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POLYMER MATRIX COMPOSITES: A SHORT REVIEW

Recently, the use of polymer matrix composites has grown exponentially, substituting for conventional materials. The most important category of composite materials when it comes to the manufacture of personal protective equipment (PPE) are polymer matrix materials (PMM). PMMs are mainly used due to their low weight, high resistance to chemical attack, high elasticity, and superior thermal and electrical properties. These featured characteristics make them the most suitable choice in a wide range of industries, such as hybrid automotive, sports, packaging, aviation, military, and construction, especially due to their low curing time and simplicity in manufacturing. However, the key to creating composite materials that can be used to produce parts with complex shapes, low density, and improved physical and mechanical properties is the identification of the right reinforcing element for the polymeric matrix. The bond created between these two phases will result in a material with a tailored design and properties that can meet the requirements of PPE. This advantage is related to the unlimited combinations that can be obtained through the mixing of metallic, ceramic, or plastic elements with the polymer matrix. This study presents a brief overview of the literature that approaches the obtaining and applications of PMM. Accordingly, the relation between the composition (type or quantity of reinforcing elements and type matrix) and the properties of the PMM was analyzed, while showing the primary limitations in circular economy integration in industries with high consumptions of PMMs.

Keyword: Polymer Matrix; Composite Materials; Circular Economy; Reinforcing Elements; Manufacturing Methods

1. Introduction

A polymer is a macromolecule made up of repetitive structural units made up of molecules. Compounds made up of several types of atoms are known as molecules. Polymers are also known as macromolecules. They are frequently composed of hundreds of thousands of atoms and can reach very large sizes. Before they are converted into polymers, these smaller units are referred to as monomers [1]. Polymers can be classified according to several criteria, chemical composition, provenance, structure of atoms, used and their interaction while exposed/subjected to temperatures, and others. In general, three types of polymers are distinguished: natural, synthetic and semi-synthetic. Organic/natural polymers come from natural sources, including plants, microbes, and animals. They are considered more advantageous than synthetic and semi-synthetic ones due to their cost-effectiveness, accessibility, degradation properties. In addition, the possibilities of being chemically modified and the high degree of compatibility come from their natural origin. Natural polymers have significant potential in the pharmaceutical, food and cosmetics sectors. Polymers derived from natural sources possess biogenetic characteristics, including cell interactions, enzymatic degradability, resemblance to the extracellular matrix, and chemical flexibility. Polymerization is the term used to describe the chemical process by which polymers are formed from monomers. However, it is important to note that polymerization is a broad term, as several chemical mechanisms are involved in distinct polymerization reactions [2,3].

Natural polymers are created and synthesized by living organisms (plants, microbes, animals, etc.) and are used without changing their chemical composition. Synthetic polymers are considered to be a relatively recent addition to the field of materials, since their integration into technological and practical applications took place in the first decades of the twentieth century. These characteristics significantly differentiate them from other materials that have been used by mankind for centuries or even millennia. In addition, given the fact that synthetic polymers are synthesized through chemical processes, the potential

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for designing new polymers is almost limitless. The wide range of possibilities has led to the development of many synthetic polymers that are used in almost every possible field of human activity involving matter or physical entities. In addition, the extended class of molecular structures leads to the development of materials with varied characteristics, thus allowing their use in many applications [4].

The term plastic is used frequently, but it is actually a synthetic (artificial) polymer. The first polymer created by scientists was developed between the 1850s and 1960s and is called celluloid. It was created by mixing nitrocellulose (a chemical mixture based on cellulose, concentrated nitric acids, sulfuric acids and oil) and camphor (natural resin), the final product being a thermoplastic called celluloid [5]. From this thermoplastic, photographic materials, films, balls for table tennis and others were initially developed. Materials used in everyday life, such as paint, rubber, synthetic fibers, and plastics, are referred to as conventional polymers. As a result of the expansion of human needs, new polymers are being developed with potential uses in a wide range of industries, including biomedicine, separation of oil from water or gas, special industries, energy production and storage [5,6]. The needs of modern society have evolved, therefore in some areas special qualities are required that standard polymers do not possess. The sources of raw materials are limited, therefore, the development of polymers from renewable materials, such as vegetable oils, is also being studied [7].

Despite being mass-produced for 70 years, plastics have surpassed most artificially synthesized materials. Although there is a wide range of polymers, at the end of 2017, only eight of them constituted 95% of the total primary plastics produced, an amount that exceeded nine billion tons. Of the total seven billion tons of plastic waste produced so far, about 10% has been recycled, 14% has been burned, and the remaining 76% is currently in landfills, landfills or in the natural environment. We can assume that the current trend of annual global plastic production will continue, estimated to reach 1.1 billion tons by 2050 [8].

2. General considerations regarding polymer matrix composite materials

A composite material is formed by combining two or more different materials, which retain their individual properties and structure at the microscopic level. However, at the macroscopic level, the resulting material possesses characteristics and properties distinct from each of its component materials. Composite materials are materials composed of several phases with a clearly defined boundary between them. By transferring properties between these phases, composites are able to achieve exceptional performance that surpasses individual component materials. Composite materials have many advantages, such as good rigidity, exceptional strength in relation to their density, high tensile strength and shock resistance. Slow propagation of cracks in the volume of the composite material, is blocked by the presence of reinforcing fibers. These reinforcement bridges in the matrix volume can control the direction and length of microcracks [9].

The properties of the composite material depend largely on the characteristics of the matrix. The matrix acts as an adhesive for the reinforcing elements and as a protective film for them. At the same time, the matrix ensures the connection between it and the reinforcement elements. Thus, the transfer of external loads to the reinforcement elements is ensured by means of the matrix [10].

Depending on the nature of the matrix, composite materials are divided into 3 classes:

- Polymer or organic matrix composites materials (PMC);
- Metal matrix composites materials (MMC);
- Mineral or ceramic matrix composite materials (CMC).

To the detriment of other composite materials, parts with complex shapes with a low density can be produced from PMC, which reduces fuel consumption and increases the speed of vehicles and aircraft. In addition, they have good rigidity, high mechanical strength and are easy to produce, at low temperatures compared to the others. The disadvantages of PMC compared to CMC and MMC are related to the temperature at which they can have applications and their sensitivity to moisture and radiation [10,11].

PMCs are divided into three main classes, thermoplastic matrix composites (TPC), thermosetting matrix composites (TSC), and elastomers. Thermosetting polymers harden through a chemical reaction that produces an irreversible crossover between polymer chains. Due to these bonds, they do not melt and are not significantly affected when exposed to heat. These, like elastomers, undergo irreversible structural changes and cannot be restored to their original shape by conventional methods. Thermoplastics melt and soften when exposed to high temperatures. Thermoplastic polymers can have semicrystalline sections of organized molecular chains, or they can be amorphous, having randomly arranged molecular chains. The advantage of this class is that they can be melted and reprocessed several times [12].

Thermosetting composites materials end their life cycle by becoming waste, the advantage of thermoplastic composites to be recycled but also to be “repaired” locally, lends itself more to reducing pollution, an issue that is increasingly discussed nowadays [13]. When heated above the glass transition temperature (Tg) or above the melting point, thermoplastic polymer matrices reach a reversible phase (solidification, melting). In addition, their ability to be molded, mechanical and chemical resistance and impermeability are desirable properties in vast applications. Acrylonitrile Butadiene Styrene (ABS), Polycarbonates (PC), Polypropylene (PP), Low-Density Polyethylene (LDPE), Polyvinyl Chloride (PVC) and Polyethylene Terephthalate (PET) are widely used and the most widespread thermoplastic polymer matrices in the field of composite materials [14]. The tensile strength and high elasticity of the PET-based polymer matrix, compared to the other polymer matrices, highlight the high usability of PET to be used for better performance [11].

Additives added to the polymer matrix are also very important. They do not affect the molecular structure of the polymer.

Under the name of compounding agents or auxiliary ingredients, additives are used to provide thermal stability to the matrix and prevent polymer aging. Additives can also improve mechanical properties, machining performance and provide special properties to the matrix (conductivity, heat transfer) [15].

3. Classification and properties of fibers used in polymer composite materials

When it comes to the reinforcing elements of composite materials, they can be in various forms and of several types. Fibers of different nature with varying lengths and diameters can be used. Particles of varying sizes, made of various materials can also be used to reinforce the polymer matrix. By changing the parameters related to volume, size, type, shape, but also the orientation of these fibers or particles, the desired composite materials can be accurately obtained [16]. Fiber-reinforced polymer composites (FRCP) use natural (NFRCP) or synthetic (SFRCP) fibers. Natural fibers can be from plants, animals or of a mineral nature Fig. 1. Animal fibers: silk, feathers and feather fibers, wool, animal hair, etc. Vegetable fibers: seeds e.g. cotton, plant leaves e.g. sisal, fibers from the bark of the plant, fibers extracted from the fruit e.g. coconut or even fibers extracted from the stem e.g. wheat straw, rice, or even bamboo and grass.

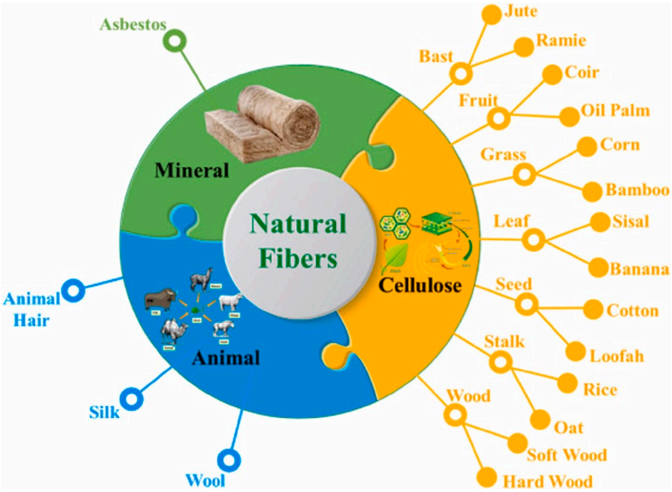

Fig. 1. Classification of fibers by origin [17]

In general, the chemical composition of these types of fibers is based on cellulose, pectin, lignin, wax and hemicellulose. These are the main chemical constituents. Hemicellulose that ensures biodegradation and moisture absorption, while lignin is responsible for the behavior of the fiber during exposure to UV radiation, and cellulose generates mechanical strength. The percentage composition of these constituents differs depending on the type of fiber as can be seen from TABLE 1 [18].

TABLE 1

Chemical composition of different types of natural fibers [18]

Fiber	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)	Wax (wt.%)
Bamboo	26-43	30	21-31	—
Kenaf	72	20.3	9	—
Jute	61-71	14-20	12-13	0.5
Hemp	68	15	10	0.8
Sisal	65	12	9.9	2
Abaca	56-63	20-25	7-9	3
Wood	40-50	20-30	20-30	1
Banana	60-65	6-8	5-10	—
Pineapple	81	—	12.7	—
Okra	60-70	15-20	5-10	3.9

From the point of view of physical and mechanical properties, the performance of natural fibers compared to synthetic fibers is not extraordinary, if we are to talk about them tested freely, however, the mechanical properties of natural fibers increase exponentially when they are integrated into a matrix. The main elements influencing the characteristics of natural fibers, especially their mechanical properties and wear resistance, are their chemical composition, structure, defects and cell size. In general, as the concentration of cellulose increases, the tensile strength of the fiber and the Young's modulus increases [19,20]. TABLE 2 shows the mechanical performance of natural fibers not integrated into a matrix.

TABLE 2

Mechanical properties of natural fibers [18]

Fiber	Tensile strenght (MPa)	Young's Modulus (GPa)	Density (g/cm^3)	Elongation at break %
Bamboo	503	35.91	0.6-1.1	1.4
Kenaf	295	-	1.2	2.79-6.9
Jute	400-800	10-30	1.46	1.8
Hemp	550-900	70	1.48	1.6
Sisal	600-700	38	1.33	2-3
Abaca	980	-	1.5	-
Wood	40-100	8-20	0.3-1	2
Banana	355	33.8	1.35	53
Pineapple	170-1672	82	1,5	1-3
Okra	68-282	5.74-16.55	-	2

The advantages of using natural fibers as reinforcement elements in composite materials, starting with high performance, low cost, simple storage, natural roughness of fibers, good sound and heat insulation properties, light weight, and most importantly biodegradation. They make natural fibers be used more compared to artificial ones. The disadvantage of these fibers is generated by the absorption of moisture, characteristic of natural fibers. This phenomenon causes the bond between the polymer matrix and the fiber to deteriorate [18].

Another problem with the use of natural fibers as reinforcement is related to the fact that the hydrophobic nature of the polymer matrix and the polarity of the fibers leads to poor adhesion between the two phases. This problem can only be solved by treating the surface of the fibers before they are integrated into the matrix [21]. Alkali-silica treatments can increase fiber compatibility, resulting in better dispersion in the polymer matrix. A surface free of impurities and improves the interaction between fiber and matrix [22]. It is also essential that the fibers and matrix are chemically compatible. Chemical interactions such as hydrogen bonds, van der Waals forces, and ionic bonds can exist between the fiber and the matrix. A better mechanical bond can be achieved by increasing the contact surface between the fibers and the matrix. The absorption of moisture by natural fibers can change their chemical and physical characteristics. Therefore, adhesion to the matrix can be affected by it. Finally, adhesion can be significantly influenced by the intermolecular interactions that occur between natural fibers and the matrix. Intermolecular forces, such as dispersion, hydrogen bonds, and ionic interactions, can improve the adhesion and mechanical characteristics of composites [23-25]. The physical and mechanical properties of NFRCP can be altered by physical (cold plasma treatment, stretching, electrical discharge, etc.) and chemical treatments that alter the chemical composition and surface of the fiber (degradation resistance, decrease moisture absorption, etc.) [26]. In addition, the polymer matrix of the composite material can also be modified by adding inorganic nanoparticles, to obtain a high-performance composite, as can be seen in Fig. 2 [27].

The use and development of NFRCP focuses on minimizing plastic pollution by developing new sustainable but biodegradable materials such as NFRCP and using them in new areas. Their use in industrial applications could be fulfilled through a sustainable design concept, as illustrated in Fig. 3 and their sustainability [28].

Due to the lower mechanical strength of natural fibers compared to synthetic fibers, synthetic fibers still remain used for

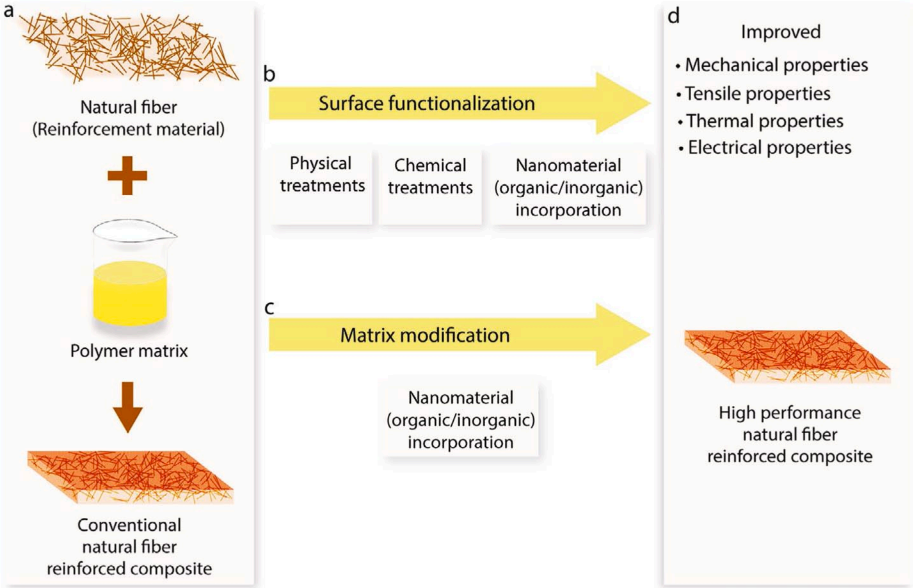

Fig. 2. Improvement of a) NFRCP properties by b) surface functionalization of fibers and/or c) modification of the matrix to produce d) high-performance natural FRP composites [27]

Fig. 3. NFRCP sustainability and life cycle [28]

some applications. Although they have difficulties in recycling, high density and high cost, synthetic fibers are used in applications where the degree of humidity and temperature at which they are used would not allow the use of natural fibers. It has also been shown that SFRCP with a lower percentage of fibers in the composition, provides better mechanical results than NFRCP which additionally uses up to about 20% fibers and the tensile strength is lower. In Fig. 4 we can see the difference in tensile strength and the percentage of fibers used in the polypropylene-based matrix composite material [29].

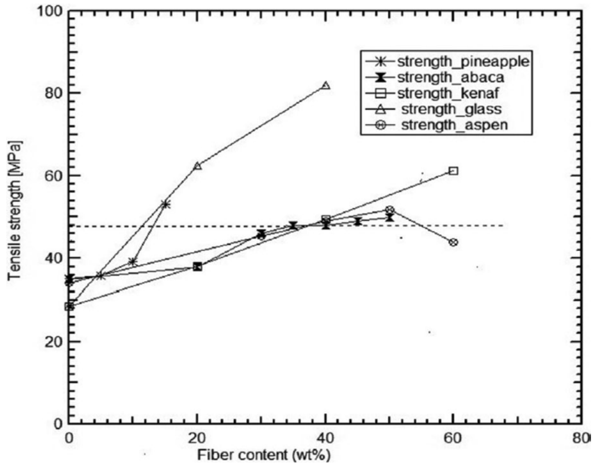

Fig. 4. Tensile strength of NFRCP and SFRCP with polypropylene matrix and different fiber percentages [29]

Synthetic fibers commonly used for SFRCP possess different properties depending on the type of application in which they are used. Electrical glass (E-Glass) is used in the manufacture of boats but also for electrical insulation, structural glass (S-Glass), used mainly in the aerospace field due to its excellent mechanical strength, carbon fiber (CF) known for its high weight-to-strength ratio and aramid fiber, with excellent resistance to traction, impact and abrasion. TABLE 3 shows the mechanical properties of synthetic fibers predominantly used in the manufacture of SFRCP [27].

TABLE 3

Mechanical properties of synthetic fibers [27]

Fiber	Tensile strenght (MPa)	Young's Modulus (GPa)	Density (g/cm^3)	Elongation at break %
E-Glass	2000-3500	70-77	2.5	4.5-9
S-Glass	4570	86-90	2.5	4.5-9
Carbon	3400-5400	230-440	1.8-1.9	1.4-1.8
Aramid	3400-4000	130-185	1.45	2.5

4. Classification and properties polymer matrix used in composite materials

As already mention, physical and chemical properties of the composite material matrix are very important in its behavior under external stresses [30]. Depending on the source of origin, polymers can be natural and synthetic [31]. The synthetic thermoplastic or thermosetting (Fig. 5), are synthesized by humans. Of the two classes of synthetic polymers, thermoplastics have various applications, due to their functions of being able to be reused. For applications where the possibility of materials to be recycled is a mandatory prerequisite, thermoplastic polymers are used, as thermosetting polymers are resistant to degradation due to their tightly cross-linked network structures [32].

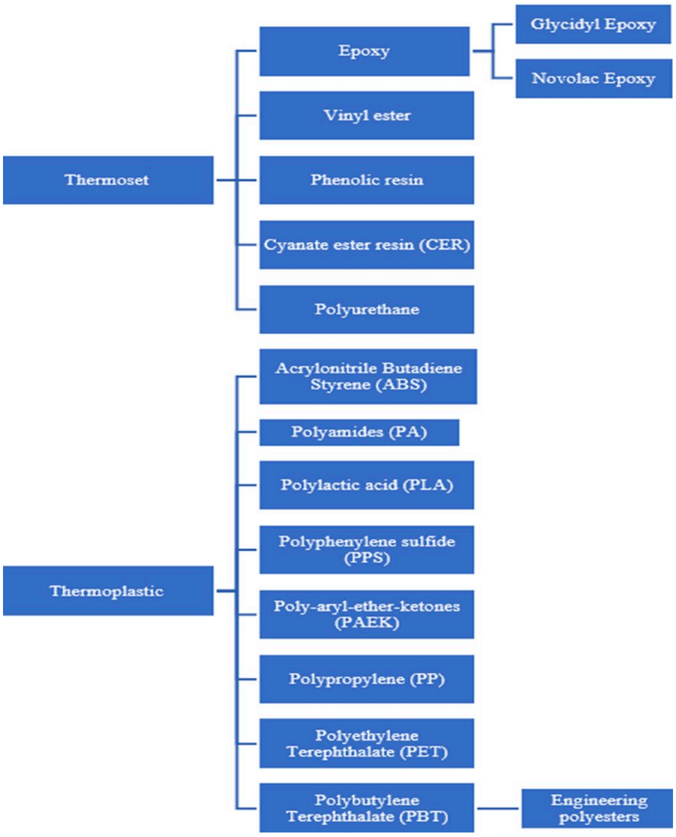

Fig. 5. Types of polymers frequently used as a matrix for composite materials

Biodegradable polymers can be degraded by the action of living organisms such as bacteria and algae, and eventually they break down into CO_2 or CH_4. These polymers can come from natural sources or they can be created from fossil fuels as in Fig. 6. The environment in which these polymers can degrade varies depending on the type of polymer, polylactic acid (PLA) degrades over a few years, while other polymers such as polyhydroxyalkanoates (PHA), polycaprolactone (PCL) are much easier to degrade, due to the numerous living organisms that can accelerate the hydrolysis of ester groups in molecules. Biodegradable synthetic polymers can also be created through conventional polymerization procedures [32,33].

When it comes to the mechanical properties of the polymer matrix, they must be carefully studied and analyzed, the performance of the composite material is closely related to the characteristics of the matrix. [33-35]. As can be seen in TABLE 4, the mechanical properties of thermosteric polymers are superior

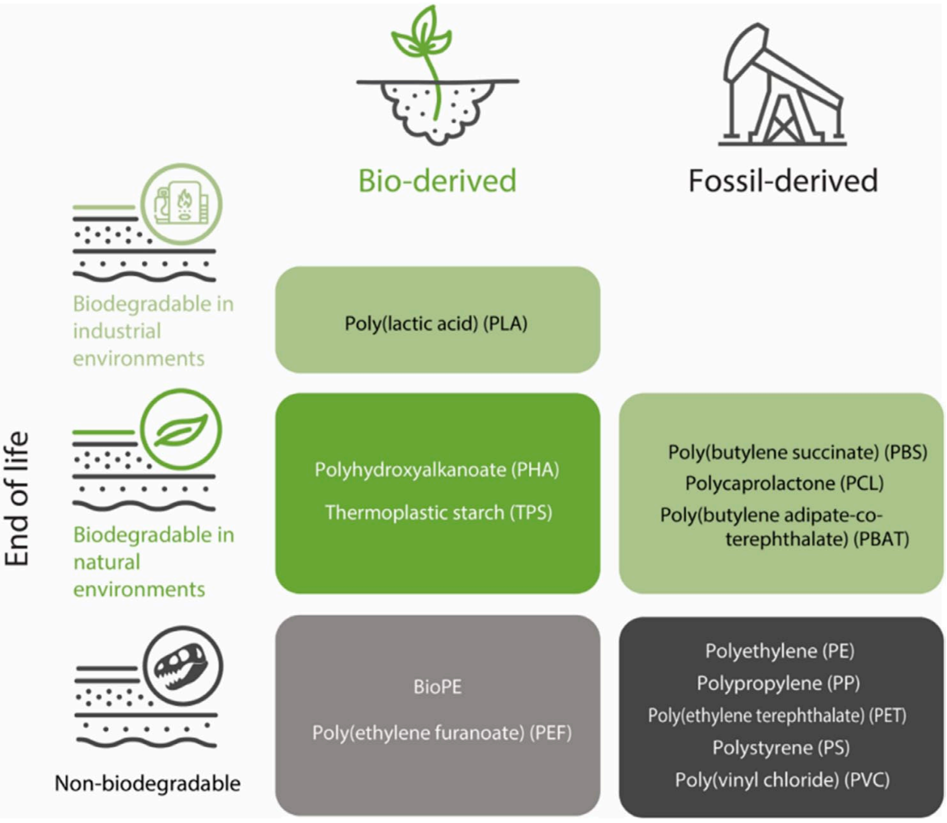

Fig. 6. Classification of polymers by source and possibility of degradation [33]

TABLE 4

Properties of polymers commonly used as a matrix in composite materials [33-35]

Category/Subcategory		Polymer	Density (kg/m³)	Tensile strength (MPa)	Elongation at break (%)	Young's modulus (GPa)
Biodegradable		PLA	1210-1250	21-63	2.5-6	0.35-3.5
		PHB	1180-1260	24-40	5-8	3.5-4
		Starch	1000-1390	5-6	31-44	0.125-0.85
Thermoplastic	**Synthetic**	Polyethylene (PE)	910-955	25-45	150	0.3-0.5
		Polypropylene (PP)	900-910	20-40	80	0.95-1.77
		Polyvinyl chloride (PVC)	1300-1500	52-90	50-80	3.0-4.0
		Polystyrene (PS)	1040-1050	35-60	1.6	2.5-3.5
		LDPE	910-925	40-78	90-800	0.055-0.38
Thermoset	**Synthetic**	Unsaturated polyester (UPE)	1200-1500	40-90	2	2.0-4.5
		Epoxy (EP)	1110-1400	28-100	2-10	3.0-6.0
		Phenolic (PH)	1300	35-62	1-2	2.8-4.8
		Vinyl ester (VE)	1200-1400	69-86	4-7	3.1-3.8

to thermoplastic polymers. This makes thermoset polymers to be used in applications where mechanical and high-temperature strength cannot be met by thermoplastic polymers [36]. Also, impregnating fibers with thermoplastic polymers is a problem due to their viscosity at processing temperature. The temperature at which the processing takes place can negatively influence the microstructural and mechanical properties of the composite and affect the thermal stability of the matrix [37,38]. The main problem of composite materials with thermosetting polymer matrix is related to the irreversible reaction of the polymer. Thermosetting polymers cannot be recycled because they cannot be deformed and the separation of fibers from the matrix is very difficult. In contrast, thermoplastic polymers can be separated from reinforcing elements (by heat and pressure) and can be recycled [39].

The polymer matrix can be divided into two broad categories according to the properties it possesses. The matrices predominantly used in composite materials are thermoplastic polymers and thermosetting polymers. Thermoset polymers possess excellent chemical resistance, have a tensile strength ranging from 20-100 MPa, thermal stability in the range of 300-450°C, and cannot be reprocessed after they have hardened. Thermoplastic polymers have good chemical resistance, tensile strength between 20-90 MPa, with a thermal stability in the range of 100-350°C, they are easier to process (PE, PP) and most importantly, they can be recycled and reused [40].

4.1. Thermoset polymer matrix

Phenolic resins are one of the main resins used to create composite materials reinforced with natural fibers [41]. These oligomer polymers offer outstanding fire and smoke resistance and can have applications in toxin filtration, the production of electronic components and in the aerospace industry [42,43]. They are used for adhesives, protective coatings or electrical insulation, possess good mechanical properties, are resistant to acids and high temperatures [44].

Cyanate ester is a heat-resistant resin that is used in composite materials used at extreme temperatures. This resin is thermally stable, with very low moisture absorption and low thermal expansion. However, through various additive methods, its properties can still be improved. The fields in which they are found vary from the aeronautical industry for the manufacture of aircraft wings, to telecommunications antennas and the creation of resistant adhesives [45,46].

Epoxy resins are usually obtained by combining them with a curing agent. This mixing-curing process is a chemical phenomenon in which the strongly cross-linked three-dimensional lattice of epoxy resin is formed. The added curing agents cause the resin to solidify at low temperatures (aliphatic amines) or at high temperatures (aromatic amines). The reaction between the epoxy resin and the curing agent leads to a reduction in its brittleness, an improvement in its behavior to crack propagation, but also to a low delamination. The properties of resins depend a lot on the length of the molecular chain in its structure, molecular weight, and its structure [47]. Depending on the type of hardener used, epoxy resins cure between 5 and 150°C and can be used at temperatures up to 175°C [48]. They are often used as a matrix in composite materials and are compatible with many types of fibers. Used as raw material, epoxy resins are used to create circuit boards, packaging materials, and computer chips [49].

Vinyl ester is a resin similar to polyester, which has similar molecular structures. The molecular structure of vinyl ester resins ensures its thermal stability and mechanical strength. This type of resins is mainly used in fiber-reinforced composite materials due to the superior performance it gives to the composite material. Chemical resistance, reduced shrinkage during curing, low degree of moisture absorption, are qualities that vinyl ester-based resins possess at the expense of polyester resins. In addition, vinyl ester resins perform better than many other resins and are cheaper than epoxy resins [48,50].

Phenolic resins is another thermosetting polymer, which have vast applications due to their fireproofing properties and very good thermal and chemical resistance. Used as a matrix in fiber-reinforced composite materials, phenolic resins offer extraordinary performance and are used in ballistic, aerospace or even electronic applications [51].

4.2. Thermoplastic polymer matrix

Polylactic acid (PLA) is a natural biodegradable polymer obtained from renewable sources (corn, potato) that is fermented in a carboxylic acid, but can also be obtained from non-renewable sources. These thermoplastic polymers are easy to produce, can be recycled and reused [52]. These biopolymers are vulnerable to high temperatures, humidity and oxidize. However, they can be used in composite materials and have applications in the aerospace and automotive industries if reinforced with carbon nanotubes (CNTs) [53]. Reinforcing them with CNT improves their thermal and mechanical characteristics. Compared to ABS, PLA is more attractive for 3D printing applications because it requires low printing temperatures between 190-230°C [54].

Acrylonitrile butadiene styrene (ABS), is a common thermoplastic, used to manufacture car body parts, pipes, industrial protective helmets, etc. It has become one of the most widely used polymers due to its ease of processing and availability [55]. This copolymer is very durable, has high resilience, is easy to process and is impact resistant [56,57]. ABS polymer matrix composites can be processed very easily by injection or thermoforming, and composite materials with complex shapes, high tensile, impact and heat resistance can be obtained [58]. The number of ABS recycling cycles is limited, the properties of the recycled ABS polymer are weaker than that of virgin ABS, but they can be improved by additives. It has been shown that by adding additives to recycled ABS polymer, its mechanical, thermal and chemical properties are better than those of virgin ABS polymer [59].

Polyester is a thermoplastic that includes natural and synthetic compounds. Saturated polyester resin is thermoplastic, and unsaturated resin is thermoset. This saturated polyester is widely used for the development of composite materials with a wide range of applications [41]. Polyester resins possess excellent thermal and electrical properties and also have low moisture absorption and good flow during processing [60].

Polyamides have been used more and more since the 1950s due to their ability to replace metal parts in the automotive industry [61]. Polyamides can be aliphatic (Nylon) or aromatic (Aramids). Aliphatic polyamides oxidize under conditions of high temperature and humidity. Aromatic polyamides have better mechanical properties compared to those of aliphatic polyamides [62]. The use of polyamides in carbon fiber reinforced composites (CFRC) gives the material resistance to fatigue, wear, corrosion, conductivity and thermal stability and in addition they are lightweight. However, the use of polyamides in CFRC is difficult because their high viscosity leads to insufficient impregnation of carbon fibers [63].

Polyurethanes are a versatile class of polymers due to the large number of applications in which they are found. They are mainly used to thermally insulate walls, cars, refrigerators. They have a long lifespan and can be easily obtained [64], but they decompose very slowly and generate a lot of waste [65]. Its additive is difficult when used as a matrix in composite materials, but it gives the composite material better impact and tensile strength than vinyl ester resins [66].

Polyethylene terephthalate (PET) is a widely used thermoplastic due to its excellent chemical and mechanical properties. It is used in a wide range of applications because it is readily available and has a low processing cost [67,68]. Its mechanical properties and microstructure can be improved with the help of additives [69]. Surface characteristics can be improved by ultraviolet or plasma treatments to give composite materials increased performance [70]. The tensile strength is around 61 MPa and the Young modulus of 2950 MPa being better than that of ABS polymer [71].

At present, the best organic thermoplastic polymer used as a matrix in composite materials is polyetherketone (polyether ether ketone – PEEK). It is used to develop high-performance composite materials, but it is very expensive. PEEK has excellent mechanical, chemical and thermal properties and is recognized for its hardness of up to 100 MPa in tensile strenght, with a Young modulus of about 3 GPa and having the melting point at about 350°C. Tests between glass fibre-reinforced PEEK, compared to non-reinforced PEEK, revealed substantial differences between the two. Reinforced PEEK showed an increase in mechanical properties of up to 66% [72]. Carbon-reinforced PEEK composites also offer excellent mechanical properties, but due to their high viscosity, cumbersome impregnation with carbon fibers and their high cost, PEEKs are not used in large-scale applications [73].

5. Methods of obtaining polymer matrix composite materials and applications

Depending on the type of matrix used, but also on the type of reinforcement elements, the manufacturing processes of composite materials may differ. The main methods by which composite materials are developed can be seen in Fig. 7 [27]. These can be done by open molding or closed molding techniques. Although combinations of two or more processes are also used in some manufacturing processes [74]. Open molding process involves exposing the materials that make up the composite material to air. Solidified of the matrix and addition of reinforcement elements takes place outdoors [30]. Closed molding is preferred in large-scale production of composite parts because most of the processes are automated and take place inside a mold [75]. The most used open molding methods for FRP manufacturing are hand layup, spray layup and filament winding [30].

Hand layup it is the simplest and cheapest way to obtain a composite material (Fig. 7a) and is specific to composite materials with a heat-resistant polymer matrix [76]. This involves the use of only a few tools (rollers, brushes and a mold into which the resin is poured and the reinforcement is added) and the whole process depends on the skill of the operator [77,78]. The reinforcement layers are placed manually in the shape to be obtained or can be cut if there are several small pieces. Resin is added over the reinforcing elements, and with the help of utensils the degree of impregnation of the layers can be ensured. In some

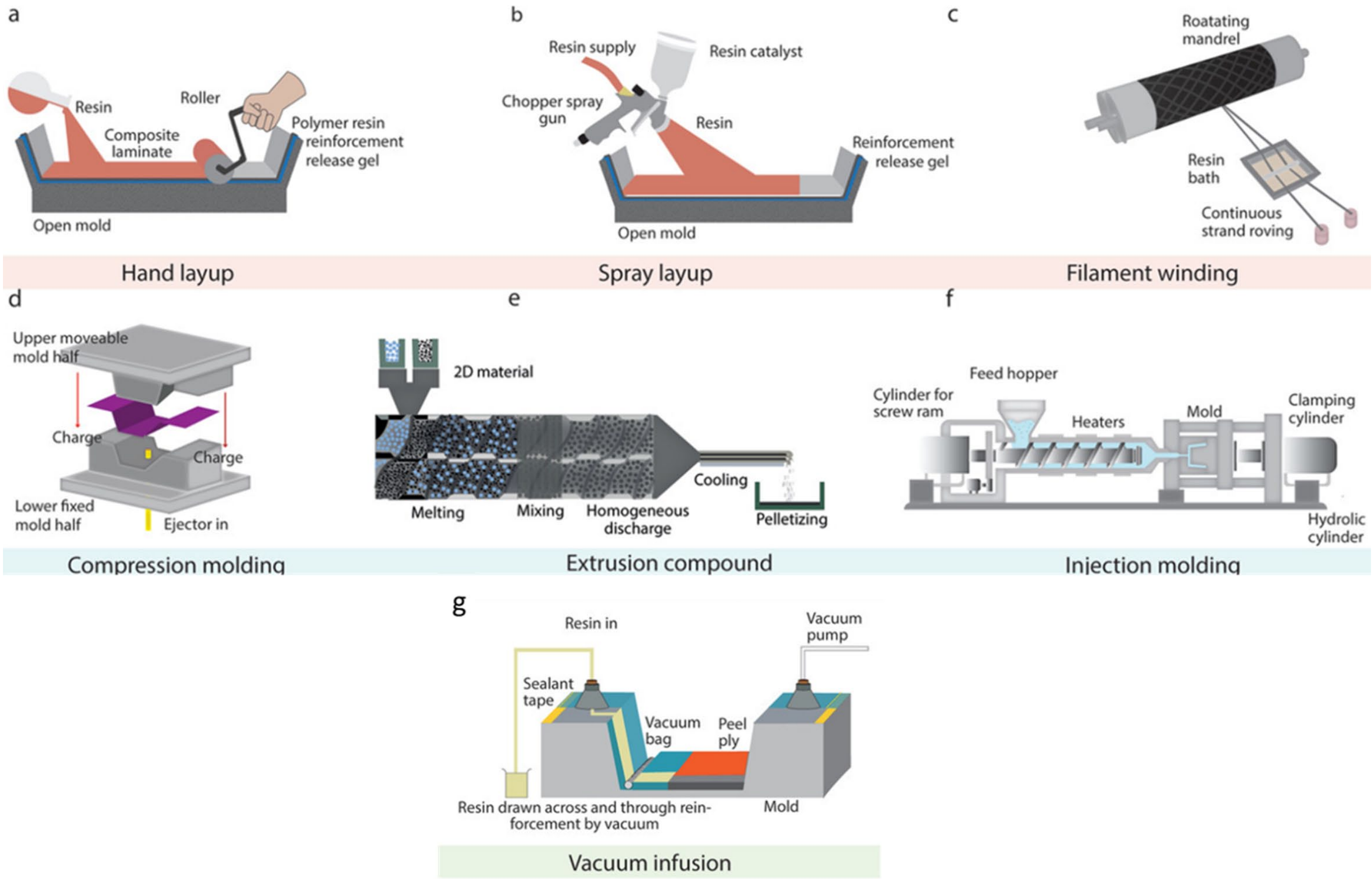

Fig. 7. The main processes of obtaining fiber-reinforced composite materials [27]

cases, cutting or spiking rollers are used to ensure that the fibers are moistened inside the fibers as well. Another advantage of this process is the fact that it is not necessary to heat the composite, and solidification occurs at room temperature [79]. This type of method is usually used for repairing or manufacturing boat decks or wind turbine blades, but also for insulating or repairing concrete structures. In addition, sandwich composites can also be created through this process [80–82]. This process was also compared with the vacuum assisted resin infusion process to study the degree of resistance of a repaired sample. Glass fiber reinforced epoxy matrix composites repaired by the hand layup method achieved good results but comparatively worse than the vacuum resin infusion process [83]. The disadvantage of this method is the poor bonding at the interface of the reinforcing elements and. In addition, the air gaps present inside the composite material, the placement of the fibers or layers of fibers, but also the pressure exerted on them during the process, are factors that greatly influence the final quality of the composite material [83,84].

Spray layup is another open molding technique that resembles the manual one discussed earlier and can be seen in Fig. 7b. For this process, a spray gun is required with which the resin is sprayed over the reinforcing elements or the resin and shredded fiber mixture can be sprayed directly from the gun. The spray gun can also be equipped with a roller on which reinforcing fibers are wound, and at the end of it the fiber is shredded by a shredder [85,86]. Similar to the manual process, the final quality of the composite material depends on the skill of the operator, but this type of process is much faster and parts with much more complex shapes can be made [87]. This type of process is frequently used in the manufacture of bathtubs for applying the outer layer over the initial shape of the bathtub obtained from an acrylic thermoplastic. This outer layer gives hardness and rigidity to the final product. It has been shown that similar mechanical properties can be achieved by using synthetic GF fibers or natural fibers such as jute (JF) in the spray gun to stiffen bathtubs [88]. The main advantages of this process are the fast production through the semi-automatic process, the easy application of coatings, the possibility of fixing defects but also the large size of the parts that can be manufactured or repaired [89].

Filament winding is also an open molding process whereby the continuous reinforcing fibre is impregnated with resin in a bath before being wound, as can also be seen from Fig. 7(c) [90,91]. It is further rotated on a rotating mandrel with the role of a mold. The mandrel can have complex shapes and the fiber winding angle can vary to provide increased strength [92]. The biggest advantage offered by this process is the reduction of up to 75% of the weight of the part. This process is mainly used for the manufacture of gas tanks, pipes, pipes or vessels [93]. Composite products, manufactured through this process, offer an excellent strength-to-weight ratio, good tensile strength and precise control of fiber orientation [94].

Compression molding is a closed molding technique. This process involves the use of a hydraulic press with two mold cavity/matrice (Fig. 7d). The fixed lower mold cavity on which the composite material is made and another mobile upper mold that presses and keeps the composite material warm to obtain the desired shape. The resin prepreg reinforcing fibers are placed inside the bottom mold and pressed. The pressing force, the holding time and the temperature at which the entire process takes place can influence the mechanical properties of the composite material [90, 95]. Through this process, a variety of products can be manufactured, from industrial protective helmets, household items, car body elements, boats, packaging and so on [96-98]. The compression molding process provides much better results compared to injection molding. The ideal composite materials can be obtained through the compression molding process, with better mechanical properties, better tensile strength, higher density and fewer air voids [99-101].

Extrusion molding process is a continuous manufacturing process of composite materials with constant cross-section. Through this process, rods, films, pipes can be made, their shape being given by its final die (also called mold) through which the composite material is forced out, being chopped, heated and mixed in the extruder body as can be seen in Fig. 7e [102]. Shredding, mixing and forcing the composite material into the mold in a liquid state is carried out with the help of at least one rotary screw. At the top of the extruder, a hopper is positioned to continuously feed the extruder with a mixture of polymer and fibers [103]. The polymer matrix with which the extruder is fed can be in the form of pellets of variable sizes [104]. In the case of injection molding, instead of the final die of the extruder, a closed mold is placed that can have complex shapes and after filling the material is allowed to cool [105].

Similar to the vacuum bag molding process is the vacuum assisted resin transfer molding. In the vacuum bag molding process the composite material is enclosed between two sheets of nylon, PVA or polyethylene and sealed at the ends. The vacuum assisted resin transfer molding (VARTM) process uses a single sheet placed over the reinforcing layers in the mold (Fig. 7g). The difference between the two processes is that the resin is infused after all the air has been extracted from the sealed form [106,107]. The resin is infused with the help of a pump and travels through the reinforcing layers to the air extraction pump. Through this process, products with large, complex shapes and a small percentage of air gaps inside can be obtained cheaply, ideal for mass productions [108,109]. The VARTM process is used in the manufacture of various parts in the aerospace, aquatic and automotive industries [109-111]. Although it is a cost-effective process, the presence of air gaps is the main disadvantage of this method, these defects being the main cause for the propagation of cracks and the failure of the material [112,113].

6. Conclusions

The need to develop new materials is a priority nowadays. Composite materials have proven through their qualities that they are an ideal candidate for replacing conventional materials. Although there is a wide variety of methods for obtaining fiber-reinforced composite materials, the main goal must remain to obtain a durable material at low cost. It is also equally important to integrate local resources in the manufacture of new composite materials that can replace conventional materials used mainly in all industries. The right method of obtaining them must be chosen according to the role that the final product must play.

Polymer matrix composites stand out and stand out at the expense of other types of matrices, due to their properties. High chemical resistance, excellent adhesion with reinforcing elements, physical and mechanical properties, fatigue resistance, low shrinkage, are necessary qualities for applications in vast fields and polymers possess them. The problem of the impact generated by the consumption of non-regenerable resources can be solved by using natural polymers that have proven to be an equally good candidate in composite materials.

However, reinforcing elements, regardless of their type, can greatly influence the final quality of the composite material, which is why it is very important to be studied. Surface treatments of natural fibers and preparation processes before integration into the matrix are vital. Natural fibers are a strong candidate over synthetic fibers, but there are still applications where only synthetic fibers can serve specific purposes. The interaction of the two phases and the connection between them in a composite material is the most important aspect. Controlling them becomes very difficult considering all the parameters that can influence them and the variety of combinations that can be obtained if one of them is changed.

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