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Review Article

Biopolymer Composite Materials in Oil and Gas Sector

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In the oil and gas industry, the demand for alternative materials is rising due to corrosion and the desire to reduce costs through weight reduction. Polymer composites are gaining attention for their corrosion resistance, favourable strength-to-weight ratio, and cost-effectiveness. The biopolymer composite is projected to have an output worth $4.95 billion between 2021 and 2025 and growth at a 5.38% compound annual growth rate. This review focuses on exploring the potential of natural fibres as reinforcement for biofibre polymer composite pipes in oil and gas, highlighting their ecofriendliness, biodegradability, and cost-efficiency. The paper assesses biopolymer composite pipes' development, challenges, and applications, particularly those using continuous basalt and banana fibres. While basalt fibre has found field applications, banana fibre-reinforced polymer composites are still in the early research stages. Despite significant oil and gas industry players already endorsing polymer composites, further research is needed for biopolymer composites to address challenges like compatibility, environmental impact, standardisation, long-term durability, production processes, and regulatory acceptance. Advancing biocomposite research and exploring new research opportunities are essential for engineering advancements and advanced materials.

1. Introduction

A polymer matrix composite is a continuous phase containing polymer as a matrix bound by fibre as reinforcement or different constituents mixed to obtain a defined property for specific performance. Most composite materials have two components, matrix and reinforcement, and when adequately explored, give properties that are not possible with the individual material [1]. The reinforcement is from either synthetic or natural fibres. The typical matrix materials include thermosets, thermoplastics, metals, and ceramics. The Polymer matrix composite material uses thermoset or thermoplastic resin and fibres as reinforcement. Usually, the fibre has higher strength and modulus than the matrix material, which enables fibres to bear the component [2]. The most important aspect must be good adhesion between the matrix and the fibre to bond them together for efficient load transfer between them [2, 3]. The reinforcing fibres modify the characteristics of the composite, such as fracture toughness, tensile strength, and stiffness [3]. Hassani et al. reported that polymer properties are also improved using other fillers, such as silica clay, to produce composite for oil and gas applications. The modified materials using this filler have demonstrated extraordinary properties, which lead to improve thermal and flame retardant, physical and mechanical, barrier, coating, electrical, permeability, and absorbent properties and can be used instead of with traditional materials [4]. Ajayi et al. [5] observed that adding clay to a polymer composite improves the strength. Furthermore, studies have shown that the properties of fibre-reinforced plastic depend on constituents' properties, the number of various segments, the direction, the type of bonding between the matrix and reinforcements, and the size, shape, and distribution of the dispersed phase [1].

The recognition of polymer composite materials in the petroleum sector is increasing because of their corrosion resistance, good strength-to-weight ratio, and reduced cost of handling [6]. Growth in the use of polymer composites and their acceptance in oil and gas has gotten to a stage where they are now threatening traditional materials like carbon steel because the products from nonrenewable sources lead to the depletion of nonrenewable sources, environmental impact, greenhouse emissions, and an increase of nonbiodegradable waste on earth [7]. Many studies [1–3], including Wambua et al. [8], reported that natural fibre composites are favoured compared to synthetic fibre. Biofibre has several advantages over synthetic reinforcing materials, such as low density, flexibility during processing, low environmental impact, good strength-to-weight ratio, biodegradability, low-cost ease of processing, and ecologically friendly compared to synthetic fibre [9, 10]. Biofibre can replace synthetic fibre as reinforcement material in fibre-reinforced polymeric composites because of the mentioned advantages for engineering applications [7, 11]. Natural fibres are abundantly available worldwide, especially in developing countries like Nigeria, which produces about 2,780 metric tons of plantain yearly [12]. The Department of Agriculture, Forestry and Fisheries of the Republic of South Africa reported that bananas contributed 51% of the R2.6 billion value of subtropical fruits produced in the country [13].

Research has shown that India is currently the world's largest producer of bananas, with China, Indonesia, and Brazil trailing close behind. The authors estimated that global banana production should reach 135 million tons by 2028, growing at an annual rate of 1.5% [14]. After harvesting the fruit from the banana plant, the farmer cuts the pseudostem, which becomes waste because it is unusable for the next harvest [15]. Interesting is the availability of the pseudostem, which is the fibre source and can be used for industrial applications. Although natural fibres are a viable option, Ihueze et al. [16] found it essential to evaluate the cost-effectiveness of plantain fibre particles for industrial implementation. This assessment will be invaluable in deciding if it can be used in the industry. The result shows that fibre is inexpensive regarding basic materials and commercially viable with less operational cost. To encourage natural fibre application for the industrial sector, the US Department of Agriculture and the US Department of Energy have a set target of 10% of materials to be basic raw materials for industries in 2020 and to increase to 50% by 2050 [17]. Also, an interesting aspect is the market growth of polymer composite in the oil and gas industry, thus dominated by a few established stakeholders. They are focusing on developing new products because of challenging global requirements. Hence, these firms are employing a range of innovations in organic and inorganic techniques to develop different polymer composite materials for the oil and gas sector market to keep hold of the market [18].

The determination to reduce the cost and improve the quality and structural performance of composites, coupled with evolving developments in polymer and research in advanced polymer composites, is the key factor supporting the enhanced use of fibre-reinforced polymer materials. There is a paradigm shift from nonbiodegradable to novel and sustainable materials that are biodegradable and environmentally friendly as alternatives to petroleum-based products. It provides value addition to waste products of nonfood farms for engineering applications and forms a part of local content development in the sector. Moreover, the review considers the application of rigid and spoolable pipes as the focus. Consequently, look at research efforts, development, potential, and challenges of using natural fibre in producing pipes for oil and gas applications. The research did not consider other areas of application of organic materials in oil and gas, like drilling fluid.

2. Study Background

Carbon steel, the dominant pipe in the offshore industry, is heavy and susceptible to corrosion, creating significant challenges in handling, especially in an offshore environment. The weight of steel piping is a factor in the high costs associated with offshore construction. Polymer composite materials have corrosion elimination and weight reduction advantages [6]. In 1986, the UK Government funded an Offshore Energy Technology Board due to the increasing need for cost cutting within the offshore oil industry. This board encouraged manufacturers to use lightweight materials to reduce overall weight and associated costs [18]. Another review on the technology gap of composite materials in the UK oil and gas industry carried out in 2007, as reported by Martin [19], showed that there were achievements in overcoming the barriers and that opportunities exist for the development of new fibre-reinforced polymer composite for the oil and gas sector. According to NOV [20], composite system saved them more than 700 tons in weight to fix a platform in the North Sea. It has shown the cost savings involved in using polymer composite. New materials can offer many advantages, but with potential challenges, Houghton [18] observed that the absence of adequate engineering documentation had significantly inhibited the use of GRP in offshore oil industry projects. Hence, it is essential to provide thorough performance documentation based on standard safety and not only on cost acceptable by the regulatory and certifying authorities before field application.

Biopolymers are polymers produced from plants, animals, or microbes. Biofibres offer several benefits over synthetic fibres since they are available in large quantities as residual and inexpensive agricultural waste. Furthermore, biofibre composites have environmental advantages, such as reduced dependence on nonrenewable material sources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and end-of-life biodegradability of components [21]. Biofibres are categorised into animal and plant fibres, with most animal fibres obtained from proteins, while plant fibres are from cellulose. The sources of animal fibres are mostly animal hair, bird feathers, and silk [22]. Various sources provide plant fibres such as shelled seeds, leftover crop stalks, leaves, and roots. These fibres are made up of cellulose, hemicelluloses, lignin, pectin, and wax. Among these constituents, cellulose is the strongest and stiffest. It has a semicrystalline polysaccharide and a large number of hydroxyl groups, which make the fibres hydrophilic. The proportion and percentage of fibres differ from plant to plant and are also distinct in various parts of the same plant [23, 24]. Figure 1 shows the classification of natural fibre.

Despite the variability in natural fibre properties, optimised mechanical and chemical processing tends to enhance fibre characteristics and matrix-fibre adhesion for a suitable application. However, a notable disadvantage of lignocellulosic fibres as reinforcements is their polarity, making them

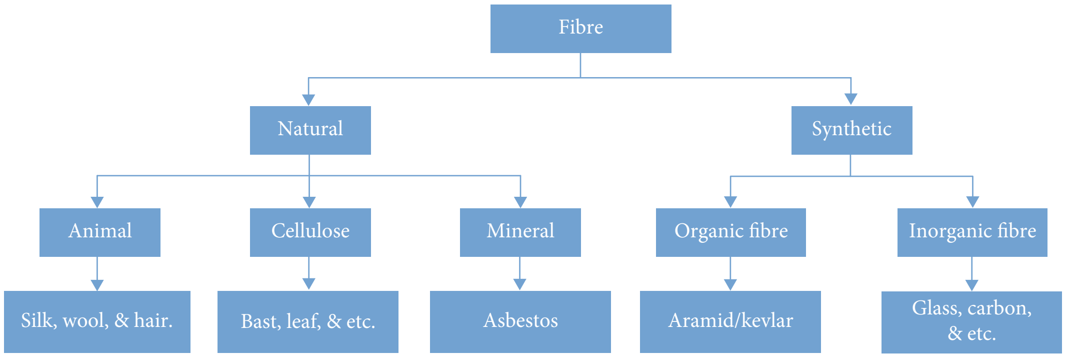


Figure 1: Classification of fibre [25].

incompatible with hydrophobic thermoplastic matrix because the fibres are hydrophilic while the matrix is hydrophobic. This incompatibility results in poor interfacial bonding between the fibres and the matrix. It leads to impaired composites' mechanical properties [26]. It also has certain limitations, as its nonhomogeneous fibre structure is susceptible to microbial attacks and rotting, and its dimensional instability, degradation, and ageing are restricted [27]. This defect can be remedied by chemical modification of fibres to make them less hydrophilic and improve adhesion between the matrix material and the fibres to bond them firmly. Researchers have carried out many investigations on the mechanical, chemical, and coupling treatment of natural fibre to improve and get the best qualities of natural fibre for field applications [22, 28–31]. The tensile strength and modulus of the composite produced with maleate polyethene were reported to give stronger interfacial bonding between the filler and matrix polymer [32]. Ibrahim et al. [33] reported that the chemical treatment of banana fibre using an alkaline treatment for reinforcement with HDPE has enhanced fibre/matrix adherence and improved mechanical properties. The chemical modification and coupling agent have a synergic effect on the properties of the composite. Moreover, reinforced polypropylene composites that went through alkali treatment and subsequent treatment by three-amino propyltriethoxysilane significantly improved the tensile and flexural properties of the composite [34].

The strength and modulus of fibre are often much higher than the matrix material. This property gives the fibre load-bearing capacity [35]. However, there must be good adhesion between the matrix material and the fibres to bond them firmly. The matrix transfers some of the applied stress to the particles, which bear a part of the load; this makes the performance of composite materials depend on fibre and matrix, and the interface between them directly impacts the performance of composite materials [36]. Their research has demonstrated that natural fibre surface modification improved adhesion between the fibre surface and the polymer matrix, eventually improving the physicomechanical and thermochemical properties of the NFPCs. Reinforcement may come either as fibre or particle. Also, depending on the length-to-diameter ratio, it may be continuous or discontinuous in fibre form. Fibre reinforcement commonly assumes a woven or nonwoven arrangement [37]. Today, researchers, technocrats, and companies are making efforts to optimise the process of biofibre extraction, such as the development of decorating machines as well as mechanical chemical modifications, to enhance fibre quality production and quantity for industrial applications to reduce environmental issues.

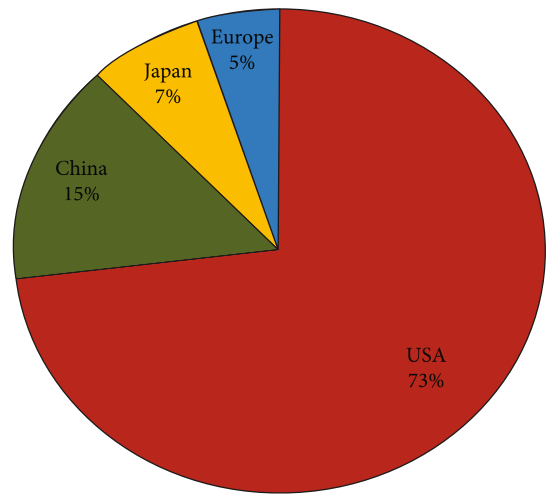


Figure 2: Countries' use of natural fibre thermoplastic composites [9].

Figure 2 represents the natural fibre thermoplastic composite used in some developed countries.

Currently, most fibres used in producing polymer composites for oil and gas applications are synthetic, such as glass and carbon fibres. As mentioned in Section 1 earlier, nonrenewable sources lead to the depletion of nonrenewable sources. Therefore, there is a need for a paradigm shift to biopolymer composites that could be fully or partially biodegradable and reduce the dependency on scarce fossil resources and greenhouse gas emissions. Additionally, it presents the accomplishments that have propelled the initial implementation of polymer composite materials in the oil and gas sector.

3. Natural Fibre-Reinforced Polymer Composite in Oil and Gas

Numerous studies have been conducted on using natural fibre-reinforced polymer composite in the marine industry; banana fibre is promising and has received attention because of its ability to withstand seawater and buoyancy. The fibre has helped the maritime sector produce boats and yachts

Figure 3: Biopolymer composite pipe [46].

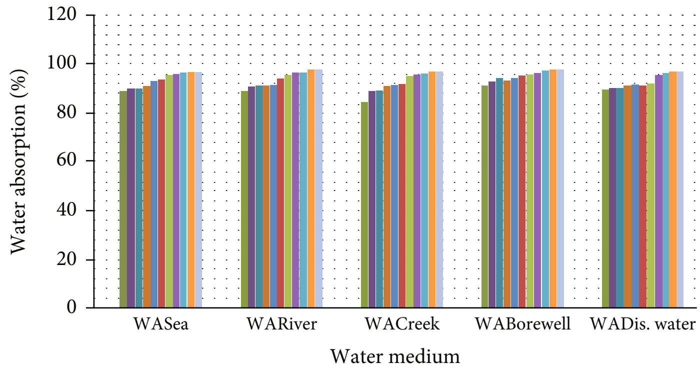
[15]. Karim et al. [38] reviewed the processing parameters and application of fibre-reinforced polymers (FRPs) in the petroleum and natural gas industries, and they recommended natural fibres for industrial applications due to the diminishing of nonrenewable and the need to focus research on the production of FRPs from biodegradable natural fibre. Natural fibres have a lower density of less than 1.6 g/cm^3 than glass fibre, approximately 2.5 g/cm^3, which ensures the production of lighter composites [39].

Among inorganic fibres, basalt fibre is receiving the attention of researchers for oil and gas applications. Continuous basalt fibre (CBF) is an inorganic, nonmetallic fibre obtained from basalt ore that produces polymer composite pipe. CBF has excellent mechanical properties, thermal stability, chemical resistance, and low moisture absorption compared to glass fibre [40]. CBF finds many applications, including reinforcing polymers for oil pipes because of its good corrosion resistance and designability with no need for thermal insulation and anticorrosion treatments due to its strong thermal and chemical stability, which can reduce the maintenance cost and prolong the service life [41]. Yang et al. [42] studied basalt fibre's application status and prospects in the oil industry. They reported that many countries have deployed CBF pipes in casing, tubing, and ground pipelines. The pipe has proven technical field applications. The data show that the BF oil pipeline can be used for 50 years at 20°C, and its corrosion degree is less than 5%, as reported by [43]. In a study conducted by Miao et al. [43], they observed electrostatic changes in fibre polymer composite. They proposed coating basalt fibre polymer pipes with acidified multiwalled nanotubes and epoxy resin to make the fibre conductive and improve its mechanical properties. The conductive property would protect the material from the electrostatic effect, which is essential in transporting oil. The industrial development of CBF is majorly in three countries, namely, Ukraine, Russia, and China, using the pool klin method as the primary production. They recommended optimisation of the production method to meet demand [40]. Market and Research [44] forecasts the market for basalt fibre to increase over the following years. Because of government initiatives and environmental laws on using greenhouse gas emission-free materials like basalt fibre, market players need to invest in research and development of basalt fibre.

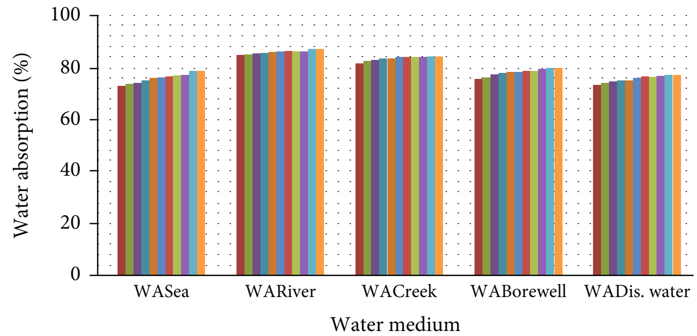
Deepa and Ramesh [45] demonstrated the opportunities for new and existing applications of banana fibre as a drive for agricultural business and value chain addition to banana cultivation with no environmental impact. In this regard, many researchers are exploring banana fibre to develop biopolymer composite pipes. Ihueze et al. [29] developed a biocomposite pipe for moderate-pressure application in oil and gas using plantain fibre particles with HDPE resin, depicted in Figure 3.

The results obtained in this study by Ihueze et al. showed that two factors might hinder the production of natural fibre composites for industrial applications [47]. The first factor is that the strength of natural fibre composites is deficient compared with synthetic fibre like glass. The second factor is the water absorption ability of natural fibres. Many scholars have attempted physical and chemical surface modification methods to overcome the drawbacks. The modification results for the water absorption experiment show an improved hydrophobic nature of modified fibres [29]. Wei et al. [48] reported that enhanced fibre surface wettability and interface compatibility between polymer and matrix increase the shear strength of polymer composite. With that, biopolymer composite can be used for domestic and structural applications. Natural fibre-reinforced composite has been used in the marine industry to construct boats and yachts because of its good resistance to seawater and buoyancy properties. Water absorption would affect its application at a higher pressure for oil and gas pipes, which can be high due to voids, and defects can increase [49, 50]. Hence, it is essential to determine the proper water absorption of new materials to perform safely in its service environment (Figure 4). Ihueze et al. [29] determined water absorption of plantain fibre in various water media, as illustrated [29] in Figures 4(a) and 4(b). The result indicates improvement in the hydrophobic nature of modified fibres at optimum concentrations of 2% NaOH and 1% acetic acid concentration. Manel Haddar and Koubaa [51] observed that 20 wt% of Posidonia oceanica fibre (POF) reinforced with unsaturated polyester improved the natural fibre's moisture resistance and dimension stability [51].

Many opportunities can be explored using natural fibre and polymer materials by physicochemical treatment to improve adhesion between the fibre and polymer matrix [52]. Banana pseudostem fibres provide a distinctive opportunity to reinforce thermoplastics, such as HDPE and PE, as the effects of the treatments on the tensile properties of banana pseudostem fibres improved interfacial bonding between banana fibres and matrix. William Jordana [53] reported that peroxide treatment enhances the tensile properties of individual fibres, whereas permanganate treatment has an inconclusive effect on the tensile properties of individual fibres.



(a)



(b)

FIGURE 4: (a, b) Water absorption for unmodified and modified fibre in different water media [29].

Ihueze et al. [29] developed plantain fibre-reinforced HDPE for moderate-pressure applications in the oil and gas industry with low energy and power consumption. The fibres developed exhibited excellent tensile strength and density. The average maximum strength for mercerised fibre was reported as 1024.986 MPa, and that of acetylated fibre was 2780 MPa. These treatments improved the hydrophobic properties of the developed material, giving a fibre density of 0.132 g/cm^3. To determine the long-term mechanical performance of reinforced polymer pipes, hydrostatic pressures and long-term hydrostatic strength tests were carried out by Ihueze et al. [54] to ascertain their desirability for oil and gas application. The result showed that at different temperature conditions, the hydrostatic strength of the PFRHDPE pipe decreased with an increase in temperature and time. However, the availability of good engineering information and data regarding composites has not kept pace with technological advances and affected the acceptance of polymer composites at the initial stage [55].

Dan-asabe [56] also developed composite pipe using banana particulates and clay filler to reinforce the PVC matrix. The pipe has Young's modulus of 1.3 GPa and a 1.24 g/cm^3 density with low water absorption and good thermal stability of 38.6% than PVC pipe. The results demonstrated that the banana composite pipe has a lower density than the other two materials and is invariably weight saving. According to Sampath et al. [57], when comparing glass fibre composite with banana fibre composite, it was noticed that the mechanical properties of banana fibre composite were similar to those of glass composites, as shown in Figure 5. However, the strength of banana composite products needed improvement. They suggested using banana fibre composite as a more environmentally friendly alternative for making commercial and industrial products.

Chen et al. [58] reported the application of bamboo winding composite pipe, another bio-based pipe for water reticulation, to replace PVC and concrete pipe for low- to medium-pressure water service and sewerage applications. These pipes are of various sizes ranging from 150 mm to 5000 mm in diameter with a wall thickness of 9 mm–38 mm and could be found application in other fields. Studies by Udayakumar et al. [59] have shown that biopolymers are biocompatible and biodegradable, which makes them useful in different industrial applications. Moreover, these biopolymers have performed a constructive role in their application perspective, demanding more interest towards the eradication of synthetic polymers completely. Green composites could replace the current synthetic composite; however, when the developed materials are new to their field of application, other mechanical qualities need to be identified and studied [60].

Moreover, as shown in Table 1, many other natural fibre and matrix materials can be exploited and utilised for various applications.

3.1. Matrix for Oil and Gas Polymer Composite. A polymer matrix composite is made up of a matrix composed of either thermoset or thermoplastic polymers. This matrix envelops the fibres and binds them together, creating a cohesive structural unit. Additionally, the matrix protects the fibres against

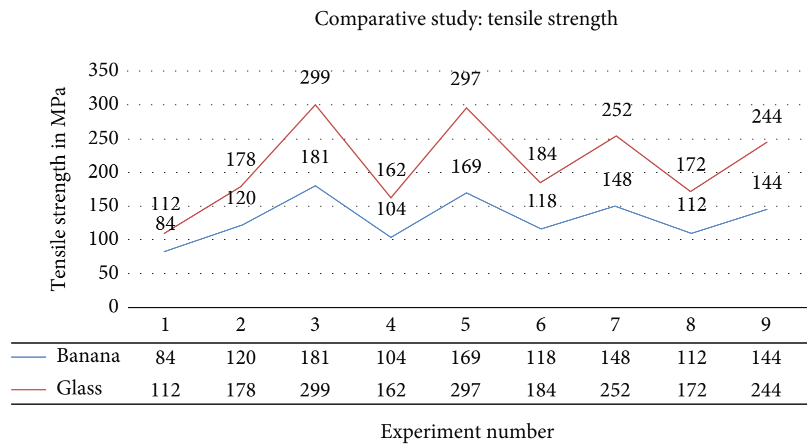


Figure 5: Comparison of tensile strength between banana and glass fibre [57].

Table 1: Natural fibres reinforced with polymers [61].

Thermoplastics		Thermosets	
Polymer	Fibres	Resin	Fibres
PP	Curcuma, coconut husk, hemp, jute, sisal, sugarcane bagasse	Polyester	Bamboo, banana, coconut flax, pineapple, hemp
PE	Banana, rice husks, sugarcane bagasse	Polyurethane	Coconut, banana, curcuma, sisal
HDPE	Banana, curcuma, sisal, wood	Epoxy	Cotton, flax, hemp, jute, sisal, pineapple
PS	Coconut husk, sisal, sugarcane bagasse	Phenolic	Flax, sisal, jute, banana
		Vinyl ester	Pineapple, sisal, jute, coconut, hemp

damaging environmental factors, as well as interlaminar shear strength and resistance against crack propagation and damage [62]. Huang et al. [63] described thermosetting polymers as a type of polymer that does not melt but can be pyrolysed at high temperatures. This is due to their linear molecular chain, which makes them more resistant to stretching under load. In contrast, thermoplastic matrices consist of linear chains that can be transformed when they become molten. As a result, thermosetting polymers can withstand higher loads and temperatures than thermoplastics. The key role of the polymer matrix in FRP composite materials is to hold the reinforcements together, distribute loads evenly, transfer load, carry interlaminar shear, and protect fibres from exposure to different environmental conditions. Thermoplastic is characterised by very good mechanical properties and has a high chemical versatility. The different types of PE include low-density polyethylene (LDPE), high-density polyethylene (HDPE), and linear low-density polyethylene (LLDPE), with HDPE being mechanically more robust than LD- and LLD-PE [64]. Eyvazinejad et al. [65] classify thermoset polymers into four categories: epoxies, polyesters, vinyl esters, and polyurethane. Epoxies generally outperform other thermoset resins in terms of tensile strength, tensile modulus, compressive strength, and resistance to environmental degradation. After conducting extensive research on thermoplastic, elastomer, and thermosetting polymers reinforced with fibres and formulated with fillers, Hsissou et al. [66] have recommended and concluded that composite materials made with thermosetting polymers exhibit exceptional mechanical and thermal resistance at high temperatures.

Matrix is also known as resin, especially in oil and gas, and it can be either thermoplastic or thermosets. Resin selection requires consideration of properties (chemical resistance, toughness, abrasion resistance, stiffness, and strength), processing (lay-down rates, process temperature, and processability), and cost (materials and processing) [67]. Evelyne El Masri et al. [68], Hughes [69] indicated that HDPE is a commonly used matrix material for producing reinforced thermoplastic spoolable pipes for oil and gas applications. These include pipes for oil and gas gathering, gas transportation, and distribution applications. Furthermore, the most commercial reinforced polymer thermoplastics for oil and gas applications are produced from HDPE (PE 80 or PE 100) [70]. Baker Hughes reported that HDPE had been used for various low-pressure, lower-temperature oil and gas applications of less than 335 psi and less than 140°F [69].

Thermosetting resins are highly useful in petroleum drilling and production engineering due to their exceptional mechanical, heat, and chemical resistance properties after modification [71]. Also, thermosets are used for coatings of pipes to protect pipelines against corrosion and improve flow efficiency, chemical resistance, and abrasion resistance [72].

The problem with natural fibres, as observed by Abdollahiparsa et al. [30], is low degradation temperatures of approximately 200°C, which makes them incompatible with thermosets that have high decomposition temperatures, especially when thermosets have been hardened with maleic anhydride. It restricts natural fibre composites to relatively low-temperature applications. Hence, most biocomposite materials are made from thermoplastics. Wael Badeghaish and Salazar [73] noted that proper material selection of fibre and matrix for oil and gas applications is key to safe, reliable, fit-for-purpose, and cost-effective operation over the design life.

3.2. Types of Polymer Composite Pipes. Polymer matrix composites (PMC) are made up of different types of organic polymers that contain short or continuous fibres and a range of reinforcing agents. This enhances properties like fracture toughness, high strength, and stiffness. The PMC is designed to support the mechanical loads through the fibres [61]. Polymer composite pipes are categorised into two types: rigid pipe, also known as reinforced thermoset resin (RTR), and flexible thermoplastic composite pipes, encompassing reinforced thermoplastic pipes (RTPs) and thermoplastic composite pipes (TCP). Due to their flexibility, they can be spooled onto a reel for efficient transportation and fast installation without needing many connections [56]. The significant difference is that RTR is produced from bonded glass outer reinforcement and thermoplastic inner liner. In contrast, RTP products use an unbonded external reinforcement, such as glass fibre, steel strip/braided cable, polymer fibre tape, and thermoplastic inner liner [74]. An important design choice is whether a bonded or unbonded reinforcing system is determined by the bend radius through which the product can be coiled [75].

3.3. Reinforced Thermoset Resin Pipe. Thermosetting plastic composites are pipes that become permanent, insoluble, and infusible after heat or a curing agent is applied. Once shaped and cured, they cannot be remelted. The properties of thermosetting resins allow them to be combined with reinforcements to create durable composites [76]. Rafiee [77] describes thermoset resin pipes as composite pipes made from materials such as glass fibre-reinforced polyester, vinyl ester, or epoxy (GRP, GRV, and GRE). These pipes are easier to transport, install, connect, and repair than traditional ones. They are produced through centrifugal casting or filament winding methods. The smaller diameter pipes have higher pressure ratings up to 20 MPa while larger diameter pipes have much lower pressure ratings of 1 to 2 MPa with various upper temperature ratings from 65°C to 100°C. The disadvantage of rigid thermoset pipe is fitting where the pipeline topography has many elevation variations or requires direction changes because stick pipe cannot be bent, and joint integrity is another concern. For smaller diameter pipes less than 12 inches, threaded mechanical connections are commonly used to join the pipes. On the other hand, adhesive-bonded bell and spigot connections are typically employed for larger diameter pipes [74]. However, spoolable pipe products of thermoset pipe referred to as spoolable composite pipes (SCP) use glass fibres encased in a thermosetting epoxy resin matrix with the reinforcement structure directly bonded to the inner liner with an adhesive. The tube is made up of a thermoplastic lining that is covered with an epoxy-based structural thermosetting laminate. When the tube is coiled, the resin in the matrix cracks to accommodate the flexural strain, but this does not affect the fibres' load-bearing capacity or the thermoplastic liner's ability to contain fluid. Flexible thermoset coiled tubing can handle high pressure, usually up to 500 bar, but due to manufacturing limitations, the product is currently only available in small diameters, typically less than 100 mm. Gibson [75] reported that thermosetting pipes are usually noncatastrophic. As pressure increases, the resin starts to crack, resulting in fluid weeping through the pipe wall. This happens before the fibres break, providing a safety margin against overload and a helpful "leak before break" mechanism. In addition, thermosetting composites offer numerous benefits, including excellent impact resistance, high toughness, remarkable damage tolerance, and good heat and corrosion resistance. However, it is essential to acknowledge that they also possess certain drawbacks, such as nonrecyclability, limitations in low-temperature storage, and longer processing cycles [78].

3.3.1. Thermoplastic Composite Pipes. RTPs are solid-walled pipes made of three layers: an inner thermoplastic liner, a composite laminate, and a fused outer jacket that is fully bonded to provide strength and stiffness with improved corrosion resistance [79]. The pipes contain a thermosetting resin and various additives to enhance specific function(s) of the pipe to achieve the design function because thermoplastic pipe such as HDPE is susceptible to a reduction in mechanical properties at elevated temperatures and is limited to 100 psi at up to 100°F. Since the strength of the pipe comes from the outer laminate layer, the mechanical properties of the pipe are improved by lining the laminate using carbon, glass, or other fibre resin. This spoolable thermoplastic pipe has pressure ratings ranging from 750 to 5000 psi [80]. Figure 6 shows a model of a thermoplastic composite pipe. Falcon [81] reported that engineering thermoplastics such as PPS are available for more demanding environments to handle temperatures as high as 175°C. In the most extreme production environments with temperatures up to 260°C, liners made of PEEK are utilised.

Al-Khabrani and A. Parvez [82] illustrated that HDPE and polyethylene-raised temperature (PE-RT) resin are used for jacket and linear material at 140°F and 180°F because of their high strength and resistance to crack growth. However, they observed that two main challenges hinder its application. The two materials are limited to the application of 180°F, and most wells in the southern area were designed with temperatures exceeding 180°F. The second challenge of RTP is the size because only two pipe sizes are available, 4 inches and 6 inches, which are approved for oil gathering and transportation in sour oil and gas fields. The transmission medium is mostly gas, with a small amount of oil and water. The pressure and temperature of the transmission medium are 9 MPa and 37°C, respectively [83].

3.3.2. Reinforced Thermoplastic Pipes. RTPs are made of a thermoplastic liner wrapped in reinforcement materials like aramid or glass fibre cords and covered in an outer thermoplastic coating. The inner liner, reinforcing layer, and

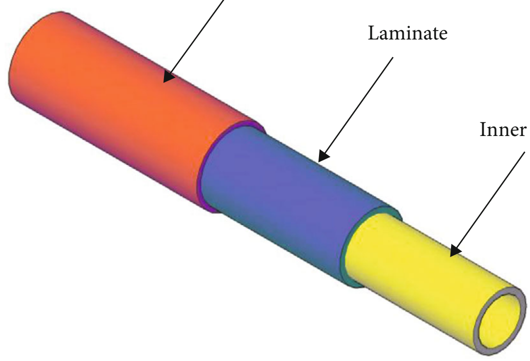


Figure 6: Thermoplastic composite pipe.

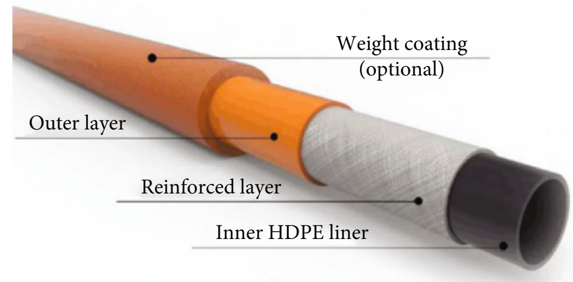


Figure 7: Reinforced thermoplastic pipe [87].

outside layers are the three layers and are not linked together, making them exceedingly flexible and spoolable [84]. Compared to standard HDPE Grade 3608, spoolable pipe products are distinguished by having HDPE Grade PE 4710 and HDPE Grade 4710 liners due to their superior mechanical property retention, stress crack resistance, crack arrest capabilities, and higher temperature mechanical qualities [74]. Enamul Hossain [85] found that the commonly used matrix materials are polyethylene, cross-linked polyethylene, nylon 11, or PVDF. The composite material used in the pipe provides chemical and temperature resistance and compressive and shear strength. The outer laminate layer is responsible for the strength of the pipe, which allows for the use of various materials for the thermoplastic liner. Typically, flexible composite pipes are made up of three layers. They are the liner, the fibre reinforcement layer, and the outer layer, as illustrated in Figure 7. The outer layer protects the pipe from external influences, and the liner contains the liquid transported through the pipe. The reinforcing layer can be attached to the liner, thus bonded, loose fit, or unbonded [86]. The tube consists of a thermoplastic liner, overwound with an epoxy-based structural thermosetting laminate. The matrix resin accommodates the flexural strain by cracking on coiling, but this does not damage the fibres' load-bearing capability during reeling and unreeling [39]. The ease of deployment realises the primary benefit of RTP as a single reel and installation, which contributes to overall project savings of up to 30-50% for typical gas applications. Additional installation benefits include reduced right-of-way requirements, reduced safety hazards, and reduced environmental impact [82].

4. Application of Composite Pipes in Oil and Gas

In 1987, the Offshore Energy Technology Board team identified that using glass-reinforced composite plastics on the shore could generate significant weight and cost savings [88]. Since then, there have been research and development activities for the oil and gas sector, as shown in Table 2.

Fibre-reinforced polymer materials are used for onshore gathering and transmission in the petroleum industry [6]. They are widely used in tubular structures such as pipes, drill pipes, risers, and tethers [90]. Other applications of composite materials include gratings, tethers, plugs, flanges, reducers, and elbows. Badeghaish et al. [91] observed a switch of attention to nonmetallic pipes as a revolutionary technology for sending pressured fluids from onshore surface to offshore subsea to downhole activities. They mentioned that in developing new designs and materials for these applications, it is crucial to comprehend how polymeric composites' physical and mechanical properties change in harsh oil environments. In the oil and gas industry, fibre glass pipe is known as FRP or glass-reinforced epoxy (GRE). Norsk Oil and Gas [92] stated that GRP has good corrosion resistance, low weight, high fatigue resistance, high strength-to-weight ratio, faster and easier installation, and cost savings compared to metallic materials. GRE pipes are used by the oil and natural gas production industry for various pipeline services, including the following applications: oil, natural gas, and water multiphase fluid pipelines [93].

The operability and durability of oil and gas production technological equipment are possible with nanocomposites for low- and high-temperature applications [94]. Figures 8(a) and 8(b) show the field application of rigid and spoolable pipe, respectively.

Airborne oil and gas [96] developed a thermoplastic composite pipe from glass or carbon reinforcement fibres and thermoplastic polymeric materials with high internal pressure rating flexibility and corrosion resistance. The feasibility of using SCP lined with pipeline-grade HDPE pipeline for hydrogen transmission was examined by [97]. The authors reported that hydrogen pressurisation during the leak rate measurements was 10.3 MPa (1500 psi), the maximum recommended pressure. Almeida et al. [98] suggested using HDPE valves instead of traditional concrete chambers, which saved about 30% of direct costs, reduced installation time, and lowered indirect expenses. Mashkov et al. [94] pointed out that adopting wear-resistant nanocomposites based on polytetrafluoroethylene in friction units and equipment for various low-high-temperature applications can improve the operability and durability of oil and gas production technological equipment. Al-Khabrani and Parvez [82] reported that the primary benefit of RTP is realised by the installation methodologies available, which contribute to overall project savings of up to 30-50% for typical gas applications.

In 2018, Saudi Aramco installed reinforced thermoplastic pipe for natural gas transportation in a 6-inch flow line at the Southern Area Gas producing department. The

Table 2: Reinforced thermoplastic pipe trial and service gas pipelines [89].

Date	Company	Field/location	Application	Press/temp	Size (in)	Length (m)
November 03	Fahum Gas Egypt	El Fayoum	Gas distribution	30 bar/20°C	4	380
April 04	VNG	Berlin plant	Brine gas waste line		5	60
August 04	Badenwerk Gas GmbH	Buchig-Oberacker	Gas distribution	25 bar/15°C	5	4500
October 04	Ruhrgas, Germany	Handover relining	Gas distribution	25 bar/15°C	4	600
March 05	SGC Syna	SJC-SBC	Sour gas	90 bar/60°C	4	6
August 05	Shell Brunei	Seria	ULLG	50 bar/25°C	5	18
August 05	Shell Syria (AFPC)	Tanak field	Production gas	98 bar/55°C	5	11
October 05	E.ON Germany	Hirschbach	Gas	22-42 bar/60°C	4	440

(a)

(b)

Figure 8: (a) Rigid composite pipe [93]. (b) 6″ flexible TCP ready for deployment in deepwater offshore in Nigeria [95].

installation was successful, and the operation was satisfactory [99]. Another success in deploying composite pipes is shown by significant oil and gas industry players like Aker Solutions, Shell, Chevron, Evonik, Saudi Aramco, Subsea 7, and Sumitomo Corp. through their investment in research and development in the area of polymer composites [100]. Some major players in producing composite pipes for the oil and gas sector are shown in Table 3.

Evelyne et al. [68] reported increased use of advanced polymer materials in industrial applications. It is expected to reduce the price of advanced polymer products by developing cheaper, more productive, and more competitive manufacturing processes. Materials for transporting oil and gas products need to have properties to withstand the service environment, like high temperature and pressure, aggressive environment, and long-term degradation; composites, thermoplastics, and thermosets are viable materials because of their unique properties [107]. Moreover, industry-accepted regression was used to determine the performance of the GRE pipe under internal pressure [108], and results showed that the pipe could withstand or surpass the operating pressure of the pipe. PETRONAS Carigali Sdn. Bhd met a breakthrough using insertion for an offshore 12-inch carbon steel pipeline with 3-inch RTP for handling corrosive fluids such as crude oil and sour. It has shown that the technology is viable for installing long pipes with cost savings [109]. Cheldi et al. [110] reported the availability of RTP in the market and improved performance of the spoolable pipes in Zubair Field, southern Iraq, and Aquila Field, Italy. The onshore Zubair Field is characterised by the high corrosiveness of crude oil and spray water and saline soils, and the Aquila Fields of the Adriatic Sea are described with sour gas wells. The positive results of this technology allow the consideration of RTP for other onshore and offshore applications after the material's compatibility with the operating limits has been determined and verified.

Dominguez-Candela et al. [111] illustrated the significant advantages of biopolymer composites, as they help reduce reliance on fossil resources and contribute to minimizing greenhouse gas emissions. These composites can be either fully or partially bio-based. Technavio [112] reported the projected market share of advanced polymer composites between 2021 and 2025 as USD 4.95 million. Furthermore, the market's growth momentum is anticipated to accelerate at a compound annual growth rate of 7.96%.

Abdel-Raouf and El-Keshawy [113] reported that natural polymer composite pipes could meet industrial applications as raw materials for pipe production are readily available. Composite materials are used for low- to moderate-pressure flow lines and gathering line systems for oil and natural gas [80]. Roseman et al.'s [114] study reported the progress of composite materials in replacing steel components in low-risk applications but not in higher-risk applications where the regulatory requirements are more stringent and the technical challenges are more complex.

The increased use of composites for other applications led to a growth of 5.2% in 2014 and the potential to grow because the government and private sector are interested

Table 3: Major companies producing composite pipes for oil and gas.

Product	Manufacturer	Specifications	Application	References
Fibrespar	National Oilwell Varco (NOV)	Size range 2-6 inches Pressure rating 2,500 to 3,500 psi Temperature rating 180°F-203°F Length 9,000 ft	Corrosive gathering and injection applications, including general and sour-produced fluids and gases, as well as hydrocarbon applications	[101]
Thermoplastic composite pipe riser and jumper	Strohm	Size 7.5 inches Length 3,000 to 6,000 m Temperature rating 250°F Working pressure 10,000 psi	Flow line, hydrocarbon production, water injection, gas lift, MEG, and chemical injection	[102]
M-Pipe	Magna Global	Size 6 inches Length 800 ft long Pressures up to 10,000 psi Temperatures up to 250°F	Flow lines and jumpers, and ultradeep water-free hanging risers	[103]
SLS Frac Plug	Halliburton	Casing size 5 1/2 inches Pressure rating 10,000-psi	Casing	[104]
Shawcor's composite line pipes	FlexPipe, FlexPipe HT, and FlexCord	Size 4 inches Pressure up to 1,500 psi Temperatures of up to (180°F) Length 25,000 meters	Upstream, midstream, and downstream industries, from oil and gas to transporting water	[105]
Thermoflex and PE flex composite pipes	Baker Hughes	Size 4-8 inches Temperatures up to 180°F Pressure up to 750-2,250 psi Reel length 2,160 feet	Gathering lines, salt-water disposal lines, gas-lift lines, water/CO_2 floods, water transport, downhole tubular pipeline rehabilitation	[106]

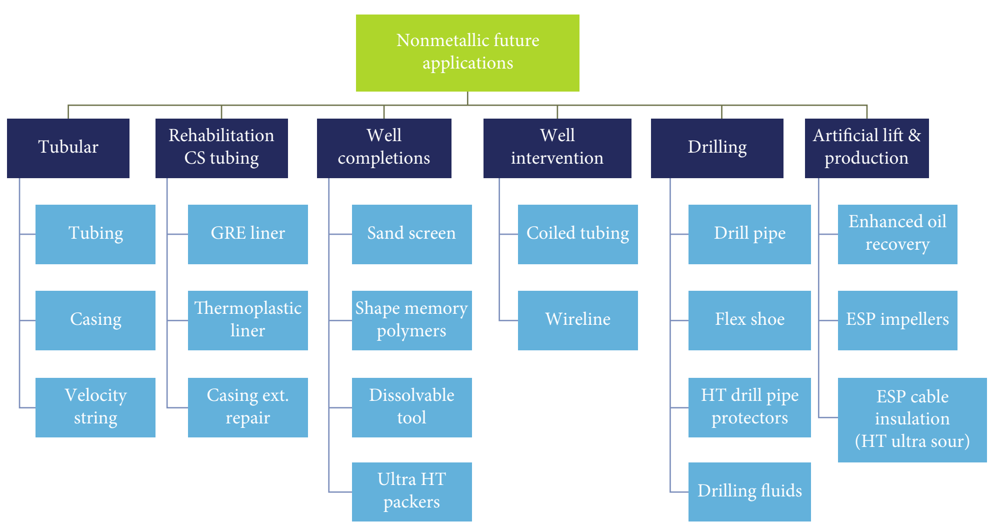


Figure 9: Summary of the future potential application of nonmetallic composite [73].

in investing more in the production of pipelines for transporting oil and gas with nonmetallic pipes to replace steel tubular with better characteristics [115, 116]. Bukhari et al. [100] mentioned areas for additional research, such as collaboration, which is vital to provide a dynamic and high-level network to increase the impact of composite materials in oil and gas. Recently, there have been concerted efforts by industry and researchers to unlock the potential and resolve the challenges based on field trials of polymer composites. The following are several promising upstream applications where the composite can be utilised and tested over the next few years, as illustrated in Figure 9.

Another critical application of polymer composites in the last 20 years has been in steel pipe repair because corrosion and metal loss cause failure in pipelines, and their rehabilitation is vital to researchers [62]. Fibre-reinforced composite restorations are becoming widely used as an alternative to installing welded, full-encirclement sleeves to repair oil, and gas transmission/transportation pipelines. This cost-effective approach eliminates external corrosion while increasing the pressure capacity of fixed pipes. In addition, it also prevents the unplanned shutdown of pipelines [117, 118]. Research on the application of polymer composite in oil and gas steel pipe repair is expanding. Some are at the research level, while others are at the application level in different parts of the world [119].

Polymeric composites have been used to repair corroded material to restore a damaged pipeline's loading capacity and structural integrity [120], including dents, mechanical damage, vintage girth and seam welds, wrinkle bends, elbows, tees, branch connections, and even cracks. ASME PCC-2 and ISO 24817 composite repair standards ensure that quality control measures are in place [121]. Lim et al. [122] reported that the burst pressure of the composite-repaired pipe increased by 23%, and it experienced significantly reduced strain in the defect region. Postflexural, hydrostatic testing indicated that the composite repairs could sustain significant damage while retaining their ability to support the pressure-carrying capability of the pipe [123].

Because of uncertainty on the effectiveness of oil and gas pipe repair using polymer composite, Gibson [75] reported that AEA Technology developed a guideline for the qualification and application of repair systems for temporary or permanent repairs. They recommended this document for temporary or long-term maintenance. Jayasuriya et al. [124] studied using natural fibre to repair corroded pipes. The results indicated that increasing the amount of BFRP layers can successfully increase the bending capacity of the pipe, and there is an optimum thickness of BFRP fabric.

Introducing natural fibres into plastics manufacturing would significantly improve the availability of a renewable source of materials to ensure long-term resource supply that supports the required industrial sustainability and expand the search for new green design opportunities at reasonable prices to enhance the future cleaner production theme. On the other hand, a significant study must still address the downsides of using natural fibres in polymer composites [125].

4.1. Challenges of Biopolymer Composite in Oil and Gas. Gibson [75] reported several barriers in the application of polymer composites in the offshore industry, including the following:

(i) Regulatory and certification requirements

(ii) Lack of relevant performance indices, especially in its service environments (including erosion, fatigue, wear and impact abuse, and fluid environments)

(iii) Lack of efficient design procedures and standards

(iv) Mass production and production of large pipe diameter

(v) Modelling tools

Since they are exposed to the same service environment, these obstacles would have an impact on the application of biopolymer composite.

Another challenge of polymer composite is poor performance in a fire when exposed to a temperature above 300-400°C. Hence, much effort has been dedicated to developing a flame-resistance composite for high-risk temperature applications [126]. Thus, Yücesoy et al. [127] reported that LDPE composite with inorganic fibre had shown thermal stability and flame retardedness [127]. Quality control and reliability are another encounter polymer composite observed by Laney [80] because there was no long-term service history to defend the use of composites in natural gas transmission. In addition, Barbosa et al. [128] mentioned that introducing new technology to very challenging applications, such as water, requires careful consideration and minimization of all engineering and project implementation risks. It is another vital area that needs consideration to defend biopolymer composite applications. Other researchers noted that five primary barriers holding back composites are (i) long-term damage mechanism database for life prediction, (ii) comprehensive testing for verification and certification, (iii) sufficient production capacity, (iv) design standards accepted by regulatory bodies and industry, and (v) NDE and on-site monitoring [129]. Plant fibres are susceptible to decomposition in humid environments [22].

Additionally, more information is needed regarding the behaviour of these composites in the sector. These challenges would also affect biopolymer composite applications in the oil and gas industry. There are three issues with the product: (1) no postevaluation of performance, (2) limited material working temperature, and (3) limited external pressure resistance [130].

5. Factors That Drive the Initial Application of Polymer Composite in Oil and Gas Pipes

New materials offer many advantages, but also, impending problems must be considered. Consequently, the new material should be used only after extensive testing and analysis. Such an approach will reduce the frequency of failures [131]. Standards were developed, reviewed, and modified to support the industrial application of polymer composite for manufacturing to meet the ever-changing requirements. Furthermore, using existing standards has reduced downtime in developing new materials. For example, DNV's Offshore Standard for Concrete Structures was instrumental in developing fibre-reinforced plastic reinforcement bars for the sector [132]. ASTM F2896-11 standard specification for reinforced polyethylene composite pipe transport of oil and gas and hazardous liquids covers requirements and test methods for materials, dimensions, etc., to manufacture multilayer reinforced polyethene composite pipe [133]. ISO 23936 provides general principles, requirements, and recommendations for selecting and qualifying nonmetallic materials for use in equipment utilised in oil and gas production environments. The guidance is intended to maintain quality assurance and prevent equipment failure that could pose a risk to the public, personnel, or the environment. It is also valuable for avoiding expensive corrosion failures of the equipment. This standard complements the material requirements outlined in relevant design codes, standards, or regulations [134].

Moreover, the International Organization for Standardization (ISO) developed ISO 24817 to ensure the safety of repaired pipes that will meet the specified performance and

Figure 10: Helical filament winding used in Composite Pipes Industry (CPI), Oman [140].

Table 4: Biopolymer research gap.

Research gap	Recommendation for future studies
Performance consistency and standardisation: properties variability due to sourcing, processing methods, and environmental conditions. Lack of standardised testing methods and quality control	Establishing standardised testing methods and quality control protocols to ensure consistent performance across different batches and sources is a significant research need.
Mechanical strength and durability: mechanical strength and durability are essential for their broader application. Understanding microbiological action on defect initiation in polymer composite	Enhancing biopolymers' mechanical strength and durability is essential for their broader application that matches or exceeds traditional petroleum-based plastics' performance.
Biodegradability and environmental impact: biodegradability of natural fibre in different service environments	Further research is required to understand the environmental fate of biopolymers in different conditions and ecosystems to ensure that they are genuinely sustainable.
Processing techniques: compatibility with existing infrastructure	Developing efficient and cost-effective processing techniques for biopolymers, including extrusion, injection moulding, and 3D printing, is essential for widespread adoption in various industries.
Achieving a consistent and even distribution of fibre particles	Improve the mixing method to achieve high-quality particulate agglomeration.
Modelling and simulation: critical performance characteristic evaluation	Establish critical performance databases for modelling, design, and final validation of composite pies in actual service environments.
Long-term behaviour and ageing: limited work on the long-term behaviour of natural fibre, especially under fatigue loading and performance history	Understanding the long-term behaviour and ageing of biopolymers under different conditions, such as exposure to sunlight, moisture, and temperature variations, is essential for predicting their performance over time.
Regulatory and safety considerations: the standard for natural fibre testing to support its application in critical structural members that is acceptable by regulatory and certification is lacking	Establishing regulatory frameworks for biopolymers is essential to ensure their safety for consumers and the environment. It includes assessing potential risks associated with novel biopolymer formulations or additives.
Economic viability: biopolymers hold promise, but their economic competitiveness still needs to be improved compared to traditional polymer composites from synthetic sources	Research focused on optimising production processes, reducing costs, and developing value-added applications can contribute to improving their economic viability.

safety requirements [135]. Colombo and Vergani [136] emphasised that designers are guided by set standards and regulations during the qualification process. However, it is essential to note that these guidelines are constantly being reviewed in light of new insights into the long-term mechanical behaviour of materials.

Other standards are available for the safe application of polymer composite materials. Despite limitations and challenges in the initial application of reinforced thermoplastic pipes in oil and gas, research in design and technological advances overcame some barriers. Moreover, the composite has impressed acceptance in the oil and gas industry.

The manufacturing aspects of polymer composite have also witnessed technological advancement. The most common manufacturing process of polymer composite pipe is continuous filament winding, centrifugal casting, and discontinuous filament winding. All these manufacturing processes are completely automatic and electronically controlled [137]. Fibreglass pipe is usually manufactured by filament with a single winding angle, designed primarily to resist internal pressure [138]. At the initial stage, FRP production is of a small diameter, typically 2″ to 6″ for medium-pressure gathering [80]. Peng et al. [139] reported that large diameters of reinforced thermoplastic for oil and gas up to 18″ diameter with a burst pressure of 24.34 MPa were developed. Figure 10 shows helical filament winding used in Composite Pipes Industry.

The main factor affecting the tensile performance of RTPs is the winding angle of the reinforced layers. With ±45° as the demarcation point, the winding angle smaller than ±45° will result in higher strength in the longitudinal direction and the lifting effect on RTP's mechanical properties of the increasing number of reinforcement layers was better than that of the increasing thickness of the lining layer; when the winding angle was larger than ±45°, the opposite results were obtained [141]. Mohaimin and Aminanda [142] reported that the optimum layer is 70 to 60 for internal and external pressures, respectively. Moreover, for the ply angle, the optimum was ±45°. They used these data to develop a chart for composite pipe design subjected to specific internal and external loading conditions. This data will be helpful in the development of biofibre wound pipes.

One of the most challenging problems in composite science is predicting the failure [143] of developed materials in its service environment. It is essential to determine the structural integrity and durability of the composite in its service environment because failure in oil and gas facilities is unacceptable because of its environmental cost impacts and disruption in product supply [144]. Nondestructive testing (NDT) and simulation tools are employed in screening and determining the structural integrity of the composite material. Williams [145] reported that nondestructive test methods are used in offshore operations to assess the damage, analyse structure repair procedures, and predict failure to provide cost-effective solutions in innovative design and problems. Daniel et al. [146] developed a new yield and failure theory for composite materials under static and dynamic loading. This theory allows for the rapid screening of new composite materials without extensive testing and offers easily implemented design tools. Toulitsis et al. [144] determined the ageing and degradation of GRP. The result showed that if protective thermoset liners succumb, subsequent ageing would involve the matrix mainly. Paim et al. [147] conducted tensile tests on glass fibre-reinforced polyurethane at room temperature and 90°C. The experimental analysis revealed that temperature within this specific range significantly influences this composite material's ultimate strength. However, the elastic properties remained unaltered regardless of the temperature variation.

Tan et al. developed the finite element (FE) models of a buried glass fibre-reinforced composite pipe simulation [148]. Their result revealed that internal pressurisation reduces pipe ovalisation due to overburden loads but tended to increase axial pipe stresses at pipe bends. Kabir et al. [149] used numerical simulation to predict fibre breaks and debonding in the fibre/matrix interface layer, considering the fibre volume fraction and fibre orientation in the blend by comparing the simulation with the experiment. A good fit between the two results was observed. The optimum number of composite laminate layers was determined using finite element analysis.

6. Research Gaps in the Field of Biopolymers

Some of the identified potential research gaps in the field of biopolymers observed in this review and reported by other researchers [6, 24, 150, 151] are summarised in Table 4.

7. Conclusion

The development of materials with superior mechanical properties and limitless capacity to satisfy desired performance requirements has been made possible by polymer composite materials, ushering in a new age in material science and engineering. Polymer composites have solved traditional carbon steel pipes' corrosion and weight problems in oil and gas. Furthermore, the durability of composite pipes has given them a good track record in a service environment. The drive to reduce cost and research in polymer developments are key factors supporting the increased use of fibre-reinforced polymer materials. Also, it receives the interest of major oil and gas industry players through investment and patronage of composite pipes. However, all the polymer composite materials used in the oil and gas industry are produced using synthetic fibre. Now, attention is being shifted to using natural fibre as reinforcement material in polymer composites to replace synthetic fibre because of its advantages. The advantages it offers from an environmental point of view include reduced dependence on nonrenewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, the biodegradability of components, and their low density. Based on this literature, the product of biopolymer composite is from continuous basalt fibre and banana fibre. Furthermore, the study observes that the development of biopolymer composites from banana fibre for a pipe application is in its infancy with no field application. Natural fibre is promising as an alternative to synthetic fibre in composite development. However, research is still at its infant stage and has some challenges, like compatibility between the hydrophobic polymer matrix, the hydrophilic natural fibre, and standardisations. However, appropriate physical and chemical treatment of the natural fibre improves the compatibility, and compatibiliser has proved to increase the bonding of the material. New materials can offer tremendous advantages, but potential problems are also possible. Hence, there is a need to determine other mechanical properties such as long-term structural integrity, environmental deterioration, fire resistance, and other properties of the developed material that meet standards acceptable by regulatory authorities for certification. The set target by the government to increase the use of natural fibre as raw material for industries is an excellent initiative to boost natural fibre used for industrial applications.

Data Availability

Data is available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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