composites. Their method involved the fabrication of bilayer hybrid composites containing a total of 50 wt% fiber loading via the hand lay-up method, with OPEFB/Kenaf fiber ratios of 4:1, 1:1, and 1:4. Pure composites containing 50 wt% OPEFB and Kenaf mats were also fabricated. Conducting impact tests while adhering to the ASTM D256 standard, the researchers found that all hybrid composites exhibited lower impact performance compared to the pure composites, with the lowest value of 1.2 J belonging to the samples containing 1:1 OPEFB/Kenaf ratios. In contrast, the pure composite containing 50 wt% OPEFB had the highest impact strength of 8.05 J. According to researchers, the improvement caused by OPEFB fibers may be due to the chemical composition of the fiber as well as the interlacing of the OPEFB fiber bundles. Notably, the 50 wt% Kenaf sample, which exhibited the second highest impact strength in this experiment, had an impact strength of 3.06 J. Evidently, OPEFB fibers may be a viable option for significantly improving the impact strength of polymer composites. Nevertheless, no neat samples were tested; therefore, no comparison was made between the epoxy and the epoxy composites. Therefore, questions regarding the degree to which OPEFB fibers improve the impact strength of epoxy require further research. Furthermore, despite the hybrid samples exhibiting lower impact strength values, it is unclear whether hybridization leads to an overall improvement or reduction in the impact strength of the epoxy. Table 3 summarizes the findings presented in this section.

Based on the findings of Arivendan et al. (2022), Rama Rao and Ramakrishna (2022) and Sulardjaka et al. (2023), the inclusion of natural fibers as fillers in the range of 10–30 wt% has the potential to impart mechanical performance reinforcement, particularly in terms of tensile strength. However, this is in contrast to the work of Suriani et al. (2021), who observed a performance degradation as low as 20 wt%. This discrepancy highlights the need for further investigations. Interestingly, Sulardjaka et al. (2023) demonstrated the potential for further enhancement via surface treatment/pretreatment of WH fibers, overcoming some of the negative attributes that can be further adopted and explored by other researchers. Unfortunately, both Awad (2022) and Hanan et al. (2020) did not report the strength performance of their neat matrix, which hinders a direct comparison. Suriani et al. (2021) indicated that a higher filler content leads to inefficient fiber–matrix stress transfer, resulting in performance reduction. Notably, future research could explore the utilization of natural fibers in fine powder form, which may offer further insight into the reinforcing effects on both the tensile and impact properties.

3. Rubber reinforced polymer composites

Fig. 2A shows the consumption of rubber for various applications (Shivamurthy et al., 2019). It can be seen that the majority (68 %) of the rubber is used in the production of tires. Waste tires constitute 2 % of the solid waste and are currently a global waste problem (Turkben et al., May 2023). According to a report published by the United States Environmental Protection Agency (EPA) at the end of 2020 (Advancing Sustainable Materials Management, 2018), approximately 18.2 % of the rubber leather generated is recycled, while the majority ends up in landfills. As a result of the global concern associated with waste rubber, extensive efforts have been made to develop eco-friendly recycling and recovery methods. Customarily, used tires are used as fuel to provide energy recovery (Abdulhameed et al., 2022). It has been reported that 25–60 % of this waste is utilized in this manner (Akbas and Yuhana, 2021). However, alternative solutions are required to address environmental concerns while adhering to budget constraints (Abdulhameed et al., 2022).

Upcycling or better termed has been reported as an effective approach for producing value-added products (Fazli and Rodrigue, 2021). In recent years, the concept of circular economy has gained significant traction. It encompasses both sustainable production and

Table 3
Summary of Findings – Natural Fiber Reinforcement.

Natural Fiber	Form	Fabrication	Outcome	References
Water Hyacinth	Strands (10 mm)	Hot Compression Molded	30 % filler increased: 192.8 % Tensile Strength 167.8 % Flexural Strength ~700 % Breaking Energy	(Arivendan et al., 2022)
Water Hyacinth	Strands (N/A)	Hand Layup Assisted Compression	Acetate anhydride treatment resulted in the highest tensile strength. Alkaline treatment increased fiber surface roughness and caused increased air entrapment.	(Sulardjaka et al., 2023)
Water Hyacinth	Course Fiber Particle (<5 mm)	Hand Lay-up Assisted Compression	10 % filler increased: 13 % Tensile Strength 17 % flexural Strength	(Owen et al., 2022)
Oil Palm	Fibers (22 cm)	Hand Lay-up Assisted Compression	50 wt% filler decreased: 66.4 % Tensile Strength	(Suriani et al., 2021)
Oil Palm Fiber Pineapple Fibers	Strands (0.8–1 mm)	Hot Compression Molding	Effective tensile strength: 50 % treated PALF yielded 33.3 MPa Effective impact strength: 50 % treated OPF yielded 5.96 kJ/m^2 *Neat values were not presented	(Awad, 2022)
Oil Palm Empty Fruit Bunch Kenaf	Mats	Hand Lay-up Assisted Compression	Effective tensile strength: 50 wt% Kenaf yielded 84.32 MPa Effective breaking energy: 50 wt% OPEFB yielded 8.05 J *Neat values were not presented	(Hanan et al., 2020)

consumption models, aiming to extend product lifecycles and unlock the value potential of waste materials that would otherwise be discarded in a linear economy (Bocchi, 2024). The incorporation of waste rubber into polymeric materials is a particularly attractive solution because it leads to cheaper material costs and improved mechanical properties (Abdulhameed et al., 2022). Interestingly, the incorporation of rubber (Irez et al., 2019; Karabork, 2022) into thermoset matrices has been reported to enhance various mechanical properties. These properties included increased toughness, hardness, and wear resistance. Fig. 2B presents the composition of passenger car tires. The majority of tire rubber is made of synthetic rubber (styrene-butadiene rubber, butadiene rubber), followed by approximately 19 % natural rubber (Turkben et al., 2023).

Recently, Shahapurkar (2021) experimented with crumb rubber with an average size of 182.24 μm in an epoxy matrix. The composite was fabricated using an open mold casting method with varying concentrations of rubber (0, 10, 20, and 30 vol%) and degassed for 15 min. It was found that a higher volume of rubber (up to 30 %) enhanced fracture stress through toughening. The rubber particles not only assist with load transfer but also bridge the crack formed in the matrix prior to rupture and provide crack shielding. The incorporation of rubber particles in the load-bearing matrix increased filler-matrix bonding, thereby increasing the overall strength of the composites, facilitated by good dispersion, and the strength of the composite increased between 28 % and 44 %. That said, based on their stress–strain curves, all their composites (0–30 %) exhibited brittle failure behavior. The composite made with 30 % rubber content was the most effective in terms of tensile strength, tensile modulus, and specific strength. Finally, while the majority of their work was very detailed, specifics of the composite mixing parameters to reduce the formation of voids were not presented.

In 2023, Shahapurkar et al. (2023) further evaluated the impact and compressive properties of their composites. Rubber-reinforced epoxy composites were fabricated identically to their previous study, as mentioned above. The cured composites were cut into the required specified shapes in accordance with ASTM D4812 and ASTM D695 standards. It has been reported that increasing the rubber content enhances the material's resistance to impact but reduces its compressive strength. The increase in the impact property was attributed to the dissipation of mechanical energy by rubber particles. Unfortunately, Shahapurkar et al. (2023) did not directly clarify the reduction in compressive strength. Thus, the incorporation of rubber particles enhances the ability of the composite to absorb energy. The cavitation of rubber particles can cause stress concentration in the polymer matrix, promoting the formation of localized deformation zones and leading to premature fracture. Following a similar critique given to Arivendan et al. (2022), Shahapurkar (2021) and Shahapurkar et al. (2023) employed only three specimens for testing, falling short of the minimum requirement: five specimens, as outlined in ASTM D638 and ASTM D4812, and ten specimens for ASTM D695 as the fillers used are considered anisotropic (Erman et al., 2012). This limited sample size raises concerns about the representation of their findings and may not accurately represent the behavior with larger sample sizes.

Nguyen et al. (2022) experimented with different concentrations of waste tire rubber particles and investigated the mechanical, dynamic, and vibration response of the rubber-filled polymeric composites. In their study, tire particles and acrylonitrile–butadiene–styrene (ABS) copolymer thermoplastics <125 μm were utilized. Composites with up to 50 wt% rubber particles were fabricated in increments of 10 wt%. ABS pellets and rubber particles were mixed in a 1:1 ratio with 99.5 % acetone in a beaker. The mixture was left for at least 10 h at room temperature to form a slurry mixture. The mixture was then stirred for 15 min and left again for 10 h, and this process was repeated until all ABS was dissolved. Throughout this process, tin foil was used to cover the beaker tightly. The well-formed slurry was then spread over a large tray up to 2.54 mm thick) and placed inside a fume hood for at least 10 h to solidify. The dried composite was then blended, sieved through a 3 mm sieve, and further dried in an oven at 80 °C. The composite filament was extruded at 175 °C with an average diameter of 2.85 mm. Finally, a 3D printer was used to fabricate the composites in accordance with ASTM D638 Type 1. It was found that the tensile performance degraded with increasing rubber content. Neat ABS yielded a tensile strength of 37.3 MPa while 50 wt% obtained only 8 MPa, revealing a 78.6 % decrease. Nguyen et al. (2022) offered several factors for this behavior, including the presence of voids where voids reduce adhesive bonding between the particle and matrix as observed in the SEM analysis. Interestingly, it was observed that the inclusion of rubber at 30 wt% and higher altered the fracture pattern. With a lower content, the specimen failed in the transverse direction, whereas a higher content displayed a sawtooth pattern. The authors explained this as a sign of weak interfacial adhesion between the matrix and fillers, in combination with weak interlayer bonding. It was also found that the vibration-isolation capabilities improved with increasing rubber content. The overall damping ratio improved by approximately 260 % between the neat and 50 wt% filler. This was attributed to the dominant elastomeric and damping properties of rubber particles. Unfortunately, no further in-depth explanation was provided.

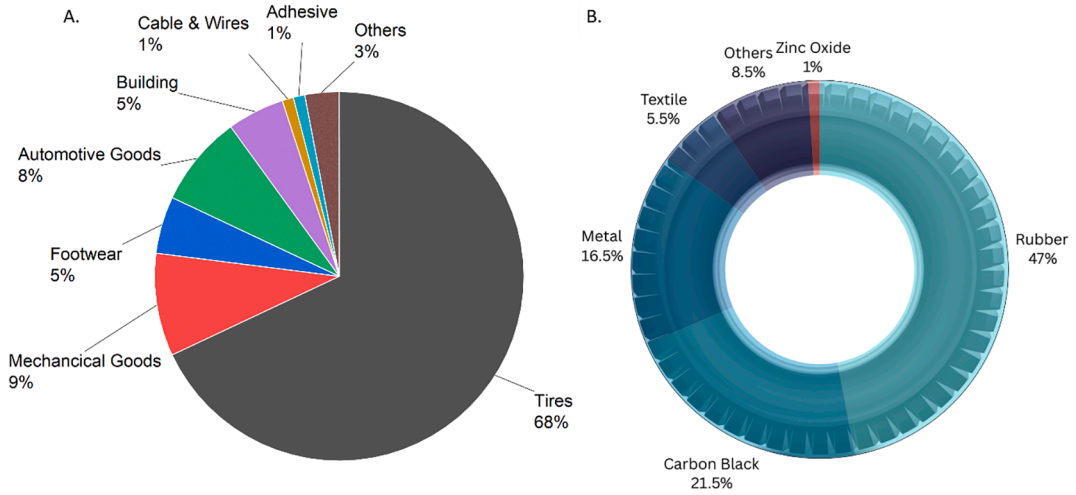

Fig. 2. A. Consumption of Rubber (Shivamurthy et al., 2019). B. Average Composition of a Passenger Car Tire (Landi et al., 2016).

Tamas-Benyei et al. (2019) placed more focus on the influence of tire-derived rubber particles on the impact strength of epoxy. In their work, the researchers procured rubber particles with an average size of 400 μm. These particles were added to epoxy at various filler loadings (0, 1, 2, and 5 wt%). The impact properties of the samples were tested under the ISO 179 standard, that is, the Charpy test. Tensile and flexural tests under ISO 527 and ISO 14125 standards were also conducted on the sample type with the highest impact strength. In terms of impact strength, the researchers' results showed that all composites exhibited enhanced impact properties, providing a maximum of 14 kJ/m^2 at 1 wt %, decreasing at higher loadings. Meanwhile, the neat values provided a strength of only 6 kJ/m^2. According to the researchers, the increase was likely due to the rubber particle bridging effect, although this effect and its connection to the impact strength were not elaborated further. The reduction from the increased filler loading was explained by the increased likelihood of rubber particles acting as weak points in the composite. In terms of tensile and flexural strength performance, 1 wt% filler loading weakened the material, from 38.11 MPa to 36.84 MPa for tensile strength, and 65.27 MPa to 52.08 MPa for flexural strength. The researchers attributed this to the rubber particles having weaker mechanical properties than epoxy. Among the papers reviewed, Tamas-Benyei et al. (2019) provided the most detailed impact-testing parameters by stating the pendulum energy, angle, and speed among other important details. However, the composite fabrication process and mixing parameters to disperse the fillers, such as speed and amplitude, are not listed.

Karabork (2022) experimented with tire rubber particles in an epoxy matrix to develop a novel composite coating. Two types of rubber powders were used: standard ground tire rubber and devulcanized ground tire rubber. Devulcanized rubber was obtained by subjecting the powder to 5 min of microwave treatment in a domestic microwave oven. Rubber powder (3 wt%) was first introduced with acetone, and then with epoxy resin. The mixture was then stirred using a mechanical stirrer and then kept in a vacuum oven for 10 min. The composite was then applied on galvanized steel substrates using a film applicator and allowed to cure for 24 h at room temperature, followed by a post-cure treatment for 2 h at 80 °C. It was found that the introduction of standard ground tire rubber improved the hardness value by 8.19 %, whereas the use of devulcanized ground tire rubber substantially reduced the hardness value by 58.5 %. Standard rubber particles were reported to inhibit the molecular mobility of the polymer chain, resulting in improved performance. On the other hand, the devulcanization of the rubber caused scission of S-S bonds within the crosslink network and degraded the main chain backbone of C-C and C-S bonds. This then affected the interaction of the devulcanization particles and epoxy matrix, resulting in a decrease in the mechanical performance. Additionally, it was found that the inclusion of rubber decreased the specific wear rate by 59 % for standard particles and 77.7 % for devulcanized particles compared with neat epoxy. The incorporation of rubber particles not only altered the wear mechanism from brittle to sticky but also reduced the surface roughness. Achieving a smoother surface goes beyond aesthetics and improved tribological properties; it also improves the fatigue strength and corrosion resistance of the product (Debnath et al., 2014). Lastly, based on the presented manuscript, the mixing speed, concentration of acetone, and its removal from the mixture were not known. It is worth noting that the presence of residual acetone alters the cross-linking process and degrades the mechanical properties, particularly the tensile properties (Loos et al., 2008).

Turkben et al. (2023) also investigated the effect of tire rubber and EPDM on the impact strength of epoxy. However, researchers have only investigated and compared the effects of both rubbers at a 30 wt% filler loading. From their experiments, it was found that both rubber types enhanced the impact strength. In the case of samples that used diluted epoxy as the matrix, the neat, tire-reinforced, and EPDM-reinforced samples had impact performance of ~3.5 J, ~7.8 J, and ~5.4 J, respectively. Evidently, tire-derived rubber led to greater enhancements compared to EPDM, and, according to the researchers, the improvements brought about by tire rubber were due to its inherent capabilities for energy absorption. Despite this, testing was not conducted on all matrix types, especially for samples that used standard, unblended, and undiluted epoxy. Turkben et al. (2023) did not provide an explanation for this.

The results of Turkben et al. (2023) differed from those commonly found in other studies. In their study, the influence of tires and EPDM rubber, which had a size range of <106 μm, on the mechanical properties of epoxy, diluted epoxy, and epoxy blends was compared. All the sample types were cured and tested for their tensile and impact properties according to ASTM D638 and ASTM D7136, respectively. Considering the samples that used standard bisphenol-A-type epoxy as their matrix, it was found that the loading of tire rubber led to higher tensile strengths, reaching maximum values of approximately 119 MPa at 20 wt%. The neat values reached only ~106 MPa. Alternatively, the loading of EPDM led to a maximum tensile strength of ~115 MPa at 10 wt%. Evidently, tire waste provided higher tensile strength values, albeit at higher filler loadings. Similar results were observed in samples that used epoxy blends as their matrix, wherein tire waste enhanced the tensile strength at a maximum filler loading of 20–30 wt%, whereas EPDM decreased the tensile strength regardless of the concentration used. According to researchers, EPDM weakened the composites because

of poor adhesion with the matrices and a higher void content. Meanwhile, the increases in tensile strength and Young's modulus in tire rubber reinforcement stemmed from the particles having a lower carbonate content compared to the EPDM. Lastly, the reduction in tensile strengths for both rubber types was attributed to the rubbers having a gel structure, which led to the occurrence of "stress condensation". However, the connection between the tensile strength and carbonate content, as well as the definition of "stress condensation" was not further elaborated, leaving ambiguity on why such changes in tensile strength occurred. Nevertheless, the work of Turkben et al. (2023) shows the possibility of rubber-enhancing composite tensile strength. The particle size used may have played a major role in providing such enhancements (Fazli and Rodrigue, 2021); hence, further studies focusing on the effect of rubber particle size should be conducted.

Nuzaimah et al. (2021) researched the effect of various chemical treatments on rubber-reinforced polymer composites. In their work, waste latex gloves were converted into rubber particles of size 0.85–1.70 mm via cryogenic grinding, and added to a polyester matrix. Four sample types were fabricated, all of which had 5 wt% rubber filler. The first type utilized untreated rubber, whereas the remaining three sample types involved a 2 h immersion in 10 % NaOH, 10 % H_2SO_4, and 5 % $KMnO_4$, after which they were rinsed and dried for 24 h at 60 °C prior to mixing. The tensile strength of the composites was tested according to ASTM D5083. From the results, NaOH treatment provided the greatest improvement in tensile strength, with a value of ~9.5 MPa. Meanwhile, the untreated samples provided a tensile strength of ~9.3 MPa, whereas the samples treated in H_2SO_4 and $KMnO_4$ had tensile strengths of ~8.4 MPa and ~9 MPa, respectively. According to researchers, NaOH treatment provided a higher tensile strength by generating a rougher particle surface, thereby improving the filler-matrix adhesion. The increased number and size of microcracks and micropores led to a greater area of contact between the matrix and filler, leading to greater stress transfer. On the other hand, researchers explained that H_2SO_4 and $KMnO_4$ treated composites exhibited inferior strength owing to the presence of residual acid on the particles, leading to increased susceptibility to moisture attacks and accelerated aging of particles. Despite these results, Nuzaimah et al. (2021) tests on the contact angle of the samples generate uncertainty regarding the validity of such explanations. First, the researchers stated that a reduction in the contact angle indicated a higher wettability and hydrophilicity of the particles, with higher wettability leading to improved polyester adherence on the rubber surface. However, while NaOH had a higher contact angle than $KMnO_4$, the $KMnO_4$-treated samples exhibited a lower tensile strength. Furthermore, previous studies have claimed that incompatibility between hydrophilic fillers and hydrophobic matrices is a major contributor to the decrease in material strength (Li et al., 2015), whereas in this study, increased particle hydrophilicity was associated with increased tensile strength. Hence, further studies on the relationship between the contact angle, hydrophilicity, and fiber–matrix compatibility would contribute to the overall body of knowledge. The results of the reviewed studies in this subchapter are summarized in Table 4.

With the introduction of higher percentages of tire rubber particles to polymer matrix, Shahapurkar (2021); Shahapurkar et al. (2023) and Turkben et al. (2023) reported improvements in both tensile and impact resistance performance, in a similar manner. In contrast, Tamas-Benyei et al. (2019) reported a significant increase in the impact strength with only 1 wt% tire rubber. However, a decrease in the tensile strength was observed in their study, as also evidenced by Nguyen et al. (2022). Based on the above results, the influence of particle size on the reinforcement remains unclear. The difference in results may be attributed to tire rubber particle sizes, as Nguyen et al. (2022) utilized tire particles with an average size of 400 μm, while other researchers used particles under an average size of 182.24 μm. However, this does not correlate with the findings of Tamas-Benyei et al. (2019). Further studies are needed to elucidate the relationship between particle size and reinforcing potential on both tensile and impact properties. Interestingly, Karabork (2022) found that the hardness and wear resistance of a composite improved in the presence of tire rubber particles. Notably, Nuzaimah et al. (2021) highlighted the potential for further enhancement via the surface treatment/pretreatment of rubber particles.

Table 4
Summary of Findings – Rubber Reinforcement.

Fillers	Form	Fabrication	Outcome	References
Tire Rubber	Particle (182.24 μm average)	Open Mold Casting	30 vol% filler increased: 44 % Tensile Strength	(Shahapurkar, 2021)
			30 vol% filler increased: 216.7 % Breaking Energy −56 % Compressive Strength	(Shahapurkar et al., 2023)
Tire Rubber	Particle (<125 μm)	3D Printed	50 wt% filler increased: −79 % Tensile Strength 260 % Damping Properties	(Karabork, 2022)
Tire Rubber	Particles (400 μm average)	Not Listed	1 wt% filler loading increased: 133 % Impact Strength 5 wt% filler loading decreased: 3.33 % Tensile Strength	(Tamas-Benyei et al., 2019)
Tire Rubber	Particle (<45 μm)	Film Applicator	3 wt% filler loading (standard) increased: 8.19 % Hardness 59 % Wear Resistance Surface Finish	(Karabork, 2022)
Tire Rubber EPDM	Particles (<106 μm)	Open Mold Casting	20 wt% tire filler loading increased: 12.3 % Tensile Strength 10 wt% EPDM filler loading increased: 8.5 % Tensile Strength 30 wt% tire filler loading increased: 123 % Breaking Energy 30 wt% EPDM increased: 54.3 % Breaking Energy *Impact tests used diluted epoxy matrix. Tensile tests used a standard epoxy matrix.	(Turkben et al., 2023)
Latex Rubber	Particles (Majority 0.85–1.7 mm)	Open Mold Casting	10 % NaOH increased: 2.15 % Tensile Strength 5 % $KMnO_4$ decreased: 3.22 % Tensile strength 10 % H_2SO_4 decreased: 9.65 % Tensile strength	(Nuzaimah et al., 2021)

4. Fiber – Rubber hybrid reinforced polymer composites

Recently, interest in hybridizing composite components has grown significantly, driven by their potential benefits (Bhowmik et al., 2024). Hybrid composites exhibit superior mechanical behavior compared with traditional natural fiber-based composites (Rashid et al., 2024). The incorporation of natural fibers and rubber individually in polymer matrices has garnered the interest of several researchers, including the authors. The hybridization of natural fibers and rubber can provide further enhancement opportunities. As evidenced by the limited research entries in Fig. 1, this hybridized material remains underexplored and requires further exploration. The following section presents recent studies related to this combination of composites.

Literature on hybridizing natural fibers with rubber in polymer composites is also limited, particularly with rubber particle thermoset matrices. In 2023, Shaik and Sankara Subramanian (2023) developed a hybrid abaca–rubber layered composite and investigated its response to a low-velocity conically shaped drop-weight test. The abaca fiber mat and rubber plies were stacked together, with the fiber covering both sides. Epoxy resin was applied to each layer, placed in a mold, and allowed to cure for 24 h while being subjected to a pressure of 0.055 kgf/cm^2. In their study, a 3.5 kg impactor was raised to 300 mm to achieve an impact velocity of 2.42 m/s, resulting in an impact force of 10.24 J. It was revealed that the addition of a rubber ply reduced the energy absorption ratio by 11.07 % and energy back to the impactor by 6.7 %. The impactor penetrated the abaca layer and encountered the rubber layer. Owing to the elastic nature of rubber, it was able to absorb strain energy. The addition of rubber layers reduced the hybrid composite failure mode by eliminating fiber–matrix debonding. However, other failure mechanisms such as fiber breakage, pullout, and matrix cracking remain. The literature presented in their work showed that fiber treatment can provide better mechanical reinforcement. Interestingly, Shaik and Sankara Subramanian (2023) did not employ any treatment process in their study. This raises questions regarding the potential for further improvement, particularly the process required to maximize the potential of this hybrid composite.

Recently, Hasanuddin et al. (2023) evaluated the mechanical properties of hybrid laminated epoxy composites comprising sodium hydroxide-treated coir, alumina/glass fiber/synthetic fiber/rubber sheets. The coir fibers were treated with 5 % NaOH solution for 10 min at 80 °C. The fibers were then blended for 10 min at 2000 rpm to induce fibrillation. The hybrid laminated composites were then fabricated using the hand lay-up assisted compression method. It was reported that the addition of fillers improved the mechanical strength for both tensile and impact by up to 183.3 % and 475.0 %, respectively. The combination of all fillers was reported to have a tensile strength of 76.03 MPa and an impact strength of 58.02 kJ/m^2. The various fillers played a significant role in the impact resistance, as they served as a stress transfer mechanism and interacted with the formation of cracks within the polymer matrix. It was also established that the impact strength performance of the composite was directly proportional to the tensile strength. Despite presenting their fractographic analysis, it was insufficient to understand the fracture behavior of the addition of fillers as it was only limited to one variation of the composite (coir + alumina + E-glass + Synthetic fabric + rubber sheet). Furthermore, the dominant failure mechanism was observed to be delamination between the rubber and matrix, indicating that both phases had poor interfacial bonding. Unsurprisingly, the developed composite exhibited brittle behavior, where failure patterns of delamination and fiber breakage were observed. Considering the challenges of fabricating complex laminated composites, it is difficult to achieve a standard thickness without its concentration and number of layers. The macroscopic image included in the work of Hasanuddin et al. (2023) suggests a thicker specimen despite the lack of scale. Nevertheless, it is unclear how they achieved the required thickness of 10 mm for flexural testing, water absorption, and thickness testing, and 12.7 mm for impact testing. This ambiguity raises concerns regarding their results and highlights the need for a clear and detailed description of their processing methods to meet the respective standard.

Aiza Jaafar et al. (2021) investigated the mechanical properties of toughened epoxy/silica/kenaf hybrid composite with the use of various contents of liquid rubber. Kenaf fibers were treated with 3 % NaOH solution at room temperature for 24 h. It was later subjected to two drying stages at room temperature for 48 h, and then oven dried at 100 °C for 6 h. In their investigation, composites were fabricated via the hand lay-up method, in which the epoxy matrix was mixed with fillers using a blender for 20 min, followed by 100 mbar of vacuum before being layered on a treated kenaf fiber mat using a paint roller. The layered composites were cured in two separate curing stages at 80 °C and then at 110 °C for 2 h each time. It was found that the impact strength of neat epoxy generally increased with a higher rubber content, revealing an effective strength of 13.47 kJ/m^2 at 5 phr. At lower contents (between 1 and 5 phr), the rubber particles were reported to be well dispersed. However, at higher contents, aggerate was formed, which increased the rubber-to-rubber contact instead of the rubber-to-matrix interaction, thus reducing the efficiency of stress transfer. The impact strength of the composite increased by 146 % with the addition of the silica powder. This was attributed to the large surface area and smooth nonporous surface of silica, which enhanced the physical interfacial contact with the matrix. However, the strength decreased with the introduction of kenaf fibers. This disagrees with Turkben et al. (2023), who claimed that silica powder increases adhesion bonding and introduces energy-absorption mechanics. Aiza Jaafar et al. (2021) justified this result with poor fiber adhesion with the epoxy matrix, even though the fibers used were treated with 3 % sodium hydroxide. Lastly, it was identified that combining 3 phr liquid rubber alongside 20 phr silica powder and 12.8 wt% kenaf fiber resulted in the highest impact strength and flexural strength at 13.83 kJ/m^2 and 62.2 MPa, respectively. Their work also pointed out that the addition of rubber reduces the stiffness of the material owing to a possible reduction in the cross-linking density of the polymer composite. Such hybridization not only reduces the dependency on the polymeric material but also improves its mechanical performance.

Yogeshwaran et al. (2020) fabricated unique layered composites using waste tire particles alongside jute and abaca fibers. The fibers were treated with sodium chloride solution for 5 h, whereas the rubber particles were treated with sulfuric acid for 1 min. Treatment of fiber and rubber particles yielded higher mechanical strength performance in terms of tensile and impact performance compared with untreated fibers by up to 27.3 % and 12.5 %, respectively. The authors attributed this to the treatment process, which improves the adhesive bonding between the filler and matrix by removing impurities. However, upon inspecting their methodology section, details regarding the introduction, amount, and size of the rubber particles still need to be presented. Additionally, micrographs were not shown to elucidate the dispersion and interaction between the rubber particles, fibers, and matrix. Finally, although the authors highlighted that three specimens were assessed using ASTM D256, it is unknown which method was used because there are four different test methods (D20, xxxx). The findings of the aforementioned studies in this subchapter are summarized in Table 5.

7. Future outlook of natural fiber – rubber reinforced polymer composites

Based on the multiple studies presented above, it can be concluded that the combination of natural fiber and rubber into polymer matrices can provide an opportunity to enhance mechanical properties, particularly impact strength. This also echoes the prospects raised by Hasan et al. (2022) through hybridization of reinforcements. Considering another approach, research conducted by Maurya et al. (2021) established that the impact strength of NFRCs does not solely depend on the fiber reinforcement but also on the polymer matrix used. Appropriate treatment of the filler will have to be considered, as excellent bonding

Table 5
Summary of Findings – Fiber and Rubber Reinforcement.

Fillers	Form	Fabrication	Outcome	References
Abaca + Rubber	Mat	Hand Lay-up	Two Rubber Layer Improvements: 11.07 % Energy Absorption Ratio 10 % Energy Loss Percentage	(Shaik and Sankara Subramanian, 2023)
Coir Fiber + Alumina + E-Glass + Synthetic Fabric + Rubber	Hybrid (Mat + Particle)	Hand Lay-up Assisted Compression	Coir Fiber, Alumina, E-Glass, Synthetic Fabric and Rubber Increased: 183.3 % Tensile Strength 475.0 % Impact Strength	(Hasanuddin et al., 2023)
Kenaf Fiber + Silica + Rubber	Hybrid (Mat + Particle)	Hand Lay-up	Effective Impact and Flexural Strength: 12.8 wt% of Kenaf, 20 phr of Silica, and 3 phr of Rubber yielded 13.83 kJ/m^2 and 62.2 MPa *Neat values were not presented	(Aiza Jaafar et al., 2021)
Jute + Abaca + Tire Rubber	Hybrid (Fiber + Particle)	Hand Lay-up Assisted Compression	Effective Tensile Strength and Impact Performance: 30:50:20 wt% of Jute, Abaca, and Tire rubber yielded 62.82 MPa and 16 J *Neat values were not presented	(Yogeshwaran et al., 2020)

leads to catastrophic brittle fracture, whereas poor interaction leads to fiber pullout (Maurya and Manik, 2023); resulting in poorer impact resistance capability. In essence, a multitude of considerations is required to develop high-quality composite materials. The challenges in developing effective NFRCs are not only in the compatibility and distribution of filler materials and processing parameters but also in balancing the filler–matrix interface.

While a number of researchers have stated that the incorporation of natural fiber reinforcement into polymer matrices has the potential to replace their traditional synthetic counterparts, it is generally compared to synthetic fillers in fiber and mat forms. The strength of a composite is predominantly dependent on the characteristics of the unreinforced matrix (Wong, 2022) and the form of the filler material.

Table 6 provides a short reference outlining the tensile strength and impact performance of various epoxy-based composites reinforced by fillers in varying forms. Research in this area should consider comparing the reinforcing potential of fillers with that of a neat matrix, establishing a clear point of reference. However, the lack of standardized specifications and performance data for fiber-reinforced composites impedes their widespread adoption and further development to replace traditional industrial materials (Saeedi et al., 2024).

The substitution of synthetic fibers with bio-based fillers can produce a relatively low environmental and economic impact, with comparable mechanical performance (Haylock and Rosentrater, 2018). However, multiple limitations in the field of composite research still exist, particularly in optimizing the filler size and loading (Samant et al., 2023), unknown long-term durability, unknown long-term reliability, and most importantly, its poor effective filler matrix interface (Awad, 2022; Jagadeesh et al., 2022; Zhao, 2022). Furthermore, the effective dispersion of fillers remains a significant hurdle (Lu et al., 2023). These constraints hinder the use of these materials in broader applications.

For sustainable production and consumption, emerging green materials need to reduce their environmental impact and be economically competitive with their synthetic counterparts. Yusof et al. (2020) and Khoshnava et al. (2018) stated that replacing synthetic composites with natural fibers reduces damage to the environment and human health. To evaluate these environmental burdens throughout a product's life, life cycle assessment (LCA) can be employed (Peake et al., 2016; Leng et al., 2018). According to Schmidt and Beyer (1998), manufacturing hemp polymer composites offers significant environmental benefits over the use of glass fibers. It resulted in a net benefit of 88.9 MJ cumulative energy demand, 8.18 kg of CO_2 emissions, 0.0564 kg of SO_2 emissions, and 0.0183 kg of NO_3 emissions per 2.6 kg of material produced under the basic scenario. Similarly, Wötzel et al. (1999) discovered that natural fiber epoxy composites required 45 % less energy and produced lower gas emissions (CO_2, SO_2, and CO) than ABS copolymers. However, there is insufficient knowledge of the durability of natural fiber composites over time, particularly their service life performance (Ead et al., 2021).

Furthermore, natural fibers offer a clear advantage in terms of cost. Based on the studies of Suriani (2021) and Ho (2012), the average cost per ton of natural fibers (USD 1394) is significantly lower than that of synthetic fibers (USD 8745). This translates into a cost difference of more than five times. Furthermore, a cost analysis conducted by d'Almeida (2001) indicated that natural fiber composites compete with glass fiber composites when considering cost-effectiveness. However, they also stated that high-strength fibers (tensile strength greater than 600 MPa) are required for a competitive advantage.

Techno-economic assessments have gained popularity as standard methodologies that help translate data such as commercial production processes into useful metrics for comparison (Faber et al., 2021; Thomassen et al., 2019). While assessments conducted by Haylock and Rosentrater (2018) found that bio-based fillers displayed mechanical performance comparable to glass fibers while producing a relatively lower economic impact, further investigations are required, particularly regarding the method of fabrication. Currently, limited research has been conducted to assess the value of hybridized natural fibers and MSW-material-hybridized reinforced polymer composites.

The effects of accelerated short-term aging on OPEFB composites were recently reported by Valle (2023). Their research found that the tensile strength increased after aging owing to nonhomogeneous fiber–matrix interaction, reducing the thickness of the exposed sample. However, impact strength was not considered. The durability of the

Table 6
Mechanical Performance of Epoxy-based Composites.

Fillers		Form	Tensile Strength (MPa)	Impact Performance	References
Synthetic	Glass (5 wt%)	Particle	25.1 (ISO 14125)	Not Studied	(Ku and Wong, 2012)
	Glass + Carbon (2 layer + 2 wt%)	Layer + Particle	~33 (N/A)	~160 J/m (N/A)	(Soni et al., 2018)
	Glass	Layer	~99 (ASTM D638)	~6.5 KJ/m^2 (ASTM D256)	(Adekomaya and Adama, 2017)
	Glass (12 wt%)	Fiber	~93 (ASTM D3039)	4 (J/m) (N/A)	(Prasad et al., 2023)
Natural/ Rubber	Water Hyacinth (10 wt%)	Fiber	36.2–41.4 (ASTM D638)	120.1–128.4 kJ/m^2 (ASTM D6110)	(Owen et al., 2022)
	Tire Rubber (10–30 wt%)	Particle	98–120 (ASTM D638)	~5.5–~8 J (ASTM D7136)	(Turkben et al., 2023)
	JuteAbaca Tire Rubber	Fiber + Particle	40.83–79.96 (ASTM D638)	13–18 J (ASTM D256)	(Yogeshwaran et al., 2020)

composite over time under various environmental conditions is essential to achieve commercial functional properties. Exposure to solar radiation, air, oxygen, rain, temperature, and biotic factors causes material degradation (Badji et al., 2018). To assess the performance of a technological solution, real-world impacts in real-world environments must be assessed by considering the actual behavior and performance of the material, including its long-term durability (Taurino et al., 2023; Hill, 2021; Faheed, 2024). Exposure to harsh environments is an essential issue for the safety and reliability of composites, particularly in the marine industry and environment (Massou et al., 2023).

Developing mechanically effective NFRCs with low environmental impacts and costs would contribute immensely to global green industries. It can also minimize the greenhouse effect, which requires much attention (Brailson Mansingh et al., 2023). This field of study will also contribute directly to the United Nations' sustainable development goals to achieve sustainable, healthy living, and a clean and safe environment. These are not limited to Goal 1 (no poverty), Goal 9 (industry, innovation, and infrastructure), Goal 11 (sustainable cities and societies), Goal 12 (responsible production and consumption of material), and Goal 13 (climate action).

6. Conclusions

Recently, the manufacturing industry has been driving towards higher sustainability because of tighter waste regulations and demands to improve cost-effectiveness. The materials transition agenda aims to substitute emission-intensive materials and incorporate emission-reduction efforts into goods and applications. This manuscript explored recent advancements in natural fiber, rubber, & natural fiber-rubber hybrid polymer composites and demonstrated their potential to enhance mechanical performances. Notably, it was established that the incorporation of natural fibers (strands and coarse particle form), between 10 – 30 wt%, tensile strength, flexural strength, and impact performance was significantly enhanced. However, the incorporation of rubber particles below 30wt%/30 vol% remains inconclusive, with conflicting results reported concerning both tensile and impact performances. Additional studies will be required to elucidate the relationship between particle size and mechanical reinforcing potential. Furthermore, the reinforcement potential of the various composites was outlined and compared with the traditional synthetic counterparts, providing valuable insights for material comparison. It was also established that the production of natural fiber composites requires lower energy consumption and emits lower gas emissions while offering a significant economic advantage on a weight basis. The valorization of biomass and waste rubber offers a promising solution to our waste management challenges, with the potential to generate economic benefits while mitigating detrimental effects on ecosystems; further supporting the concept of a circular economy. Research opportunities exist, particularly investigating field performance, service life performance, and techno-economic assessments of natural-fiber-based composite materials. Further research into toughening brittle polymer matrices without significantly compromising other mechanical properties through hybridization warrants further consideration and attention. Overall, this review paper underscores the untapped potential of readily available natural fibers and discarded waste rubber, necessitating further investigation and consideration in this exciting field.

CRediT authorship contribution statement

Dominick Wong: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Gio Fabito:** Writing – original draft, Investigation. **Sujan Debnath:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Mahmood Anwar:** Writing – review & editing, Supervision. **Ian J. Davies:** Writing – review & editing, Supervision.

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.

Data availability

Data will be made available on request.

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